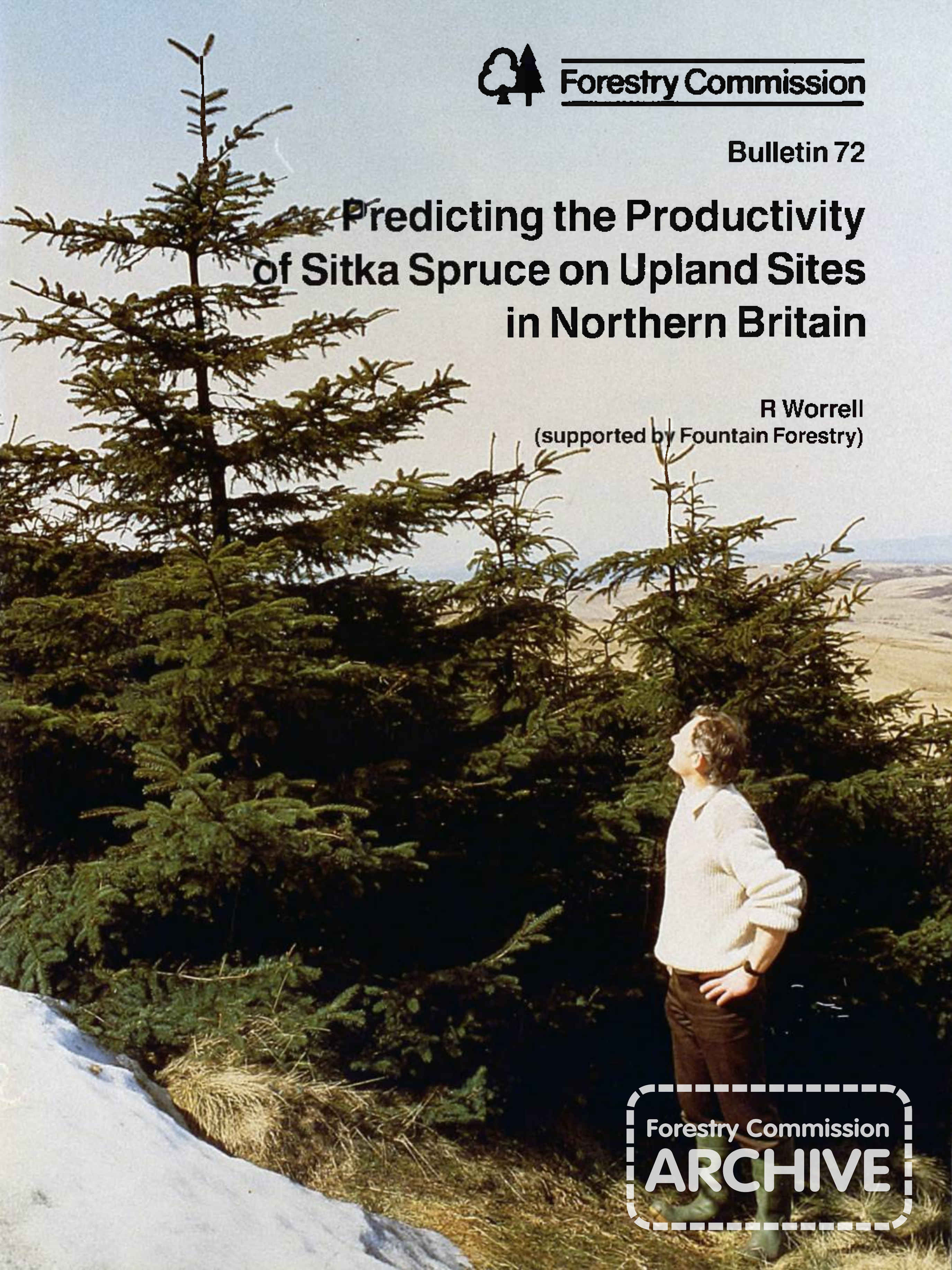
Forestry Commission

Bulletin 72

Predicting the Productivity of Sitka Spruce on Upland Sites in Northern Britain

R Worrell
(supported by Fountain Forestry)



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Predicting the Productivity of Sitka Spruce on Upland Sites in Northern Britain

R. Worrell
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Study financed by
FOUNTAIN FORESTRY LIMITED

FOUNTAIN

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FRONT COVER: 17-year-old Sitka spruce showing effects of climatic exposure at the upper edge of plantation (altitude 550 m) at Glendevon Forest, Ochil Hills, Tayside.

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Foreword

The major expansion of forestry in Britain over many decades has been essentially located in the uplands on land sub-marginal for agriculture. Whereas success could at one time be measured by the attainment of a minimum level of yield, it became increasingly important to predict levels of productivity more precisely. With the passing years local experience, based on crop growth, sometimes in trial plantations, supplemented by correlations with single factors such as soil or exposure, provided adequate local guidance for foresters.

The research described in this Bulletin integrates the main environmental factors influencing the growth of Sitka spruce at high elevations in order to estimate future Yield Class. The project was initiated by Fountain Forestry Ltd and the Forestry Commission and was jointly guided by the Forestry and Natural Resources Department of Edinburgh University and by the Forestry Commission. It was wholly funded by Fountain Forestry with the generous acceptance that the results would be made available to all.

S. A. Neustein

Chief Research Officer (North)

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Predicting the Productivity of Sitka Spruce on Upland Sites in Northern Britain

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Summary

This Bulletin provides a means of estimating the General Yield Class of Sitka spruce on upland sites from easily assessable site factors. Estimates of planting limits under various site conditions are also given. The information is intended for use in land acquisition and investment decisions, and in land-use evaluation.

The information on a forest site which is needed to make estimates of Yield Class or planting limits is as follows: location, elevation, topex, aspect and soil type. Use of diagrams and tables enables estimates of the 'Potential Yield Class' of sites to be made. Potential Yield Class is the Yield Class a site is capable of sustaining provided that adequately intensive silviculture is applied. Areas of poorer growth and stocking can be allowed for by reducing Potential Yield Class values to give estimates of Provisional Yield Class applicable to forest compartments.

