THE PREDICTION OF COOL-SEASON FORAGE OAT YIELD USING TEMPERATURE AND SOLAR RADIATION DATA

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ABSTRACT

A crop growth model based on temperature and solar radiation was designed to predict winter forage oat dry matter yield. A three stage predictive model was fitted to a data set from regional forage production trials (Taylor *et al.*, 1976). Temperature (degree days) was used in the model to drive yield after an initial crop emergence period and radiation was used when leaf area development was estimated to be sufficiently advanced to intercept a high proportion of solar radiation. The model compared favourably with forage oat yield data published in New Zealand between 1966 and 1984 by various authors. The model can be used by farm managers at any growing site at any autumn sowing date and a practical example is given.

Data presently available in the literature was found to be inadequate to formulate models predicting rates of physiological development, nutritive values, yields of regrowth after harvests and crop yields under various levels of crop management. Some of the implications for future agronomic field work are discussed.

Additional Key Words: crop growth model, crop-weather interactions

INTRODUCTION

A variety of grass and cereal crops are grown in New Zealand for use in mid to late winter and in spring. Models that could be used to predict the yields of these crops would be of use to farm managers faced with decisions over sowing dates and stock-buying and selling policies. Such models would have to take account of yield variation between sites and with different sowing dates. To be practical, they would have to be based on readily available data and be simple to use.

These requirements pose a challenge to agronomists. Yield data for forage crops in New Zealand are usually presented in the form of growth curves (Douglas, 1980). Since these curves are site-specific, year-specific and sowing date-specific, they cannot be used easily by farm managers. Clearly, agronomists must find methods for removing these specificities and constructing general models for forage yield that are of use to managers.

In this paper, we outline one approach to this problem. Using data for cool-season forage oats, we demonstrate construction of a simple model for predicting yields based on temperature and radiation data. We then indicate how this model might be used by farm managers as a planning tool. Some of the implications of this modelling approach are also discussed and suggestions are made on how agronomic work could be done to improve data sets used in future models.

DATA

The most comprehensive and consistent set of data for cool-season forage oat yields available in New Zealand is provided by Taylor *et al.* (1976). The crops in their trials were sown in the 3-day period, 15-17 April 1975 at Kaitaia, Rukuhia, Palmerston North, Timaru, Invermay and Gore.

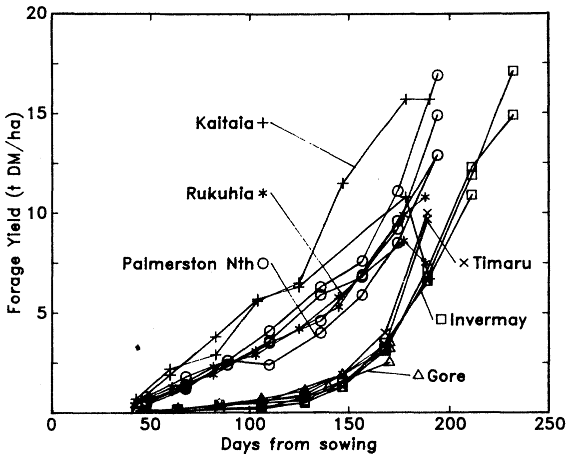

Figure 1: Forage oat yield recorded after a common sowing date in the regional forage trials of Taylor *et al.* (1976). More than one cultivar is shown at each site.

Eight oat cultivars were represented in the trials, although we were not concerned with differences between cultivars in this analysis. Crops at different sites were managed as uniformly as possible during the trials. Crop yields were measured at regular intervals and data on stages of development and nutritive value were also collected.

Yield data for the oat crops in the above trials are displayed in Fig. 1. The difficulty in interpreting data presented in this manner is obvious. However, close examination will show that there are considerable variations in yields between sites at various times after sowing and that most of this variation arises during seedling emergence and early development. At the North Island sites (Kaitaia, Rukuhia, Palmerston North), forage yields accumulate fairly steadily after the first 50 days. At the South Island sites (Timaru, Invermay, Gore), there is a much longer period (of the order of 150 days, or until mid-September for the mid-April sowing date) before crop yields begin to accumulate steadily.

