MacMillan, Douglas C. (1991) *Predicting the general yield class of sitka spruce on better quality land in Scotland.* Forestry, 64 (4). pp. 359-372. ISSN 0015-752X.

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Predicting the General Yield Class of Sitka Spruce on Better Quality Land in Scotland

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SUMMARY

The ability to predict accurately the potential site productivity of unplanted land is extremely important for forestry investment appraisal, production forecasting and land use planning at regional and national levels. This paper describes a model for predicting the General Yield Class (GYC) of Sitka spruce (*Picea sitchensis* (Bong.) Carr.), the most important commercial forestry species, on better quality land in Scotland. Using principal component analysis and multiple step-wise regression techniques 36.8 per cent of the total variation in GYC was explained by variation in 10 site and crop variables. The *F* statistic from the analysis of variance was significant at the 1 per cent level. Site factors most highly correlated with GYC were those related to climatic exposure (elevation and topex), soil moisture status (site drainage class and soil drainage class), crop age and soil type. Mean estimated deviation of predicted GYC from actual GYC ranged from 1 $m^3 ha^{-1} yr^{-1}$ for average sites (that is sites where the dependant variables were close to their average values) to 2.7 $m^3 ha^{-1} yr^{-1}$ for extreme sites. The predicted GYC for 15 independent sample sites was 18.5 $m^{-3} ha^{-1} yr^{-1}$ compared to a true mean of 18.9 $m^3 ha^{-1} yr^{-1}$. This compares favourably with predicted means of 22.1 and 13.6 $m^3 ha^{-1} yr^{-1}$ from two earlier models.

INTRODUCTION

Tree growth rate has the greatest influence on the rate of return from a forestry investment since it determines timber yield and in many cases rotation length. The classification of the growth rate of forest crops in the United Kingdom is based upon the estimation of their General Yield Class (GYC) (Rollinson, 1986). GYC can be defined as the maximum average rate of volume increment that a particular stand can achieve and is determined from the relationship between top height and age (Edwards and Christie, 1981).

The accurate prediction of GYC is important for land acquisition, plantation valuation, production forecasting, the choice of appropriate silvicultural and management practices and land use planning.

In the past, foresters have generally relied on their own field experience when assessing the GYC of unplanted ground or on generalized models based on rules of thumb which incorporate little or no supporting data (Busby, 1974). A number of objective models for predicting GYC of some of the major commercial species have however been developed. Most have been limited in application because they were either developed for use at the forest or regional level and were not sufficiently robust for more general application (McGarry, 1979; Blyth and Macleod, 1981) or have incorporated factors which are too time consuming or technically difficult to measure (Adams *et al.*, 1970; Malcolm, 1970; Page, 1970; Blyth, 1974). More recently Worrell (1987b) produced a reliable and robust model for predicting the GYC of Sitka spruce, but only for sites in upland Britain where exposure is the major factor limiting tree growth. On land at lower elevations other factors such as soil type (Blyth and MacLeod, 1981), droughtiness (Jarvis and Mullins, 1987) and the movement of moisture through the soil (Page, 1970; Blyth and MacLeod, 1981) are thought to have a greater influence on tree growth.

Current government policy initiatives such as the better land supplement within the Woodland Grant Scheme, the Farm Woodland Scheme and Set-Aside to Woodland are now encouraging the afforestation of more fertile agricultural land at lower elevations. The prediction of GYC on better quality agricultural land is however difficult because no reliable predictive model has been developed for such sites and most foresters lack the relevant experience of crop performance.

The aims of this study were therefore to:

1. quantify the variation in GYC in crops of Sitka spruce, the most important commercial forestry species planted in Scotland, growing on land of better quality;
2. develop a reliable predictive model for GYC to complement Worrell's upland model which is sufficiently robust for use on better quality sites throughout Scotland and which incorporates data that are relatively easy and quick to collect;
3. draw inferences from the data about the site factors influencing the growth of Sitka spruce on better quality sites.