Introduction

In recent years forestry enterprises have required increasingly precise information on the timber yields expected on the land under their management. Such information is essential when land is acquired for forestry, as potential productivity is an important consideration taken in combination with land prices. It is also of use in choosing appropriate silvicultural practices and in production forecasting. A limited amount of information is available from studies carried out 10–20 years ago (e.g. Busby, 1974), but in general currently used guidelines are inadequate and managers must rely to a large extent on local experience. Information on probable yields and suitable upper planting limits is particularly scarce for high elevation and exposed sites.

The widespread use of Sitka spruce in upland afforestation during the last 30 years has made it possible to obtain information on the relationships between productivity and site factors for a wide range of site types. In addition, assessment of trial plantations at high elevations and tatter flag data (Savill, 1974; Reynard and Low, 1984) have created a substantial pool of information on tree growth in relation to site factors on high elevation and exposed sites.

Previous research (Malcolm, 1970; Malcolm and Studholme, 1972; Mayhead, 1973; Blyth, 1974) has shown that the productivity of Sitka spruce on upland sites in northern Britain is related to the following easily assessable site factors:

- elevation,
- geomorphic shelter (e.g. 'topex'),
- soil type.

The aim of the research project described in this Bulletin was to develop a means of estimating the Yield Class of Sitka spruce on upland sites from such easily assessable site factors. (Yield Class is an estimate of the maximum mean annual increment of stem volume per hectare per year (Edwards and Christie, 1981).)

The results are based on the analysis of data from 160 temporary sample plots which were established at regular intervals of elevation spanning the upper 200 metres of plantations at 18 sites (main fieldwork sites). The sample plots were chosen to incorporate the following features:

pure Sitka spruce of Queen Charlotte Island provenance spanning as large an elevational range as possible, terminating at or near the local upper planting limit;

crop age preferably within the range of 20 – 30 years;

topography and soil conditions not unduly variable;

site and crop performance broadly representative of the surrounding area;

crops free of extraordinary establishment problems such as poor drainage, frost damage, heather 'check' or obvious nutrient deficiencies.

Data were also collected from small groups of plots and single plots in regions with less extensive areas of suitable plantations (supplementary sites). The latter included yield data from Forestry Commission high-elevation trial plantations. The locations of the fieldwork sites are shown on Figure 2. At each plot estimates of General Yield Class (GYC) were made and the following site factors were assessed: elevation, geomorphic shelter (topex), aspect, slope, soil type and soil depth. Topex is the sum of the angles of elevation to the skyline at the eight cardinal points of the compass (see Pyatt, 1977; Wilson, 1984).

In addition, estimates of wind climate, temperature and annual rainfall were made for each plot using extrapolated tatter flag and meteorological data. Tatter flags are cotton flags which lose material by attrition at a rate roughly proportional to the mean windspeed of the site (Lines and Howell, 1963; Savill, 1974; Reynard and Low, 1984). A method of predicting site windiness (estimated tatter rate) from the location, elevation, topex and aspect of each plot was developed based on data from 564 widely distributed tatter flags. Temperature estimates (mean annual accumulated temperature above 5.6 °C) were extrapolated from data from 70 meteorological stations.

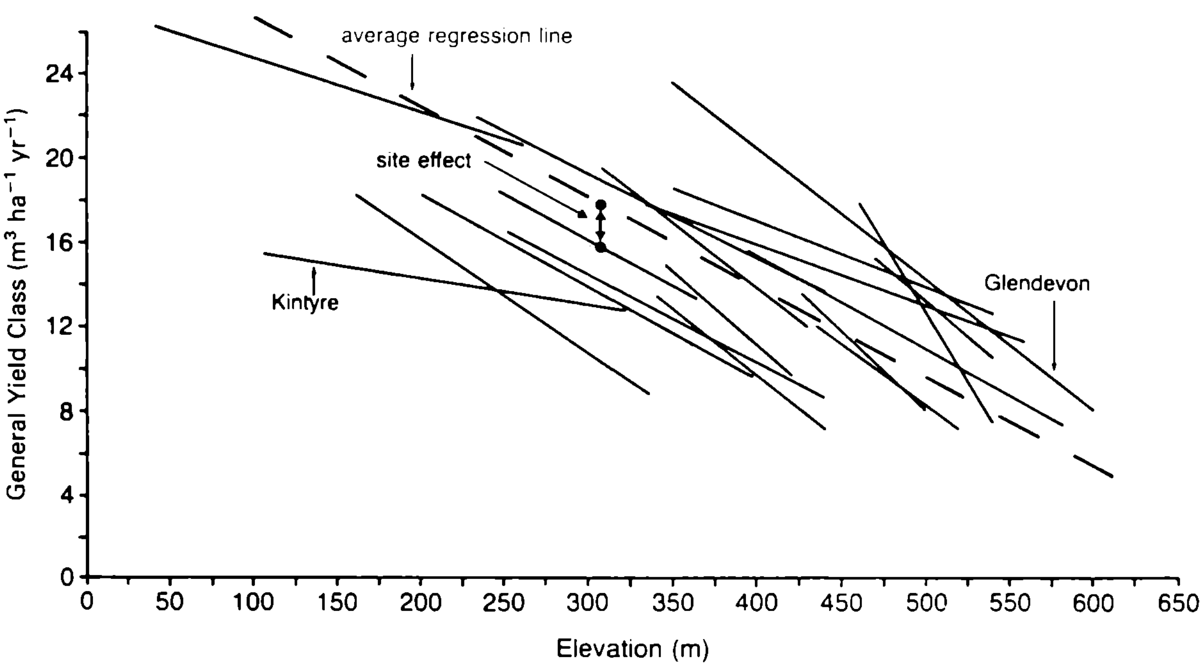
Analysis was carried out using correlation and multiple regression techniques. The regression model upon which this Bulletin is based expresses the productive capacity of a site in terms of its elevation, temperature and windclimate, geomorphic shelter (topex), aspect and soil type (see Appendix 2). To predict GYC for an upland site using this model, information on the following site factors is required: location, elevation, topex, aspect and soil type. These factors are broadly similar to those used for windthrow hazard classification, making the two systems easy to use in combination.

Factors Affecting Productivity

Elevation

Productivity (GYC) was found to decline by an average of 3.0–4.0 $m^3 ha^{-1} yr^{-1}$ per 100 metres increase in elevation due to the effects of increasingly adverse climatic and soil conditions. Yield Class and elevation were fairly closely correlated at most of the sites but the relationship varied considerably between sites (Figure 1). The elevation of the planting limit also varied between sites, ranging from about 600 m at inland and southern sites such as Glendevon (Perthshire) to about 350 m at coastal sites such as Kintyre (Argyll).