Fig. 1 demonstrates the challenge faced by modellers. We require a simple model that will give predictions of crop yields for any given autumn sowing date for diverse sites. The specific objective in the work we report here was to fit a model to the data in Fig. 1. To derive this model we obtained daily temperature and solar radiation data from the Meteorological Service, Wellington. Monthly summaries of these weather data are given in Taylor *et al.* (1976).

A MODEL FOR FORAGE OAT YIELDS

Models that relate crop yield to absorbed photosynthetically-active radiation have been discussed in a number of papers (e.g. Monteith, 1977; Gallagher and Biscoe, 1978; Wilson and Jamieson, 1984). These models can be written in the form

$$Y(h) \alpha \int_s^h Q \, dt \qquad (1)$$

so that crop yield, Y, on day h (harvest) is assumed to be proportional to the total amount of photosynthetically-active radiation intercepted by leaves between sowing (day 0) and harvest (day h). Q is the radiation flux and has units of megajoules per unit area per unit time.

Since models based on (1) have proven successful for predicting crop yields, we used it as the starting point for the model described in this paper. In the trials described by Taylor *et al.* (1976), radiation data were available as daily totals of incident solar radiation rather than as absorbed photosynthetically-active radiation. This means that equation (1) had to be modified in several ways. First we assume that there is some minimum yield, say Y_m, when ground cover by leaves is well advanced and a large proportion of solar radiation is being intercepted by the crop. Then, treating photosynthetically-active radiation as a constant fraction of solar radiation and altering the integral in (1) into a daily summation, we can write

$$Y_t = Y_m + b_1 \sum_{i=m}^{t} R_i \qquad (2)$$

Here, Y is yield on day t, t is the day on which the minimum yield, Y_m, is reached, R_i is the solar radiation on day i (days between t_m and t) and b_l is a coefficient. This coefficient takes account of the proportion of solar radiation that is photosynthetically-active and absorbed by leaves and of the conversion of photosynthetically-active radiation into crop dry matter.

To apply (2) to Taylor *et al.*'s (1976) data it is necessary to estimate the minimum yield, Y_m, and the time, t_m, when this is reached. It seems reasonable to suppose that temperature could play a major part in determining when this yield is reached. Inspection of Fig. 1, for example, suggests that the upswing in yield accumulation is much delayed at colder sites such as Gore, Invermay and Timaru. We assumed, therefore, that Y is determined by temperatures in the period after sowing.

A number of models could be used to relate yield to temperature in the early stages of growth. We chose to use the familiar "degree day" model,

$$D(t) = \sum_{i=0}^{t} (T_i - T_b)_+ \qquad (3)$$

where D(t) is the degree day sum on day t, T_i is the average of the maximum and minimum temperatures on day i, T_b is the base temperature and the subscript + is used to indicate that only the positive values of (T_i - T_b) are summed. To relate degree days to yield, we postulated a simple model with two parts. In the first, young plants must accumulate a certain number of degree days, D_e, before there is any effective yield; this can be viewed as a degree day requirement for crop emergence, and the time t_e, at which D_e is reached, can be treated as an emergence time. The second part of the degree day-yield model is for the period between t_e and t_m, the minimum yield day of equation (2); for this, we assume yield increased in proportion to accumulating degree days.

Combining this model with equation (2) above, we have a three part model for yield prediction:

(1) From sowing (t = 0) until the degree day sum D_e is reached, yield is effectively zero: i.e.,

$$Y(t) = 0, \; t<t_e, \qquad (4)$$

where t_e is the day on which degree day sum D_e is reached.

(2) From t_e until t_m yield increases linearly with the degree day total: i.e.,

$$Y(t) = b_2 * (D(t) - D_e), \; t_e < t < t_m, \qquad (5)$$

where b_2 is a constant. Note that

$$Y_m = b_2 * (D_m - D_e) \qquad (6)$$

where D_m is the degree day sum when the minimum yield Y_m is reached.

(3) From t_m onwards, yield is proportional to accumulated daily solar radiation as given in equation (2).

The model expressed in equations (2) - (6) was fitted to Taylor *et al.*'s (1976) forage oat data. It required 5 independent coefficients to be estimated: the slopes b_1 and b_2, the base temperature T_b, and the degree day totals D_e and D_m. Estimates were obtained using a nonlinear regression program with observed yields for all sites as dependent variables and daily average temperature and solar radiation totals at the sites as independent variables.

