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Multidate spectral reflectance as predictors of yield in water stressed wheat and barley

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Abstract. Spectral reflectances of several crops at Phoenix, Arizona were measured during two growing seasons using a hand-held radiometer, the Exotech Model 100A, that had a spectral bandpass configuration similar to scanning radiometers aboard Landsat 2 and 3. During the period of grain filling, yields of two wheat and one barley variety were well correlated with the integrated daily values of a modified vegetation index derived from reflectances in MSS Bands 5 and 7 (0·6–0·7 and 0·8–1·1 μm respectively). The derived model accounted for 88 per cent of the variability in yields from 103 to 656 g/m^2 which were due to differential experimental soil moisture conditions (20 to 70 cm applied water).

1. Introduction

The potential social, economic and political benefits arising from the accurate prediction of agricultural harvests make the development of crop yield models very attractive. Thus, we have developed several simple approaches to yield modelling of agricultural crops, each of which is amenable to remote sensing and requires little or no additional input of ancillary ground data. Our previous models predict yield by assessing crop vigour before harvest by regularly measuring canopy temperature, albedo, or rates of senescence (Idso *et al.* 1977 a, b, 1980). In this paper, we report on a new yield prediction technique that is based on multidate measurements of reflected radiation from small grains and is capable of accurately predicting yields from crops grown under a wide range of moisture-stress conditions.

Several indices derived from Landsat waveband radiances have been proposed to characterize various agronomic parameters such as green ground cover, leaf area and biomass (Tucker 1979). Some appear well suited for yield prediction because of their responsivity to the photosynthetically active biomass of the canopy. These exploit the fact that, as the density of green plant material increases, reflectance decreases in the visible wavebands and increases in the near-infrared region of the spectrum. When plant leaves senesce, the reverse is true. Tucker *et al.* (1980), using a hand-held radiometer with a slightly different bandpass configuration than the Landsat wavebands, have shown that the ratio of I.R. to red radiances and also the normalized difference between I.R. and red radiances [(I.R. − red)/(I.R. + red)] are correlated with final yield in wheat. They concluded that, although single-date sampling was sufficient to predict yield in their study, it would not be optimum if planting dates were staggered or if plants in the fields were not at the same phenological stage. Aase and Siddoway (1981) confirmed the correlation between single date spectral vegetation indices and both final grain yield and dry matter production but further noted that the relationship deteriorated rapidly as the wheat ripened and then senesced. We felt that a method which accounts for the time trend of spectral reflectances over a critical period rather than single-date observations would predict yield more accurately.

2. Methodology

For the past 2 years, we have measured the spectral reflectances of small grains during the winter–spring growing season at Phoenix, Arizona. Our data base included multidate observations from a total of 30 experimental Produra wheat (*Triticum durum* Desf. var. Produra) plots (24 in 1977 and six in 1978) and six plots each of Briggs barley (*Hordeum vulgare* L. var. Briggs) and Anza wheat (*T. aestivum* L. var. Anza) in 1978. Widely varying yields were established by two different planting rates in 1977 and differential irrigation regimes during both years. Sufficient nitrogen and phosphorous had been added to the Avondale loam soil (a fine, loamy, mixed (calcareous), hyperthermic, Antropic Torrifluvents) to ensure that no nutrient deficiency would occur during crop development. Row spacing was 18 cm both years. In 1977, 12 plots had a north–south row orientation and 12 were planted in both north–south and east–west directions to achieve a greater stand density. In 1978, all rows were in an east–west direction.

Our spectral measurements were made using a hand-held radiometer (Exotech† Model 100A, 15° F.O.V.), with bandpass characteristics resembling those found on current Landsat satellites (MSS4, 0·5–0·6 μm; MSS5, 0·6–0·7 μm; MSS6, 0·7–0·8 μm; and MSS7, 0·8–1·1 μm). The radiometer was hand-held approximately 2 m above the soil surface and thus viewed a circular area of about 0·5 m in diameter at the beginning of the season and less as the canopy grew to a height of 1 m. Six 4-band 'scans' were made in the designated target areas of each plot and averaged. Bidirectional reflectance factors were calculated as ratios of mean canopy radiance to incident global irradiance, as determined by frequent measurements (i.e. 1–1/2 min intervals) of reflected radiation from a horizontal barium sulphate reflectance standard. Data were obtained on most clear days between 09.20 and 09.40 hours (MST) and measurements were continued until after canopy senescence in all plots. Final grain yields were determined by hand-harvesting the areas (about 13 m^2) of each plot that were regularly viewed with the radiometer.

