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Herbage yield in agroforestry systems as a function of easily measured attributes of the tree canopy

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Abstract

Data from an experiment that measured rates of herbage yield below different tree canopies have been used to investigate the relationship between annual herbage growth and readily estimated parameters of the canopy structure of evergreen conifers. Canopy structure data were collected by destructive sampling of trees removed from the experimental area immediately prior to its establishment, and from subsequent measurements on growing trees during the following 2 years.

In New Zealand, it was found that relative pasture yield (the ratio of growth below a canopy to open pasture growth) was linearly related to green crown length in the case of *Pinus radiata* canopies. More recently, a family of relationships between relative pasture yield and green crown length, indexed by the mean height of trees forming the canopy has been derived. For our data, the regression of annual herbage yield on green crown length is good ($R^2=92.5\%$) but shows systematic variation in the residuals. Hence, other related explanatory variables were investigated to see if any gave a more satisfactory fit to the data.

By assuming that individual trees have a canopy in the shape of a regular cone, the areas of the projections of the tree canopies at different inclinations to the vertical were calculated. If it is further assumed that the canopies are of even density, the projections can be used to estimate the proportion of direct light which is incident on the herbage under the trees as a function of the angle of the sun above the horizon. A regression using both vertical and horizontal projections in varying proportions indicated that the best fit to the data was obtained using the horizontal projection alone ($R^2=94.0\%$).

These results indicate: first, that the horizontal projection of the crown gives a good, simple prediction of annual herbage yield; and secondly, that the horizontal component of incident light is most important for herbage growth at Scottish latitudes.

Keywords: Herbage yield; Agroforestry system; Tree canopy; Canopy

1. Introduction

Many models of agroforestry systems in the temperate climates of the Northern Hemisphere already exist, for example Doyle et al. (1986), Sibbald et al. (1987), Thomas (1990), Anderson (1991) and Thomas (1991). However, some of these models were built using data that were

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derived from research on more conventional forestry and agriculture (e.g. Doyle et al., 1986; Sibbald et al., 1987) and some used data from the Southern Hemisphere (e.g. Anderson, 1991). There is a constant need to update these models to incorporate relevant advances in scientific understanding: such advances include equations for some of the key components of agroforestry systems derived from an analysis of data collected in the conditions for which the models will be applied.

The objective of this paper is to use data from an experiment that measured rates of herbage yield and microclimatic conditions below nine different agroforestry canopies (Sibbald et al., 1991) to derive a relationship between percentage of annual open herbage yield and some easily measured parameters of tree canopy structure in an evergreen conifer. A similar exercise has been conducted for Radiata pine (*Pinus radiata*) in New Zealand (Percival and Knowles, 1988).

Percival and Knowles (1983) used Green Crown Length (GCL, the sum of the heights of the green crowns of individual trees, in metres, per hectare) as a simple measure of canopy structure and they found relative pasture yield (percentage of open pasture growth per annum, RPY) to be linearly related to GCL. GCL takes account of tree density (trees ha^{-1}), the total height of trees and the extent to which lower branches have been removed by pruning.

As the New Zealand database expanded, Percival and Knowles (1988) derived a family of relationships between RPY and GCL where the mean height of individual trees (expressed as an individual tree crown length range) was used to identify individual functions. The two crown length ranges that are relevant to the trees in our experiment are 2.5–7.5 and 7.6–12.5 m.

2. Materials and methods

The experiment has been described in detail elsewhere (Sibbald et al., 1990, 1991). In summary, Sitka spruce trees (*Picea sitchensis* (Bong.) Carr.) at three heights (3, 5 and 8 m (low, intermediate and tall) at the start of the experiment) were thinned to three spacings (4×4, 6×6 and 8×8 m) by removal of trees from the original 2×2 m spacing. The lower branches of the tallest trees were removed by pruning up to a height of 1.3 m. In addition, control areas with no trees were set up in unplanted areas adjacent to the afforested ground.

As the site was being established, but before the trees were finally thinned, 12 trees were removed from each of the three tree height sites. The trees selected represented a stratified sample across the range of tree heights present at each site. Each of the 36 sample trees was transported to a laboratory where it was recorded photographically. Total height of the tree was then recorded along with point of attachment of each live whorl. At each whorl, the length and vertical angle of attachment of two diametrically opposed branches were recorded. Subsequent to these destructive procedures, the height and the length of the vertical projection of two diametrically opposed branches on the lowest whorl were measured annually for each tree in a sample of those remaining in the experiment.