Figure 1. Relationships between GYC and elevation at individual sites (main sites only).



Location

Values of GYC *at any specific elevation* were higher on inland and southern sites (e.g. Glendevon) than on coastal and northern sites (e.g. Kintyre – see Figure 2). This geographical variation in Yield Class was investigated by comparing the GYC/elevation lines for the individual sites with the mean GYC/elevation line for all the sites (analysis of covariance). The displacements of the lines for the individual sites from the mean GYC/elevation line (called 'site effects' in Figures 1 and 2) were plotted on a map. Contours at intervals of 2 m^3 ha^{-1} yr^{-1} were then interpolated by computer (Figure 2).

The pattern is similar to the geographical distribution of both site windiness (e.g. Forestry Commission wind zones – see Miller, 1985) and site temperature, suggesting a major influence of these factors on the productivity of upland sites.

Wind-climate and temperature

Yield Class was found to be fairly closely correlated with both site windiness (estimated tatter rate) and site temperature (estimated mean annual accumulated temperature above 5.6 °C). For 142 plots which had received standard silvicultural treatment as described below, these two climatic variables accounted for 78 per cent of the variation in GYC.

The relationship between GYC and elevation, tatter rate (adjusted to sea-level) and accumulated temperature (adjusted to sea-level) was used to produce a more detailed map describing the geographical variation in the GYC/elevation relationship (Figure 3). This map forms the first step in assessing the Potential GYC of an upland site. It is based on data from 70 meteorological stations and 110 tatter flag sites using the method described in Appendix 2 and illustrated in Figure 4.

Figure 2. Variation in GYC/elevation relationship – 'site effects' in m^3 ha^{-1} yr^{-1}.
■ main sites, ▲ supplementary sites.

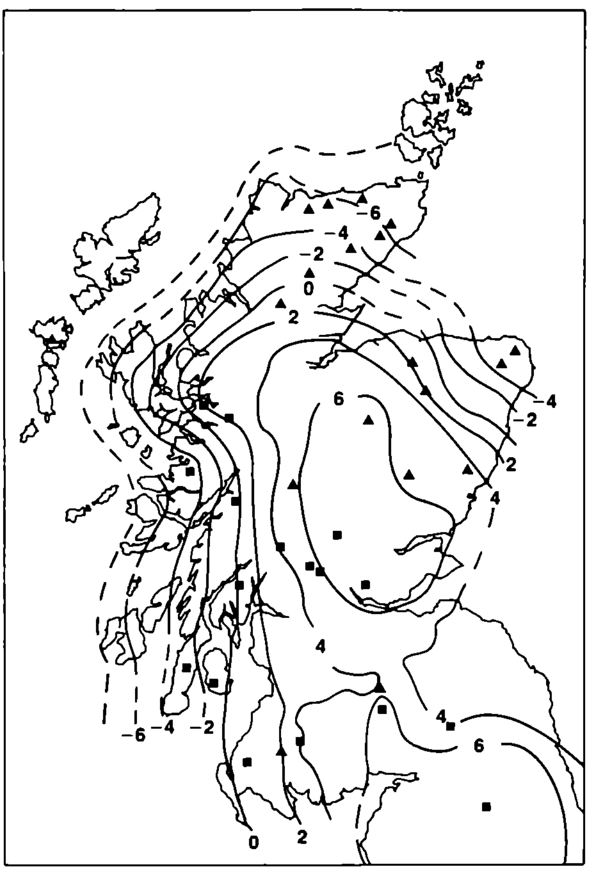


Figure 3. Yield Class zones.

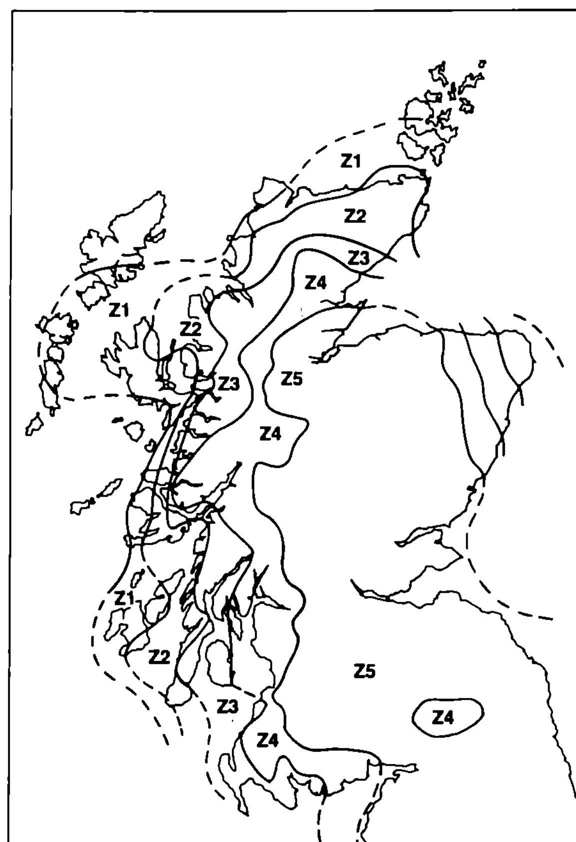
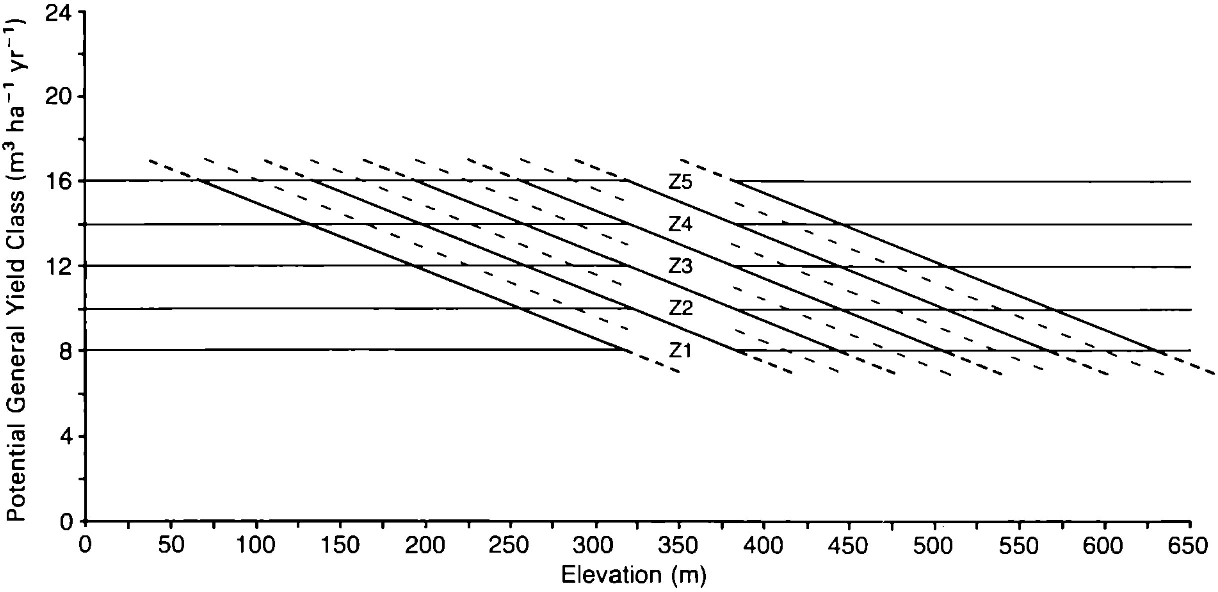