METHODS

Sampling strategy

The sampling strategy was aimed at pure crops of Sitka spruce in eastern and southern Scotland planted on better quality sites at low elevation. In the context of this study better quality agricultural land was defined as being land in Land Capability for Agriculture (LCA) Class 5 or better (Bibby *et al.* 1982) and for which Worrell's upland model was not applicable. Worrell's model was developed specifically for sites at moderate to high elevations in northern Britain where exposure is the major factor influencing tree growth. The lowest elevation to which his model applies ranges from 40 m in the most exposed western areas to 300 m in sheltered inland sites. Figure 1 shows the distribution of better quality land in Scotland (as defined above) and the location of the forests in which sampling occurred. Within these general guidelines the sample plots were located in crops of Sitka spruce of at least 1 ha between 25 and 55 years old. Crops less than 25 years of age were excluded since the assessment of GYC is more sensitive to measurement error in younger crops and they are unlikely to express the full potential of the site in terms of the effects of competition for moisture and nutrients (Coile, 1952).

Data collection

The sample plot was located at least 10 m from the crop boundary to avoid any possible edge effect. Crops receiving immediate shelter (within 50 m of the plot) from older stands were avoided. Top height was determined from the average height of the three trees in a 0.03 ha plot with the largest breast height diameter (Edwards and Christie, 1981), excluding individuals displaying irregularities of form (badly forked) or signs of disease. Number of growing seasons (crop age) was determined from compartment records. Values for crop age and top height were used to determine GYC to the nearest 0.1 $m^3 ha^{-1} yr^{-1}$ from the published models (Edwards and Christie, 1981).

At the centre of each plot a soil pit was excavated to determine Major Soil Group (MSG), and Major Soil Sub-Group (MSSG) according to the Macaulay Institute's soil classification (Soil Survey of Scotland, 1984). Slope (°) and aspect (°) of the plot were assessed using an Abney level and compass respectively and soil drainage class was assessed from profile morphology. Site drainage of the plot was based on the interpretation of slope form and soil moisture movement through the plot. Three classes were recognized. Shedding (net loss of soil moisture, typical of convex slopes), normal and receiving (net influx of water, typical of concave slopes). Topex score following the procedure outlined in Wilson (1984) and elevation were derived from Ordnance Survey topographical maps (1:50 000 scale). Yield Class Zone (YCZ), which is based on estimated sea level values for accumulated temperature and tatter rate was interpolated from the relevant map in Forestry Commission Bulletin 72 (Worrell, 1987b). Climatological data on rainfall, (Meteorological Office, 1977) accumulated temperature and potential water deficit (Birse and Dry, 1970) which were taken from 1:625 000 maps were not included because their measurement was considered to be unreliable due to the scale of error associated with even very small locational mistakes. The assessment of YCZ was considered to be more reliable because it was relatively easy on such a simple map to interpolate between each zone. A total of 128 datasets were collected.

ANALYSIS

Of the site variables recorded at each plot ten were considered to be relevant to the prediction of GYC. MSSG was not included in the final model because