The data collected from the sampled trees that were felled at the thinning stage and data on tree height and canopy diameter measured on a sample of trees in the field in 1987 and 1988, have been used to calculate the crown apex angle of the trees in the three height classes, assuming that the crown is a perfect cone.

The crown apex angles and the annual measurements of tree height and branch length were used to calculate some simple descriptors of the canopy. These were: (1) green crown length (GCL) as defined by Percival and Knowles; (2) vertically projected green crown area (VPGCA), the sum of the vertical projections of each tree on to the ground; (3) horizontally projected green crown area (HPGCA), the sum of the horizontal projections of each tree on to a vertical plane. The latter two projection areas can themselves be combined to calculate the shaded area in a horizontal plane owing to incident light at any angle; the effects of overlapping shadows are ignored.

Herbage yield was measured by harvesting ryegrass (*Lolium perenne* cv. Perma) growing in sward boxes, ten times per year over the two growing seasons of 1987 and 1988. The grass was sown in 1986 in boxes 60×60×33 cm filled with free-draining soil from the same source. The boxes were subsequently transported to the experimental area and located so that the grass sward was level with the surrounding ground. The use of sward boxes in this way controlled unwanted random variation and removed below-ground competition between trees and herbage. Nitrogen in the form of a slow release, granular fertilizer was applied at the rate of 150 kg-N ha^{-1} twice during each of the years 1987 and 1988 (a total of 300 kg-N ha^{-1} year^{-1}) to ensure that it was not limiting herbage growth.

In order to account for spatial variation in the square area between selected groups of four trees, a sampling grid of nine equal squares was used; one sward box was located randomly within each cell. The stratified layout of sward boxes was replicated three times within each tree height by spacing combination. In addition, nine sward boxes were located in each of the control areas.

3. Statistical analyses

Herbage yield data were collected from each of the treatment combinations and from the two open controls in each of 2 years to give 20 sets of data. Annual herbage yield (AY, Mg (t) DM ha^{-1}), calculated using the sum of the ten harvests averaged over boxes in the groups of nine squares has been analysed as a function of the different canopy variables using regression techniques. The effect of additional sources of variation, such as between sites, between boxes and between years within boxes, has also been investigated. All fitted regression lines are presented in the form $y=a(1-bx)$ so that the average proportional decrease in growth per unit increase in the explanatory variable is immediately apparent.

4. Results

Table 1 shows the mean and standard error of the crown apex angle for each of the three heights of tree.

Table 1
Mean (and standard error) of the crown apex angles of three heights of Sitka spruce

Mean/SE	Tree height (treatment)		
	Low	Intermediate	Tall
Mean	23.4	20.6	17.6
SE	(1.26)	(1.74)	(1.56)

Table 2
Mean annual herbage yield (Mg (t) DM ha^{-1}) for the two open sites in each of the 2 harvest years

Year	Tree height (treatment)	
	Low/intermediate	Tall
1987	9.29	8.20
1988	9.01	8.08

Table 3
Proportion of annual open herbage yield for each of the nine canopy structures

Tree spacing	Tree height (treatment)		
	Low	Intermediate	Tall
4×4 m	0.56	0.10	0.15
6×6 m	0.86	0.75	0.69
8×8 m	0.80	0.84	0.82

The GCL values range from zero (open) to 4000 m ha^{-1} compared with Percival and Knowles (1988) range of zero to 10 000 m ha^{-1}. VPGCA was calculated and values lie in the range zero (open) to 12 261 m^2 ha^{-1}, calculated values for HPGCA lie in the range zero (open) to 9376 m^2 ha^{-1}.

Means of total annual herbage yield for the two open sites and for each of the two measurement years are shown in Table 2. These values fall centrally within the range of annual yields (5.4–12.8 Mg (t) ha^{-1}) for ryegrass pasture receiving 300 kg-N ha^{-1} year^{-1} in the GM20 series of trials (Morrison et al., 1980) as would be anticipated for a site at this location.