Figure 4. Average potential GYC at various elevations according to Yield Class zone.

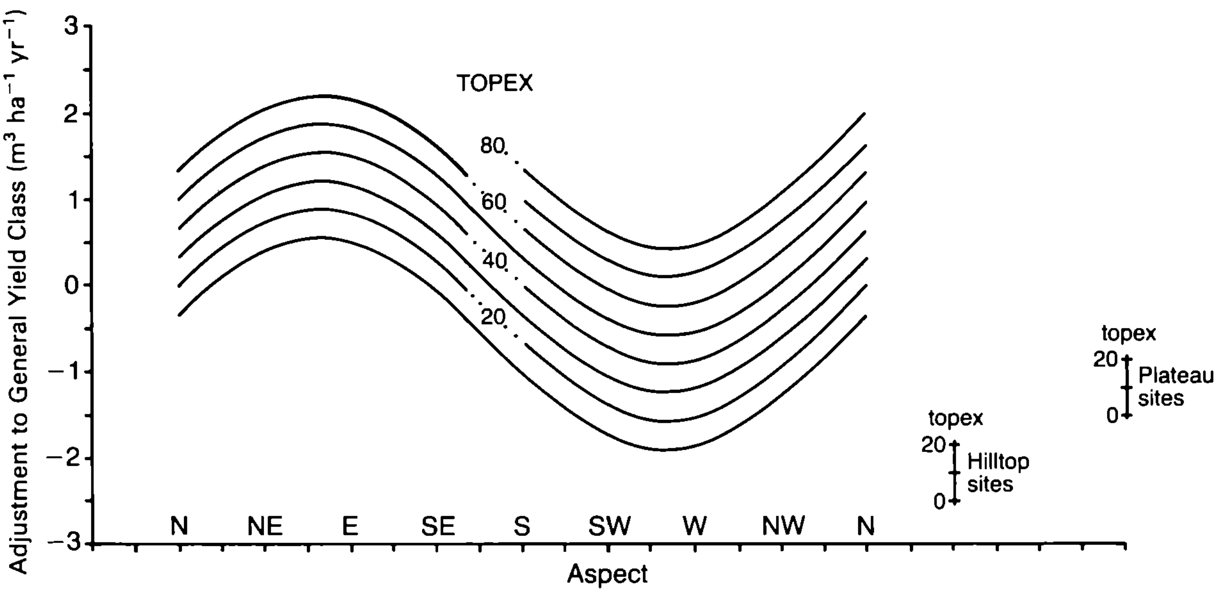


Geomorphic shelter and aspect

GYC was also correlated with geomorphic shelter (topex) and aspect as shown in Figure 5. Productivity was highest on north to east facing slopes and lowest on south to west facing slopes and increased with increasing levels of geomorphic shelter. GYC was on average 2.5 m^3 ha^{-1} yr^{-1} higher on north-east aspects than on south-west aspects and increased by 0.3 m^3 ha^{-1} yr^{-1} for every 10 points increase in topex. Hilltop sites (topex 0) showed GYC values of about 2.5 m^3 ha^{-1} yr^{-1} lower than average sites with topex values of 30. A difference between comparable topex values of hilltop and plateau sites is illustrated in Figure 5 and explained in Appendix 2.

Similar patterns have been shown in other areas of the British Isles (G. J. Mayhead, unpublished), though reduced growth on north facing slopes has been reported from Galloway (Gale and Anderson, 1984). These patterns are largely a reflection of the effect of wind on the growth rates of trees on upland sites. Analysis of tatter flag data showed a converse pattern, with tatter rate being highest

Figure 5. Effect of aspect and topex on Potential Yield Class.



on west facing slopes and decreasing with increasing values of topex (Worrell, 1987).

Problems arise in describing the effects of geomorphic shelter and aspect on wind flow and growth in extremely dissected terrain. In such areas changes in local wind climate can be abrupt due to the effects of wind-funnelling. This can lead to high wind exposure in SW-NE oriented valleys which would otherwise be expected to be fairly sheltered. Conversely, east facing sites in such terrain, even at high elevation, can be considerably more sheltered than expected from the topex score. It has not been possible to take full account of such effects in this study.

Soil type

The different soil types were found to order themselves with respect to productivity as follows: brown earth > surface water gley > podsol, iron pan, peaty gley > flushed peat > unflushed peat. Podsols, iron pans and peaty gleys showed average values of GYC with brown earths deviating from this by about +2 m^3 ha^{-1} yr^{-1}, surface water gleys by about +1 m^3 ha^{-1} yr^{-1}, flushed peats by about −1 m^3 ha^{-1} yr^{-1} and unflushed peats by about −2 m^3 ha^{-1} yr^{-1} (see Table 1). These values were derived by including the effects of soil type in multiple linear regression models (see Appendix 2).