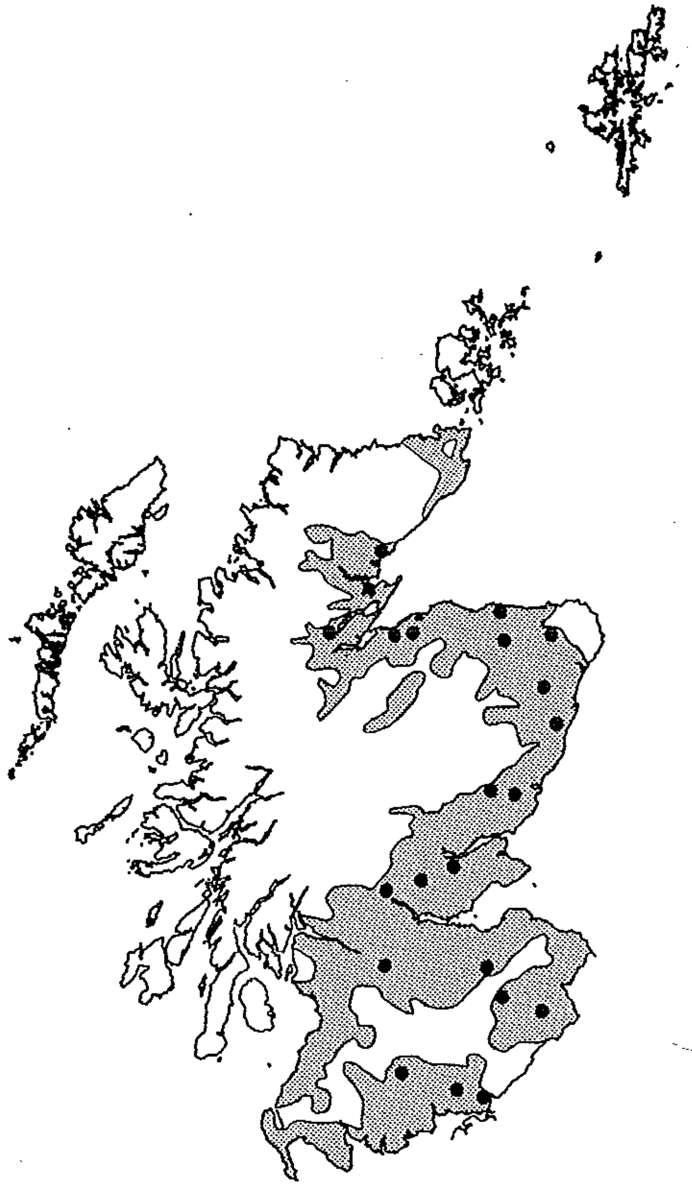
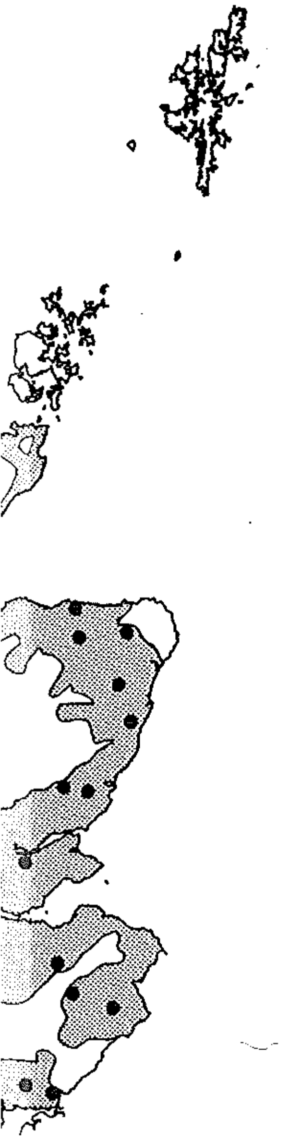


Figure 1. Location of forests (●) used in sampling the General Yield Class of Sitka spruce on better quality land in Scotland (shaded area).



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it was highly correlated with MSG (R^2 = .86). Qualitative variables such as site drainage, soil drainage and MSG were scored to reflect a linear ordering based on observable trends with GYC in the data. Soil drainage classes were ranked in the following way: free (−2), moderate (−1), imperfect (0), poor (1) and very poor (2). Site drainage was scored 1 for shedding, 2 for normal and 3 for receiving sites but were subsequently transformed by squaring to allow for non-linearity of the residuals. MSG was ranked in the following order: alluvial (1), brown earth (2), gley (3), podsol (4) and organic (5). Alluvial and organic (peat) soil groups occurred in a total of only seven plots and were not included in the final model on the grounds of insufficient data. Aspect (°) was transformed into a north–south (cosine) and an east–west component (sine). A list of the variables included in the final analysis is given in Table 1 together with their mean and range values. Total number of data sets used in the final analysis was 121.