The yield of understorey herbage expressed as a proportion of the open-grown yields for the nine

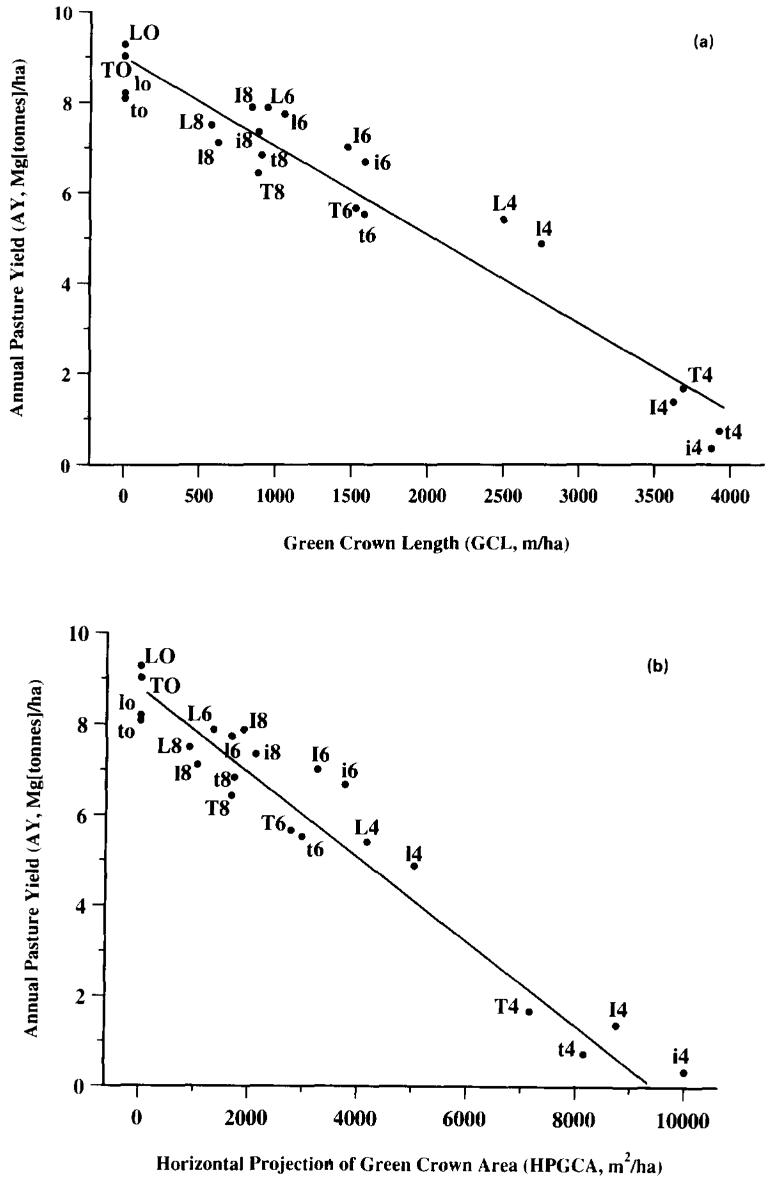

Fig. 1. Total annual herbage yield plotted against (a) GCL and (b) HPGCA, with fitted regression lines in each case. (The letters L, I and T indicate tree height; low, intermediate and tall, respectively; upper and lower case indicate 1987 and 1988, respectively. The numbers 0, 4, 6 and 8 indicate tree spacings; open (no trees), 4×4, 6×6 and 8×8 m, respectively.)

canopy structures is shown in Table 3.

The linear regression of AY on GCL explains most of the variation in our data (Fig. 1 (a)). The fitted line is:

$$AY = 8.98(1 - 2.18\times10^{-4}\times\mathrm{GCL}) \qquad (1)$$
$$(R^2 = 92.5\%, P < 0.001)$$

However, the residuals from this equation demonstrate a systematic lack of fit and fitted values at the highest levels of GCL are consistently overestimated suggesting that the use of a non-linear measure of canopy size would be an improvement.