Table 1. The effect of soil type on Potential Yield Class

Soil type	Adjustment to Potential GYC (m^3 ha^{-1} yr^{-1})
Brown earth	+ 2
Surface water gley	+ 1
Podsol	0
Iron pan	0
Peaty gley	0
Flushed peat	− 1
Unflushed peat	− 2

The relatively small range in GYC (4 m^3 ha^{-1} yr^{-1}) attributable to the effects of soil type is due to two reasons. Firstly, changes in soil type are related to elevation, and the effect of elevation on productivity has already been accounted for in the analysis. Secondly, modern site amelioration techniques reduce the variation in productive capacity of the different soil types.

Planting year

The plantations surveyed varied from 15 to 53 years old (planted between 1933 and 1970), apart from a few experimental plots which were 10 years old. Productivity was significantly correlated with the year of planting, with GYC increasing by about 1 m^3 ha^{-1} yr^{-1} for every 10 years increase in date of P year. This is presumably a reflection of the progressively increased levels of silvicultural inputs which have been applied to crops established during the period 1930–1970.

Estimating Potential Yield Class

The potential productivity of a site can be considered in this context to be the Yield Class which is attainable if standard silviculture is applied successfully. Standard silvicultural practice is defined as that which has been recommended by the Forestry Commission during the past 20 years (1965–1985). Yields may be considerably below this potential if silvicultural treatments, particularly cultivation, fertilising and heather control, are inadequate. Because it is difficult to achieve appropriate silvicultural treatment over extensive areas, reductions to these values of Potential Yield Class should be made to give Provisional Yield Class estimates applicable to whole forest compartments and blocks.

The following section describes how estimates of Potential Yield Class can be made from the site factors: location, elevation, topex, aspect and soil type. Firstly, an estimate of *average* Potential Yield Class is made for a site with reference to its location (see Figure 3) and its elevation (see Figure 4). For certain 'broad brush' purposes this estimate of Potential Yield Class may be adequate. Secondly, adjustments are made to take account of the effects of aspect, geomorphic shelter (topex) and soil type (see Figure 5 and Table 1). A detailed description of the estimation of Potential Yield Class is given below and an example of the application of the system for mapping Provisional Yield Class is given in Appendix 1.

Method

1. The 'Yield Class zone' in which the site is located is determined from the map (Figure 3). Although this zonation is similar to the wind zonation used for windthrow hazard classification, it is not identical because it describes the effects of both site temperature and windiness on tree growth on upland sites.
2. The *average* Potential Yield Class for the appropriate zone and elevation is determined from Figure 4. For example at 400 metres in zone 4 the average Potential GYC is estimated to be GYC 12.4. This estimate applies to a site with a poor mineral soil (e.g. peaty gley) and a topex value of 30.

3. An adjustment is made to this average Potential GYC to take account of the effects of aspect and topex using Figure 5. For example the adjustment necessary for a west-facing site of topex 40 is –0.7 m^3 ha^{-1} yr^{-1}. The adjustments for level sites (hilltops and plateaux) are shown separately. Note the low productivity levels of hilltop sites. Adjustments for the effects of topex on sites with values in excess of 60 (east facing) and 80 (west facing) should be made at the levels indicated by the lines 60 and 80. In extremely dissected terrain, users of this Bulletin should take appropriate account of possible wind-funnelling effects.

4. Adjustment for the effect of soil type is made using Table 1. For example a site on a flushed peat requires a deduction of 1 m^3 ha^{-1} yr^{-1}, whereas one on a surface water gley requires the addition of 1 m^3 ha^{-1} yr^{-1}.

Thus an estimate of the Potential GYC for a site in zone 4 at 400 m with a westerly aspect and a topex value of 40 on a flushed peat is made as follows:

Average value (see Figure 4)	12.4
Adjustment for topex/aspect (see Figure 5)	–0.7
Adjustment for soil type (see Table 1)	–1.0
	10.7 m^3 ha^{-1} yr^{-1}

For an equivalent site on a surface water gley the Potential GYC would be:

$12.4 - 0.7 + 1 = 12.7$ m^3 ha^{-1} yr^{-1}.

Provisional Yield Class estimates for forest compartments

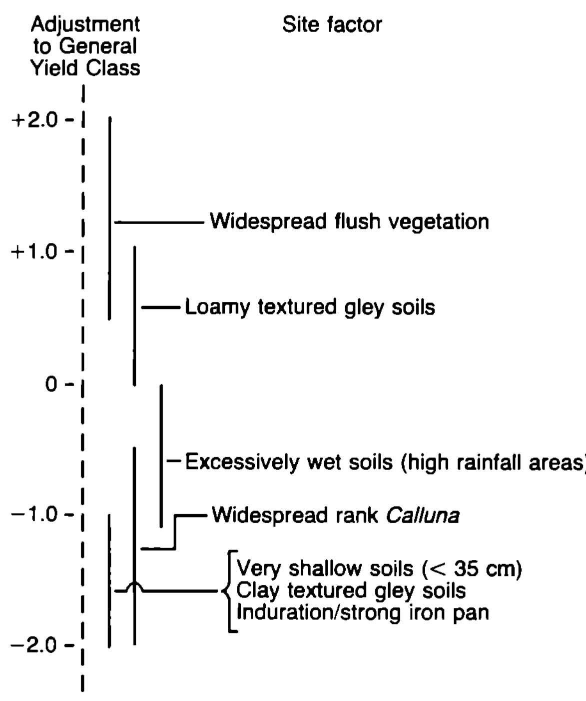
Estimates made as described above represent the Potential Yield Class attainable if standard silvicultural techniques are successfully applied. It may be desirable to reduce the estimated values by up to 2 m^3 ha^{-1} yr^{-1} to take account of areas of poorer growth or stocking which frequently occur in forest compartments. Usually a reduction of 1 m^3 ha^{-1} yr^{-1} is adequate to convert Potential Yield Class to Provisional Yield Class estimates applicable to forest compartments but this will vary according to local conditions and the standard of the silviculture applied. Users of this Bulletin are encouraged to apply reductions consistent with their experience of local conditions.