TABLE 1: *Minimum, maximum and mean values for GYC and the 10 site variables used in the model*

Independent variable	Minimum	Mean	Maximum
Age (years)	25	40	55
Elevation (m)	15	161	333
Topex (°)	3	27	92
Slope (°)	0	7	24
Cos (north–south)	−1	0.065	0.998
Sin (east–west)	−1	0.117	1.000
Site drainage class	1.0	2.02	3.00
Soil drainage class	−2	−0.89	2
Major Soil Group (MSG)	2	2.8	4
Yield Class Zone (YCZ)	3.5	5.1	5.7
General Yield Class (GYC) (m^3 ha^{-1} yr^{-1})	11.5	18.9	27.0

Notes:
Site drainage classes: 1 shedding; 2 normal; 3 receiving
Soil drainage classes: −2 free; −1 moderate; 0 imperfect; 1 poor; 2 very poor
Major Soil Group: 2 brown earth; 3 gley; 4 podsol

Principal component analysis (PCA) was employed for data exploration and analysis. The technique uses the deviations of the standardized values of the variables in the form of a correlation matrix. PCA has the advantage over multiple regression of reducing the number of variables which have to be considered without the danger of discarding a potentially important variable. It does this by extracting from the original data a series of principal components each of which is a function of all the original variables (Seal, 1964). The first new variable (principal component) extracted is that linear additive function of the old variables which accounts for the largest possible amount of variation in the data. Each additional new variable accounts for the largest amount of remaining variation such that it is independent of (orthogonal to) the previously derived principal components (Green, 1979). As each component is orthogonal to each other and uncorrelated it is straightforward to select between them in stepwise multiple regression to predict GYC (Malcolm, 1970). Correlation between site variables in linear multiple regression analysis on the other hand could result in variables which might have a large influence on the dependent variable being excluded or interpreted as being of only minor importance due to the inclusion in the model of another highly correlated but perhaps less ecologically significant variable. In PCA the interpretation of site variable effects is based on the size and sign of the load values attributed to each site variable within each component and on the value and statistical significance level of the regression coefficients of the individual principal components in the regression procedure. The final interpretation of site effects is therefore less direct than in straightforward multiple analysis but offers the researcher a more reliable approach since the final predictive equation is a function of all the original site variables.

RESULTS

Following stepwise regression analysis of GYC against the ten principal components, six principal components with a t value significant at the 5 per cent level for the regression coefficient (b) were identified (Table 2). The form of the regression equation is given below.

$$\mathrm{GYC} = 18.975 + 1.441(\mathrm{PC5}) + 0.590(\mathrm{PC2}) + 0.422(\mathrm{PC1}) + 0.552(\mathrm{PC3}) + 0.678(\mathrm{PC7}) - 1.122(\mathrm{PC10}).$$

[Regression Model 1]

Principal component (PC) 5 was selected first on the basis of having the highest t-value and accounted for 19.5 per cent of the total variation in GYC. None of the five other components selected accounted for more than 5 per cent of the variation.

The load values of the latent vectors for the six components selected in the final model are shown in Table 3. PC [5] which has the greatest effect on GYC predictions since it has the largest b value is primarily a function of crop age, elevation and cosine (north–south aspect). The relationship between all three variables and GYC is negative, that is as values for crop age, elevation and cosine increase GYC decreases. For cosine, this indicates that higher GYC is associated with southerly aspects. PC[2], which was selected second, is primarily an expression of site drainage, soil drainage, YCZ and sine (east–west aspect). The relationship between these four variables and GYC is positive. Higher GYC values are therefore associated with receiving sites, more poorly drained soils, a better climate zone and easterly aspects. PC[1] was the third component selected in the stepwise procedure and is primarily

TABLE 2: *Estimates and* t-*values of regression coefficients* (b) *of the six principal components included in the model*

	b estimate	s.e.	*t*-value
Constant	18.975	0.223	86.93
PC[5]	1.441	0.233	6.18***
PC[2]	0.590	0.181	3.25***
PC[1]	0.422	0.145	2.92***
PC[3]	0.552	0.209	2.64***
PC[7]	0.678	0.265	2.56**
PC[10]	−1.122	0.504	−2.23**

** 5% significance
*** 1% significance

an expression of elevation, topex, slope and MSG. PC[10] has the second highest *b* value but was selected last due to a relatively large standard error which reduced its *t*-value. The effect of the regression coefficient estimate for PC[10] on GYC is therefore large but only explains an additional 2.2 per cent of variation in GYC. Total variation explained by the model was 36.8 per cent. The *F* statistic from the analysis of variance was significant at the 1 per cent level.