A comparison of our data with the addition of

Table 4
Variation in annual herbage by successive addition of explanatory variables (Regression analysis; accumulated analysis of variance)

Change	d.f.	Sums of squares	Mean square	Variance ratio
+HPGCA[a]	1	139.933	139.933	4140.97
+site	1	1.075	1.075	31.81
+year	1	0.00004	0.00004	0.00
+site·year	1	0.00025	0.00025	0.01
+HPGCA·site	1	0.589	0.589	17.42
+HPGCA·year	1	0.01153	0.01153	0.34
+HPGCA·site·year	1	0.042	0.042	1.25
+age	3	5.658	1.886	55.81
+remaining between-group	6	1.467	0.244	7.23
Residual	5	0.169	0.038	
Total	21	148.945	7.093	

[a]HPGCA, horizontal projection of the green crown area

the functions from Percival and Knowles (1988) for the crown length ranges 2.5–7.5 and 7.6–12.5 m showed that adding the height of individual trees to GCL does not further explain the trend in our experiment.

A better fit is achieved by regressing *AY* on HPGCA (Fig. 1(b)). The fitted line is then:

$$AY=8.78\times(1-0.106\times10^{-4}\times\text{HPGCA}) \quad (R^2=94.0\%, P<0.001) \tag{2}$$

This is a slightly better fit than the regression of herbage yield data to GCL (Eq. (1)). Furthermore, the residuals of this equation do not demonstrate such a systematic lack of fit. A non-linear regression treating the angle at which shadows are cast as a parameter to be estimated (generating values between those for VPGCA and HPGCA) found that no improvement could be made on Eq. (2). Thus, HPGCA provides the best single predictor of *AY*.

Of the residual variation remaining after the regression on HPGCA, all but 2% can be explained by the addition of further terms (Table 4). Although this indicates that there is no systematic difference between years, it does indicate systematic differences between sites and between age class of trees (taking the open areas as a fourth age class), together with a site×slope interaction. Furthermore, the variation remaining between groups of boxes is significantly greater than the variation between years within groups ($P=0.02$). Whilst the effects of site and age class are still significant when tested more correctly against residual between groups of boxes variation ($P<0.01$ and $P=0.02$, respectively), the evidence for a site×slope interaction is then not significant ($P>0.2$).

5. Discussion

The regressions of *AY* with both GCL and HPGCA are very highly significant. However, Eq. (2), the relationship between *AY* and HPGCA, is the better fit suggesting that under the regular conical crowns of Sitka spruce in the uplands of the UK, lateral rather than vertical shading may have the greater effect on understorey herbage yield.

A comparison of our data with the addition of the functions from Percival and Knowles (1988) for the crown length ranges 2.5–7.5 and 7.6–12.5 m showed that adding the height of individual trees to GCL does not further explain the trend in our experiment. This could of course result from differences in climate (differences in the mean angle of the sun between New Zealand and the UK, for example) or tree structure (*Picea sitchensis* compared with *Pinus radiata*). Certainly *Picea sitchensis* has a more regularly shaped crown and this makes it possible to calculate a value for the total area of tree crowns on a unit area of land. The slope of the relationship between green canopy area and relative herbage yield will of course vary with different canopy densities.

The very strong relationship that has been established between green crown area and relative herbage yield forms a sound basis for modelling the reduction in annual pasture yield that will result below the canopies of evergreen conifers in the UK given that the simple canopy dimension of HPGCA can be measured directly or calculated from a model of tree growth. The further division of the residual (see Table 4) is interesting in that it demonstrates there is more to be discovered about the effect of tree canopies on herbage growth. It should not be forgotten, however, that the simple linear regression provides an excellent predictor which is sufficiently good for all practical purposes.

Empirical effects of canopy density might be tested in such a model by varying the slope of the equation relating *AY* to HPGCA on the basis of relative crown density measurements made on Sitka spruce and other species of evergreen conifer that have crowns in the shape of regular cones.

It may therefore be assumed for temperate zones in the Northern Hemisphere that, in terms of an easily measured parameter of crown structure, the horizontal projection of the green crown area is the best predictor of relative pasture yield for pastures growing below the regular cone-shaped crowns of conifers. The slope of the regression line will be a function of canopy density and so may vary with stage of growth or species of tree. Considering the extent of the variation in annual pasture yield that is explained, there would appear to be little variation in canopy density over the range of tree heights in this experiment.

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