Precision of estimates

A system of predicting GYC based on such readily assessable site factors is obviously subject to error. Errors will result mainly from the influence of lesser site factors (e.g. soil nutrient and water status, site microclimate). Field trials and statistical analysis of this system have indicated that on the scale of a forest block the average error (predicted GYC – actual GYC) is expected to be within the range ± 1 m^3 ha^{-1} yr^{-1}. On some sites errors may be less than this whilst on other sites, particularly in regions where fewer original data were available (NW Highlands, E. Scotland), errors may be greater. In 95 cases out of 100, estimates using this system are expected to be within ± 2.4 m^3 ha^{-1} yr^{-1} (95 per cent confidence limits).

It should be emphasised that for most purposes and on the majority of sites, satisfactory estimates of Yield Class will be obtained by following steps 1–4 above (page 8) and applying a reduction to take account of variations in silvicultural treatment. If necessary however, some account can be taken of variation due to factors other than those already included in steps 1–4 above by making further adjustments to predicted GYC values as indicated on Figure 6. Such relevant special factors include the widespread presence of flush vegetation (positive) or restricted rooting depth (negative) due to indurated, excessively clayey, very wet or very shallow soils. The values shown in Figure 6 are subjective estimates made by the author and are not based on analysis of data.

Figure 6. Adjustments to GYC for special site features.



Note: Adjustments not to be used additively

Estimation of Planting Limits

The minimum acceptable Yield Class, and consequently upper planting limits, will vary according to the economic criteria applied by the forest manager. Gale and Anderson (1984) recommended a minimum GYC of 10 based on a comparison of likely discounted costs and revenues in the Galloway region, but values as low as GYC 7 have been suggested (Hummel and Grayson, 1962; Malcolm and Studholme, 1972).

Figures 7 to 9 show estimates of the highest elevation at which GYC values of 8, 10 and 12 are likely to occur for an average upland site (topex 30, poor mineral soil e.g. peaty gley). To achieve, for example, GYC 10 in the uppermost compartment of a forest block it is recommended that planting is carried out to the elevation shown in Figure 8. The uppermost part of the compartment may show values of GYC lower than GYC 10 (due to areas of poor stocking and growth) but this should usually be compensated for by rather better growth lower down in the compartment. Adjustments to the values of elevation to take account of the effects of geomorphic shelter, aspect and soil type can be made by reference to Table 2.

Figure 8. Elevation at which GYC 10 can be expected.

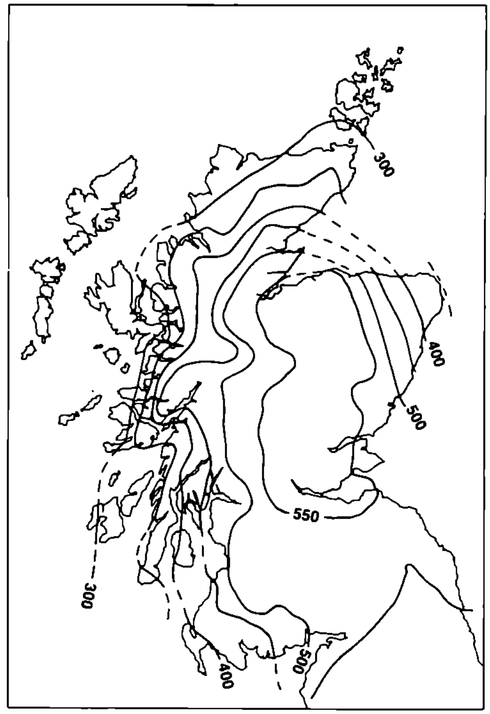


Figure 7. Elevation at which GYC 8 can be expected.

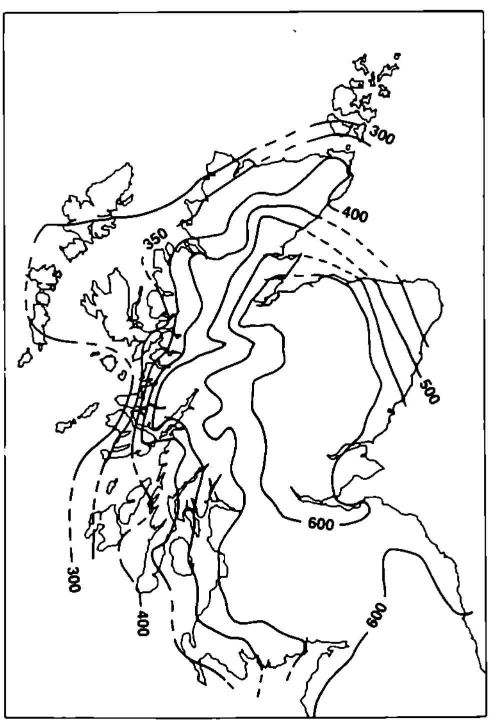


Figure 9. Elevation at which GYC 12 can be expected.

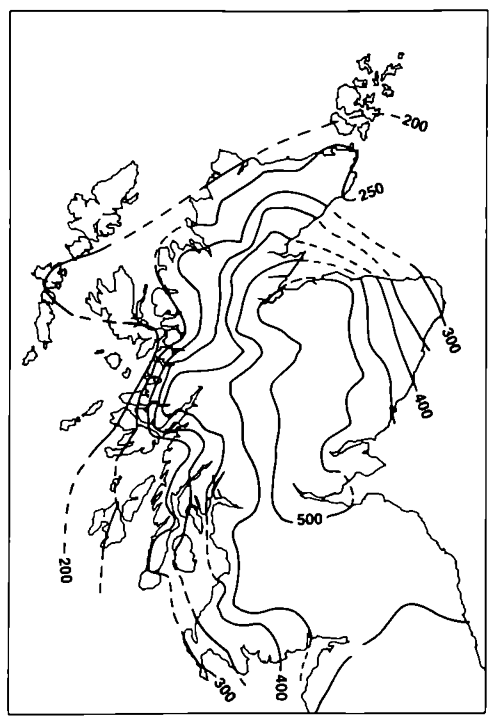


Table 2. Adjustments to the elevation of planting limits due to various site factors

Site factor	Adjustment to planting limit (m)
Geomorphic shelter	
Topex 0– 9 (hilltop)	– 80
Topex 0– 9 (plateau)	– 30
Topex 10–30	– 10
Topex 30–60	+ 15
Topex >60	+ 40
Aspect	
N	+ 10
NE	+ 30
E	+ 30
SE	+ 15
S	– 10
SW	– 30
W	– 30
NW	– 15
Soil type	
Surface water gley	+ 30
Podsol, iron pan, peaty gley	+ 0
Flushed peat	– 30
Unflushed peat	– 60
Variation due to special site conditions (as for Figure 6)	+ 60

For example the planting limit to achieve Yield Class 10 in southern Arran on a site with western aspect, topex 10–30 and a flushed peat soil is:

average planting limit (Figure 8)	425 m
adjustment for topex (Table 2)	–10 m
adjustment for aspect (Table 2)	–30 m
adjustment for soil type (Table 2)	–30 m
	355 m

For an equivalent site with an eastern aspect the limit would be:

$425 - 10 + 30 - 30 = 415$ m.