From the component loadings in Table 3 it is clear most site variables are not acting on GYC in a straightforward manner. Only MSG has a consistent (negative) effect on GYC. In Figure 2 the component loadings for PC[5] and PC[2], the components selected first and second respectively in the step-wise

TABLE 3: *Load values for the six principal components included in the model*

Site variable	Principal component					
	(5)	(2)	(1)	(3)	(7)	(10)
Age	−.504	−.131	+.223	−.591	+.073	+.073
Elevation	−.492	+.134	+.428	+.013	−.134	−.114
Topex	+.167	+.157	+.502	+.197	−.300	+.654
Slope	+.194	−.262	+.516	+.085	−.274	−.657
Cos	−.452	−.079	−.016	+.613	+.304	−.075
Sin	+.288	+.380	+.122	−.403	+.189	−.147
(Site drainage class)^2	+.075	+.559	−.028	+.132	+.243	−.273
Soil drainage class	−.209	+.499	−.231	+.082	−.666	−.134
Major Soil Group (MSG)	−.253	−.076	−.366	−.201	−.262	−.032
Yield Class Zone (YCZ)	−.197	+.392	+.215	−.042	+.336	+.043

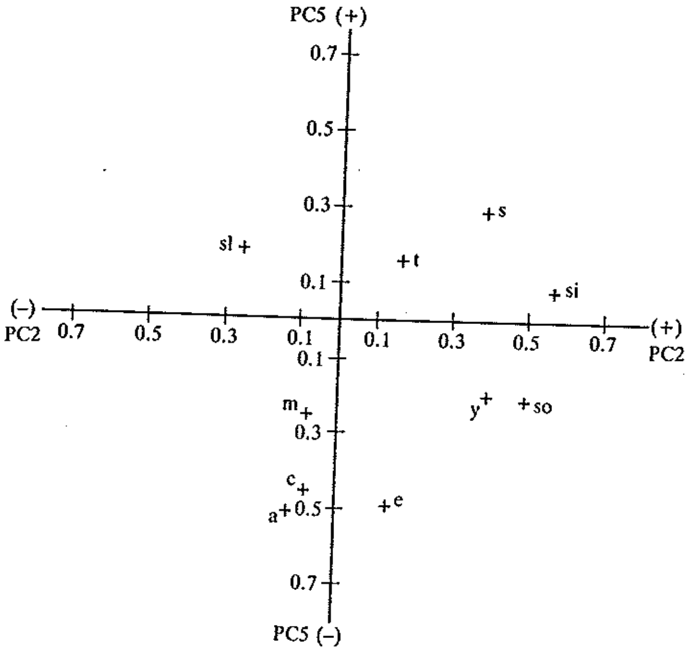

Figure 2. Plot of the principal component (PC) load values for PC5 and PC2. The dispersion around the origin indicates the strength and direction of the correlation between the site variables and General Yield Class for the two components. Variables plotted are topex (*t*), slope (*sl*), MSG (*m*), cosine (*c*), sine (*s*), age (*a*), elevation (*e*), YCZ (*y*), soil drainage (*so*) and site drainage (*si*).

procedure are plotted. In both components site drainage, aspect (sine) and topex are positively correlated with GYC while crop age, MSG and cosine are negatively correlated. Elevation, soil drainage and YCZ are all correlated negatively on PC[5] but positively on PC[2]. This apparently contradictory effect of particular site variables in the two components probably reflects responses in GYC to particular site combinations which are of ecological significance. For example, PC[2] is dominated by the positive effect of site drainage and soil drainage on GYC. That is higher values of GYC are favoured by receiving sites and more poorly drained soils. Steep slopes are not, however, positively associated with either receiving sites or poorly drained soils and subsequently are negatively related to GYC in PC[2].