RESULTS

The overall fit of the model to Taylor *et al.*'s (1976) oat data is illustrated in Fig. 2. The co-ordinates of data points in this figure are observed yields at days of sampling at each site (y co-ordinate) and accumulated values of temperature and then radiation to the same days (x co-ordinate).

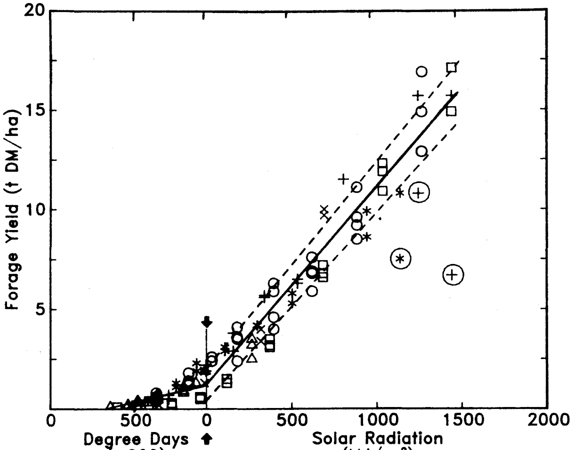

Figure 2: Forage oat yield from Taylor *et al.* (1976) plotted as a function of degree days and solar radiation. Dotted lines approximate one standard deviation either side of the line. Symbols are similar to Fig. 1. Crops infected with crown rust are circled.

A preliminary analysis of the data gave a value of 0.7 °C for T_b, so for simplicity of application, the model was refitted with T_b set at zero. The lines drawn through the data in Fig. 2 are based on fitted values of 0.00992 (t DM/ha)/(MJ/m²) for b_1, 0.00202 (t DM/ha)/C for b_2,325 (C) for D_e, and 921 (C) for D_m. Fig. 2 illustrates the three parts of the model: yield is zero until 325 degree days are accumulated, yield then increases in proportion to degree days until 921 degree days are accumulated, at which stage the yield has reached 1.203 t DM/ha (from equation (6)); thereafter yield increases in proportion to accumulated radiation.

The lines fitted through the data in Fig. 2 account for 81% of the variance in observed yields. Data points which were heavily affected by crown rust (circled) were omitted when fitting the model. The dotted lines in Fig. 2 approximate one standard deviation to either side of the fitted lines and provide a rough indication of uncertainties associated with the model.

The performance of the model at individual sites is illustrated in Fig. 3. Here, yields from the sequential harvests for two cultivars at Kaitaia, five cultivars at Palmerston North, and three cultivars at Gore (cf. Fig. 1) are compared with yields predicted by the model at these sites (the solid lines). It is clear that the model provides reasonable estimates for forage yield at these sites. At Gore and Palmerston North, there is a pronounced change in slope when predicted yield reaches 1.2 t DM/ha (Y_m) and the driving variable switches from temperature to radiation. The model appears to account satisfactorily for the increasing delays from northern to southern sites associated with establishment and early growth.

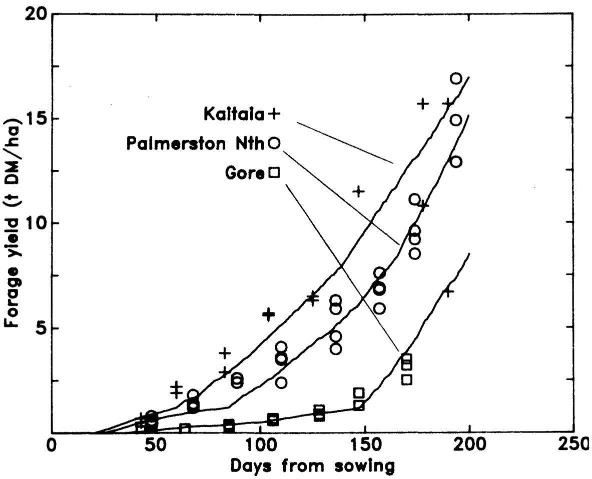

Figure 3: Predicted forage yield (solid lines) at 3 of the sites shown in Fig. 1, compared with the observed yields from Taylor *et al.* (1976) for 2 cultivars at Kaitaia, 5 cultivars at Palmerston North and 3 cutivars at Gore.