For a plateau site (topex 0–9) on a deep unflushed peat in Caithness, the planting limit is predicted as:

$350 - 30 - 60 = 260$ m.

A worked example of the use of this system for estimating planting limits and Provisional Yield Classes is given in Appendix 1.

Limitations to Use

Estimates of GYC made using the procedure described in this Bulletin will only be reasonably reliable within the elevation ranges indicated for the individual zones in Figure 4. Application of this method to sites at lower elevations will generally result in over-estimation of Yield Class.

It should also be noted that the Yield Class zone map and the planting limit maps are based on a scatter of about 170 points and the boundaries are not strictly definitive. This is particularly true of areas with a poor coverage of tatter flag sites and meteorological stations (e.g. western Highlands).

It should be emphasised that this system is designed to augment the knowledge of practising forest staff, not to replace it. In many cases estimates of productivity and planting limits made by locally experienced staff will be as good as, or better than, estimates made using this Bulletin.

APPENDIX 1

Example of Application

Figure 10 depicts a site map of land acquired for forestry located in zone 4. Contours and soil types are shown. The points marked ● are locations for which topex values have been estimated from field visits or by reference to a topex map. The points are chosen to represent the range of site conditions (elevation, aspect, topex and soil type). Yield class estimates calculated for these points are used as a basis for preparing a provisional yield class map (Figure 11). The number of points necessary will vary according to the variability of the site. Usually a scatter of points located at about 50 m intervals of elevation and at intervals of about 0.5–1 km along hillsides should be sufficient.

Estimation of planting limit

It is decided to plant the area up to the highest elevation at which GYC 10 can be expected. For an average site this is expected to be about 470 m (see Figure 8). This level is marked as a blue dashed line (1) – (1) on Figure 10. This line passes through two combinations of site conditions. The section marked a – a faces south with topex values of 30–60 and a flushed peat soil. The section marked b – b has south-west aspect with topex values of 60+ and peaty gley/iron pan/podsol soils.

The planting limit for the section a – a is estimated to be:

average level (Figure 8)	470 m
adjustment for topex (Table 2)	15 m
adjustment for aspect (Table 2)	−10 m
adjustment for soil type (Table 2)	−30 m
	445 m

The planting limit for the section b – b is estimated to be:

average level (Figure 8)	470 m
adjustment for topex (Table 2)	40 m
adjustment for aspect (Table 2)	−30 m
adjustment for soil type (Table 2)	0 m
	480 m

These levels are marked on Figure 11 as red line L – L.

It may be desirable to deviate from the economic limit for landscaping purposes. As an aid to landscape planning, it may be helpful to establish additional GYC limits (e.g. 2 m^3 ha^{-1} yr^{-1} above and below that selected). This would allow the effect of the landscaping proposals on yields to be assessed.

Estimation of Yield Class

Potential Yield Class and Provisional Yield Class can be calculated for the points marked (●) on Figure 10 using the procedures 1 to 4 described on page 8. Table 3 (below) shows the site information for point P1–P5 and the necessary steps for the calculation of potential and provisional yield class estimates.

Provisional yield class estimates are calculated in a similar way for all the points on Figure 10 and these values are used to prepare a yield class map (Figure 11). The yield class map can then act as a basis for assigning provisional yield class values to subcompartments.

Table 3. Calculation of Potential and Provisional GYC estimates from site factors for points P1–P5

Site type (elevation, aspect, topex, soil type)	Average Potential GYC (1)	Adjustment for aspect and topex (2)	Adjustment for soil type (3)	Potential GYC (1+2+3)	Provisional GYC
P1 270,S,61,SWG	16.5	+0.7	+1	18.2	17.2
P2 300,S,52,POD	15.6	+0.3	0	15.9	14.9
P3 350,S,51,POD	14.0	+0.3	0	14.3	13.3
P4 400,S,46,PG	12.4	+0.2	0	12.6	11.6
P5 450,S,35,FP	10.8	−0.2	−1	9.6	8.6

(1) From Figure 4 (2) From Figure 5 (3) From Table 1

Figure 10. Map of site characteristics.
Unbroken lines = elevation contours (250–600) in metres.
Dotted lines = soil type boundaries.
• = locations at which topex values estimated.
Blue dashed line = highest elevation at which GYC 10 can be expected.