To aid interpretation and to facilitate the practical application of the model for GYC prediction the regression equation was redefined as a function of the independant site variables based on the load values and the regression coefficients of the six principal components included in the original model. This model takes the form:

$$\text{GYC} = 22.545 - 0.118\,(\text{age}) - 0.008\,(\text{elevation}) + 0.059\,(\text{topex}) - 0.095\,(\text{slope}) - 0.328\,(\cos) + 0.632\,(\sin) + 0.252\,(\text{site drainage})^2 - 0.528\,(\text{soil drainage}) - 1.032\,(\text{MSG}) + 0.56\,(\text{YCZ})$$

[Regression Model 2]

Table 4 presents the predicted GYC values for four 'typical' better quality sites in Scotland and the contribution made to the predicted GYC value by each site variable based on this model. For all sites crop age is set at 40 yr to standardize its effect on GYC. Forty years was chosen as the most appropriate age since it approaches the normal rotation length for Sitka spruce and is close to the average sampled crop age which was 39.8 yr. Site 1 has a predicted GYC of 16.53 and represents a low elevation podsol site in north-east Scotland. Favourable elevation and soil drainage is offset by poor MSG, low YCZ and topex value. Site 2 is a brown earth at low elevation with a predicted GYC of 22.39. This higher value can be attributed to better MSG, YCZ, site drainage and topex. Sites 3 and 4 are gleys at an elevation of 180 m. The higher GYC predicted for Site 4 is due primarily to higher topex, a more favourable aspect and a receiving location. Over the normal range in possible values for the 10 site variables on better quality land crop age, topex, site drainage, soil drainage and MSG appear to have the biggest influence on the predicted GYC. Slope and aspect are the least influential. Interpretation of the relative influence of the individual site variables based on this model should not be too rigorous however since the regression coefficients are derived from a reduced model using only six of the original 10 principal components.

Validation

The model was tested using an independent data set of 15 samples from better quality sites in Scotland. Predicted values from the validation set are plotted against actual values in Figure 3. Predicted values based on Worrell's model for upland sites (Worrell, 1987b) and Busby's guidelines (Busby, 1974) are also plotted for comparison. The predictions of GYC for the 15 plots varied from the observed values in the range 0.0–2.9 $m^3\ ha^{-1}\ yr^{-1}$ and on average by 1.5 $m^3\ ha^{-1}\ yr^{-1}$. The actual mean for the validation set was 18.5, compared with a predicted mean of 18.9. For almost all sample sites Worrell's model consistently overpredicted GYC, with a predicted mean for the 15 sites of 22.1 $m^3\ ha^{-1}\ yr^{-1}$. Worrell's model was developed using data collected on upland sites and this over-estimation would tend to suggest that it would not be valid to extrapolate his model on to better quality sites at lower elevations. The guidelines presented by Busby (1974) seriously underestimated GYC for most sample sites and gave a predicted mean of only 13.6 $m^3\ ha^{-1}\ yr^{-1}$.

Prediction intervals from the model (95 per cent confidence interval) for a new individual observation ranged from ± 4.9 $m^3\ ha^{-1}\ yr^{-1}$ to ± 5.3 $m^3\ ha^{-1}\ yr^{-1}$. The estimated mean deviation of the predicted values from the actual values (derived by the multiplying the standard error of the predicted Y value by the ratio $(2/\pi)^{-2}$, Worrell, 1987a) was 1.0 $m^3\ ha^{-1}\ yr^{-1}$ for average sites and 2.7 $m^3\ ha^{-1}\ yr^{-1}$ for extreme sites. (An average site is a site where the values of the site variables are close to their mean, an extreme site occurs where the site variables are far from their mean; it does not

TABLE 4: *Predicted General Yield Class (GYC) for a sample of better quality sites in Scotland*