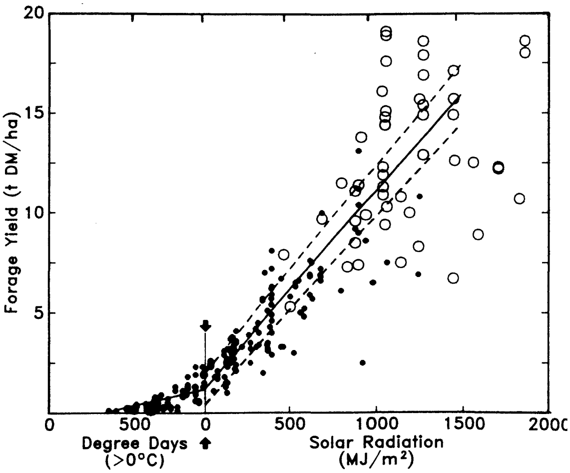

Figure 4: All published data from autumn-sown oat forage crops (1966-1984) superimposed on the degree day/radiation model. Data collected after heading are indicated with circles and these crops may have a low nutritive value.

A further indication of the effectiveness of the model is provided by Fig. 4. This figure includes all published yield data from cool-season oat trials grown in New Zealand between 1966 and 1984. (References from K.A. Hughes on request). Since nutritive value of oats drops off rapidly after heading, crops harvested after this stage are indicated on the figure. Superimposed on these data are the fitted lines from Fig. 2 which show predicted yields based on accumulations of temperature and radiation. Although the overall concurrence between observed and predicted yields is worse in Fig. 4 than in Fig. 2, the model still passes through the centre of the data. We consider this satisfactory, given that the data in Fig. 4 were collected from trials under diverse management (unlike the data in Fig. 2) and where various extraneous factors such as low fertility, water-logging, poor plant establishment, and frosts may have affected yields.

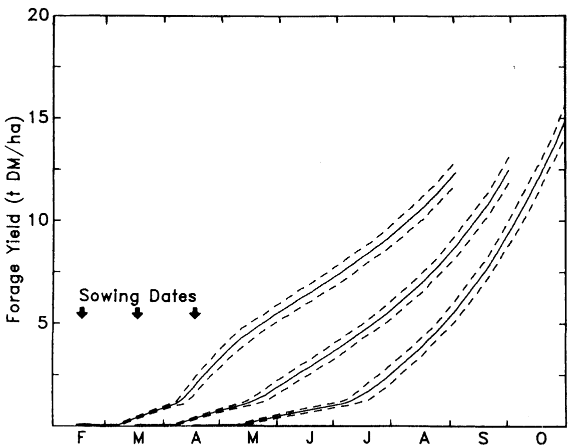

Figure 5: Predicted forage oat yield after 3 sowing dates at Palmerston North: 15 February, 15 March and 15 April. Dotted lines approximate one standard deviation either side of the predictions.

AN ILLUSTRATION OF USE OF THE MODEL

A manager wishing to grow oats as a forage might ask the following questions: when should the crop be sown in order to have a yield of say 8 t DM/ha available on August 1 in an average year?; if harvest was deferred until September 1, how much extra yield would be gained? We shall illustrate use of the model to answer these questions for a single site, in this case Palmerston North.

Since it is impossible to predict the temperature and radiation data required as inputs for the model, yield predictions (the output of the model) must be made using historical values for daily average temperature and solar radiation. We have used 11 years (1972-1982) of temperature and radiation records from Palmerston North (meteorological station E05363) for this purpose. Analysis of these data showed that temperature and radiation sums accumulated from a given date were remarkably conservative from year to year, despite relatively large year to year variations in temperature and radiation values on particular days. Thus, when the data were used in the model for each of the 11 years (and with a common sowing date for all years) there was relatively little variation in yield predictions from year to year. We have, therefore, used 11-year means for temperature and solar radiation to illustrate the application of the model at Palmerston North.

Table 1 shows predicted yields at various harvest dates for mid-February, mid-March and mid-April sowing dates. The table could be used by a farm manager to answer both of the questions posed above: an oat crop sown in mid-February at Palmerston North should yield more than 8 t DM/ha by August 1 in an average year; deferring harvest until September 1 should result in an extra forage yield of 2.7 t DM/ha.