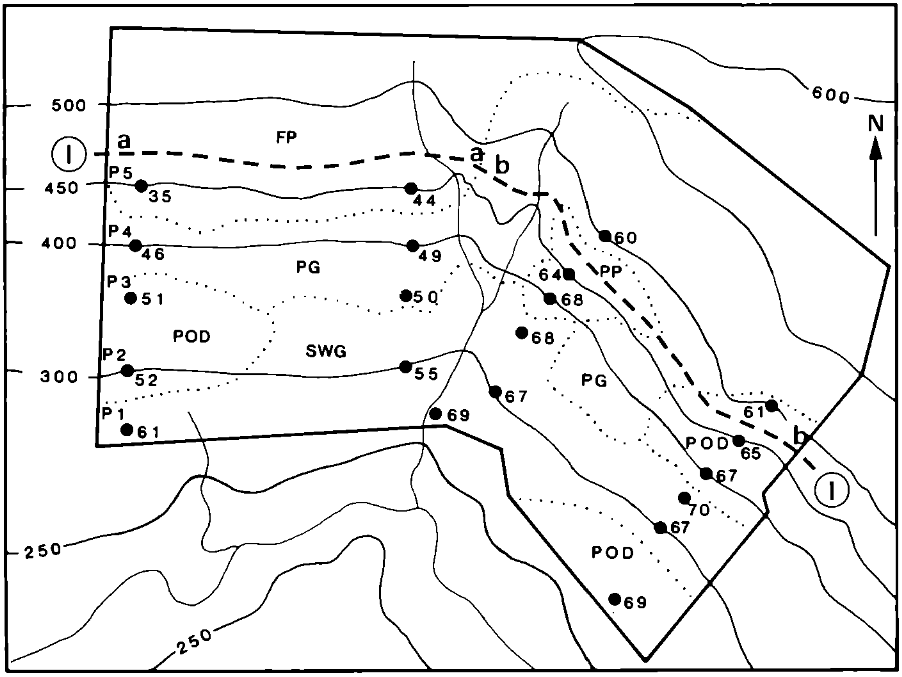
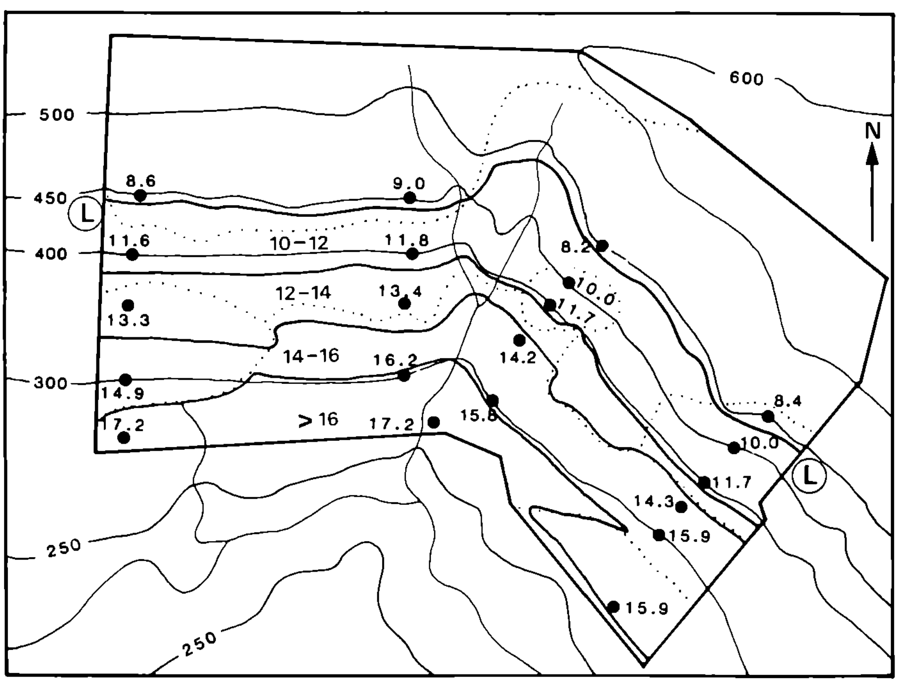


Figure 11. Provisional Yield Class map.
Red lines = Provisional GYC boundaries.
Legend for details printed in black is the same as that for Figure 10.



APPENDIX 2

Technical Description of Model

This appendix describes briefly how the values and diagrams in this publication were derived. For a more complete description see Worrell (1987). The basic multiple regression model which forms the basis for most of this guide is given below.

GYC = 20.95 − 0.032(elevation) − 1.02(adjusted tatter rate) + 0.081(adjusted accumulated temperature) + 0.0332(topex) + 1.17 (sine aspect) + 0.328(cosine aspect) − 1.73{hilltop sites} + 0.97 {valley bottom sites} − 0.107 (crop age) + 2.04{brown earths} + 1.07{surface water gleys} + 0.41 {iron pans} + 0.36{peaty gleys} + 0.28{podsols} − 0.56 {flushed peats} − 1.89{unflushed peats}

The strategy used was to select from the large number of possible equations those which accounted for the greatest proportion of variation in GYC, and in which all the effects of the predicted variables were significant, were logical, and which gave a reasonably complete picture of the properties of a forest site. The fact that many of the site variables are correlated among themselves does not invalidate the methodology of multiple regression, although it gives problems in interpretation.

The standard error of the predicted GYC was calculated as $S.E. = \sqrt{(S^2 + R/M)}$

where S = standard deviation of fitted y value
R = residual mean square of regression equations
M = number of new observations to which the prediction is to apply.

The effects of qualitative variables were estimated using dummy variables which are indicated by { } in the equation above. Values of the dummy variables were adjusted to be relative to a mean of zero rather than to the value of an arbitrary reference category. The adjusted meteorological variables are values extrapolated to sea-level. Figure 3 (yield class zonation) was derived by setting elevation as 350 m, topex as 30, aspect effects as zero, crop age as 20 (P1965) and soil effects as zero. Values of sea-level tatter rate and sea-level accumulated temperature for about 110 tatter flag sites and 60 meteorological stations were then entered into the equation. This gave values of predicted potential GYC at 350 m for Scotland and northern England which ranged from 7 in extreme west and north coastal areas to about 17 in some inland areas. These values were then used as the basis for a computer interpolated map with contours at intervals of 1 $m^3 ha^{-1} yr^{-1}$. The centre of zone 1 was set at GYC 8, zone 2 at GYC 10 etc for the five zones. There was some evidence for the existence of a sixth zone but this was omitted because it was based on data from very few sites, several of which were thought to be atypically favourable.

In Figure 4 the GYC values of the zones were extrapolated upwards and downwards from 350 m at a rate of 3.2 $m^3 ha^{-1} yr^{-1}$ per 100 metres.

Figure 5 is derived directly from the function:

change in GYC with aspect = 1.17 (sine aspect) + 0.328 (cosine aspect) + 0.0332(topex − 30).

The term (topex − 30) takes account of the fact that a topex value of 30 was assumed when constructing the yield class zone map. Valley bottom sites were ignored due to insufficient data. The differentiation between hilltop and plateau sites was made by reference to the results of the analysis of tatter flag data.

The values for adjustments due to soil types were arrived at by inspection of the coefficients for the dummy variables for soil type in the above (and several similar) regression models. The values were rounded to the nearest whole number.

Planting limits were calculated by transposing the model to give estimates of elevation for known Yield Class values (8, 10 and 12). These were based on the adjusted tatter and temperature values and apply to the following site conditions: topex 30, crop age 20 (P1965), aspect and soil effects at average values.

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