Site variable	Site 1		Site 2		Site 3		Site 4	
	Data	(Δ GYC)	Data	(Δ GYC)	Data	(Δ GYC)	Data	(Δ GYC)
Constant	—	22.54	—	22.54	—	22.54	—	22.54
Age (years)	40	(−4.72)	40	(−4.72)	40	(−4.72)	40	(−4.72)
Elevation (m)	80	(−0.64)	100	(−0.80)	180	(−1.44)	180	(−1.44)
Topex (°)	15	(+0.88)	40	(+2.36)	20	(+1.18)	40	(+2.36)
Slope (°)	8	(−0.76)	4	(−0.38)	4	(−0.38)	4	(−0.38)
Aspect cos	0.819	(−0.27)	−0.643	(+0.21)	0.996	(−0.33)	0	(0)
sin	0.574	(+0.36)	0.766	(+0.48)	−0.087	(−0.06)	1	(+0.63)
(Site Drainage Class)^2	1	(+0.25)	4	(+1.01)	4	(+1.01)	9	(+2.27)
Soil Drainage Class	−2	(+1.06)	−2	(+1.06)	1	(−0.53)	1	(−0.53)
Major Soil Group (MSG)	4	(−4.13)	2	(−2.06)	3	(−3.10)	3	(−3.10)
Yield Class Zone (YCZ)	3.5	(+1.96)	4.8	(+2.69)	5.0	(+2.80)	5.0	(+2.80)
Predicted General Yield Class		16.53		22.39		16.97		20.43

necessarily follow that extreme values of GYC will be predicted for extreme sites.) For non-extreme sites therefore the model can be considered precise enough for most applications including site acquisition and production planning.

DISCUSSION

Average GYC for the sampled crops of Sitka spruce was 18.9. This suggests that significantly higher yields of timber can be expected on better quality land than from the more traditional upland sites where average GYC generally ranges between 14 and 16 (Kupiec and Philip, 1989).

From the principal component analysis it is clear that the factors influencing GYC on better ground are numerous and interrelated and that no one factor has an overriding effect on tree growth. A strong negative relationship between GYC and elevation for Sitka spruce has been described by Worrell (1987a) and Malcolm (1970). Increasing elevation being associated with a deteriorating climate for tree growth (Grace, 1975). On better quality sites sampled in this study, elevation has a weaker negative relationship with GYC.

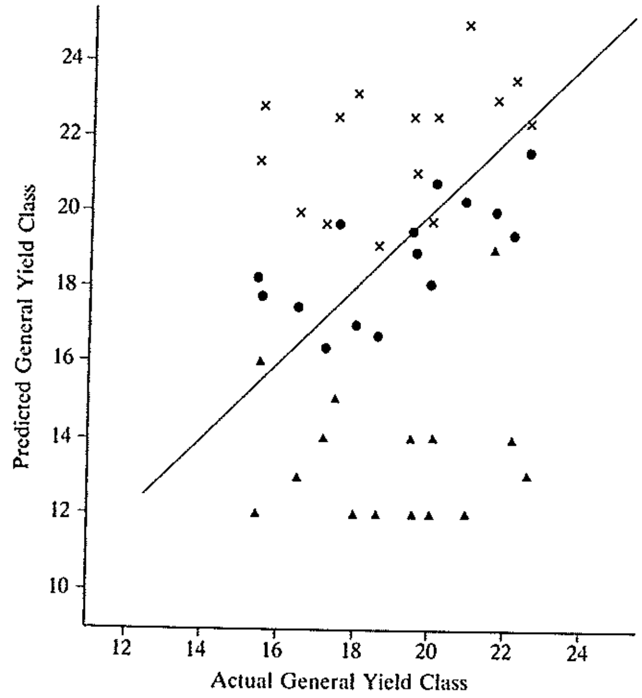

Figure 3. Plot of predicted General Yield Class (GYC) against actual GYC for the validation data set of the Better Land Model (●). Predicted GYC for Worrell's upland model (*x*) and Busby's guidelines (▲) are plotted for comparison.

Topex has a significant effect on GYC. Higher topex values imply greater topographic shelter which in turn favours tree growth. This effect has been reported by Worrell (1987a) and Blyth and Macleod (1981).