TABLE 1: Predicted oat yield at Palmerston North after 3 autumn sowing dates. Predictions are based on 11-year means for daily average temperature and solar radiation data. (Separate predictions for each of the years indicate S.D. of 1.2 t DM/ha).

Harvest date	Sowing date Feb 15	Mar 15	Apr 15
May 1	3.3	0.7	0.0
June 1	5.5	1.9	0.4
July 1	7.2	3.6	1.0
August 1	9.3	5.6	2.4
September 1	12.0	8.4	5.2

Predicted yield curves for the three sowing dates in Table 1 are shown in Fig. 5. The dotted lines lie one standard deviation above and below the mean predicted forage yield curves. Thus, in two years out of three we could expect yields to lie between the dotted lines for each of the sowing dates, on the basis of sowing date alone. Errors associated with fit of the model (as indicated in Fig. 2), which have not been included, at least doubles the width of the band of variablility around the mean. However, altering sowing date will have a much greater effect on yields at any harvest date than will variability in the weather from year to year.

DISCUSSION

We have described a predictive model, which, although simple does succeed in bringing together data from the diverse sites shown in Fig. 1. We have also compared the model to published yield data from a large number of sites in New Zealand. It can be used to predict autumn-sown forage oat yield for any New Zealand growing site, provided the crops are well established on fertile soils and not subject to drought, water logging or excessive frosts.

Precise estimates of uncertainty have not been given because these are difficult to calculate with nonlinear regression analysis. However, the estimates of variability which have been calculated indicate that the manager's choice of sowing date is likely to have a far greater impact on yield reached on a given date than variability in the weather.

There is a large amount of variability present in the yields achieved by the various experimenters shown in Fig. 4. This suggests that varied crop management may have had major effects on yields. Future agronomic work needs to consider levels of crop management along with the effects of the different development rates of cultivars. Other species also need to be considered and preliminary analysis of Tayor *et al.*'s (1976) wheat data indicates that a similar model can be fitted to it.

We have formulated a model for dry matter yield, and it is the best we could devise with the available data. However, it does not completely meet the needs of farm planners. In practice, farm managers would probably find that models incorporating some estimates of nutritive value would be more useful. The most important measures of nutritive value include the digestible nutrient concentration per unit of feed (e.g. metabolisable energy/kg dry matter) and the concentration of proteins and minerals (Ulyatt *et al.,* 1980). Nutritive value varies with stage of physiological development, and the quality decreases rapidly after heading (Eagles *et al.,* 1979; Hughes and Haslemore, 1984). The data in Fig. 4 indicate that heading occurs in autumn sown oats at about 8-9 DM/ha and a farm manager may wish to plan grazing or harvesting to occur no later than this to ensure a high feeding value.

Guides for future work

We have illustrated how the data set of Taylor *et al.* (1976) has been useful and the lessons learnt have implications for future agronomic reseach. Taylor *et al.*'s data set included dry matter yields, estimates of crop development stage (Feekes scale) at each harvest, some measurements of nutritive value and notes on crop growth and soil fertility at each site. In contrast, many of the papers reviewed during the seach for data to include in Fig. 4 gave very little information other than estimates of dry matter yield, making it very difficult to explain the poor yields obtained in some trials.

It would be useful if future descriptions of crop growth and development included more precise measures of the number of days to reach key stages of development, e.g. floral initiation, heading and flowering. This would allow the development rate of crops from diverse experiments to be modelled more easily. On the other hand, knowing the development stage at each harvest is necessary for modelling forage yields where more than one harvest and regrowth is being considered, as is often the case in farm practice.

Technological advances since Taylor *et al.*'s work carried out in 1975 now enable better descriptions of the early development of leaf area and solar radiation interception to be obtained in young crops. These measurements would make future models of early growth easier to develop. Agronomists planning field work can refer to McAneny and Kerr (1984) for further advice on plant and soil measurements required for "minimum data sets" before commencing field work.

We have demonstrated the construction and method of using a crop growth model using New Zealand published data. We conclude that future agronomic field work can be improved by considering some of the points outlined above, and that through this exercise have demonstrated the potential of more unified regional trials around the country.

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