In this study soil moisture status of the site appears to have an important effect on GYC and the absence of a site variable which adequately describes moisture availability is perhaps one of the main reasons why Worrell's upland model consistently over-predicts GYC when extrapolated on to better quality ground. In the case of site drainage class Sitka spruce responds favourably to receiving sites where the roots are likely to be fed with a replenishing supply of oxygen and nutrients from above. This result was also found by Page 1970 and Malcolm 1970. Shedding sites are less favourable for growth and this may partially reflect the crops response to site droughtiness (Jarvis and Mullins, 1987). GYC is also influenced by soil drainage class with poorer drainage reducing growth. This effect is likely to be linked to the presence of anaerobic conditions in the rooting layer (Blyth and MacLeod, 1981). The soil environment is complex and it is difficult to capture fully the range of conditions likely to influence tree growth using qualitative variables ranked on a linear scale as was done in this study. Bearing in mind the observed effect of soil moisture conditions on GYC future research should be directed towards a fuller investigation into soil moisture properties and their classification for yield studies.

The only site variable to exhibit a consistent relationship in all six components with GYC was MSG. Highest GYC values were associated with brown earths, followed by gleys and then podsols. Mayhead (1973), Worrell (1987a), Malcolm (1970), Blyth and Macleod (1981) and Conry and Clinch (1989) also report a similar pattern. Although alluvial and organic soils were not included in the final model due to a lack of sample sites, observable trends in the data for alluvial soils suggest that they behave in a similar pattern to brown earths or gleys depending on the drainage class. GYC values on organic sites varied tremendously and seemed to depend on the degree of flushing at the site and on the drainage class.

The positive effect of east and south facing slopes on GYC reflects the greater shelter from prevailing south-westerly winds on east facing slopes and greater levels of solar radiation received on south facing slopes. Jack (1968) observed higher growth rates on southerly aspects compared with northerly aspects. Worrell (1987a) on upland sites found north-easterly aspects to be most favourable to growth; the beneficial effects of a southerly aspect presumably being overridden by increased exposure from south-westerly winds on higher elevation sites.

The effect of crop age on GYC in this study is very pronounced and is similar in scale to that reported by Worrell (1987a) where GYC increased on average by 1.0 $m^3 ha^{-1} yr^{-1}$ every decade in crops planted before 1960. In this study GYC increased on average by 1.2 $m^3 ha^{-1} yr^{-1}$ per decade. A strong effect of crop age was also noted by Kilpatrick and Savill (1981). Changes in silvicultural practices, specifically the intensification of establishment treatments to encourage faster early growth (ploughing and fertilizing) over the last 30 yr or so is undoubtedly influential. Other reasons might include the effect of higher agricultural inputs to the land before afforestation post 1945 and the general improvement in genetic stock and plant condition in recent years. Environmental pollution (acid rain) may also be causing a reduction in growth rate in older crops due to induced deficiency of essential base cations such as calcium and magnesium (Shortle and Bondietti, 1990).

Variation in GYC not explained by the variables used in the PCA could have arisen from a number of sources such as inaccurate measurement of site variables including GYC, incorrect crop age, the failure to select site variables highly correlated with GYC and failure to recognize crops which had suffered from check. Neverthless, this model, developed specifically for better quality sites in Scotland performs better at predicting GYC than either Worrell's upland model (Worrell, 1987b) or Busby's (1974) guidelines.

Practical application of the model in the form presented in Model 2 depends only on the collection of the relevant site information. For site acquisition purposes a sampling procedure similar to that outlined for windthrow hazard assessment (Miller, 1985) is likely to produce reliable average GYC values at compartment or forest level. The model does not specifically predict for either organic or alluvial soil groups but from the limited site data available a deduction of 2–4 $m^3\ ha^{-1}\ yr^{-1}$ for unflushed peats would be appropriate, with flushed peats ranked as a gley. The more poorly drained alluvial soils (drainage classes 3, 4 and 5) should be treated as gleys and freely drained alluviums (drainage classes 1 and 2) as brown earths.

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank the Forestry Commission and the numerous private estates who allowed me access to their forests for the purposes of GYC estimation. I would also like to thank the survey staff of Land Use Division, MLURI, who carried out the site characterization of each sample plot; Dr Stephen Buckland and Betty Duff (SASS) for advice on statistical analysis and programming; Dr Rick Worrell for his constructive comments during the preparation of this study; Pat Carnegie for map production and Christain Garden for typing the paper.

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Paper received 18 July 1990.