3. Results

The approach we took to model grain production under varying soil moisture conditions used the vegetation index (Rouse *et al.* 1973) which recently had been referred to as the normalized difference (ND) parameter (Deering 1978). It is defined as

$$\mathrm{ND} = \frac{\mathrm{MSS7} - \mathrm{MSS5}}{\mathrm{MSS7} + \mathrm{MSS5}}$$

where MSS5 and MSS7 are reflectances measured in wavebands 0·6–0·7 μm and 0·8–1·1 μm respectively. When we plotted the time trajectory of this index for each experimental field, a consistent pattern emerged that was correlated with final yield. Figure 1 illustrates this with data from four Produra wheat fields in 1977. The curve shown for each field was generated from 49 clear-day measurements of ND (over an

† Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the authors or the U.S. Department of Agriculture.

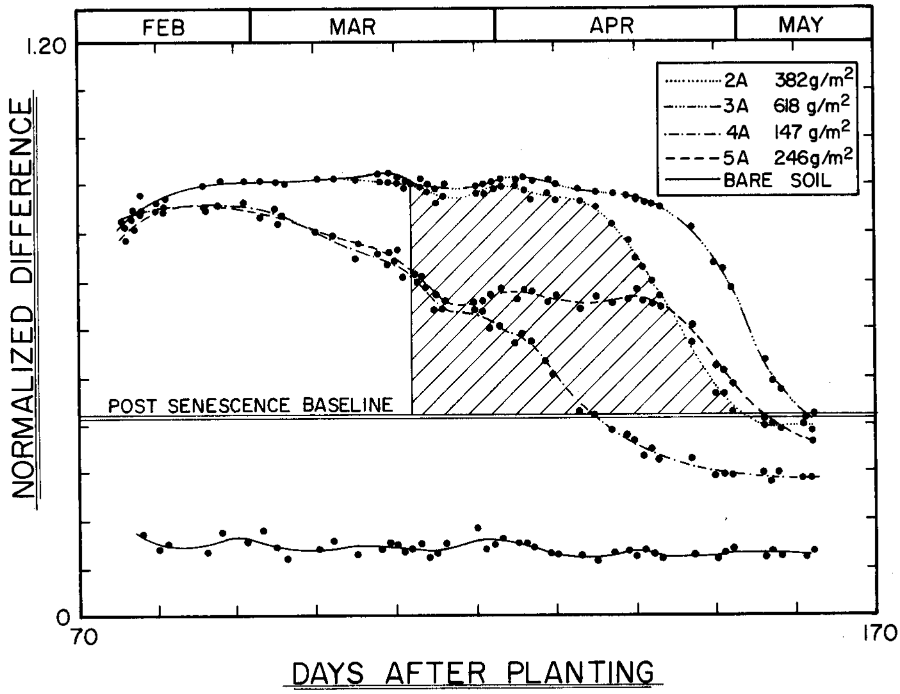

Figure 1. The normalized difference parameter, ND, versus time for four Produra wheat fields with widely varying yields and a bare soil plot in 1977. The shaded portion under the curve for plot 2A is a graphic representation of the integration technique described in the text.

84 day period) that were smoothed with a sliding third-degree polynomial curve-fitting approach similar to the sliding parabola method of DeChateau *et al.* (1972). We observed that yields were highest where ND was elevated for lengthy periods; conversely, yields were lower where ND was depressed during the grain-filling period. Such a relationship between ND and yield is theoretically sound, since the greater the amount of photosynthetically active tissue following heading and the longer its duration, the more photosynthate is available for input into grain kernels. Figure 1 shows that the use of single date or maximum index values for yield prediction could be misleading. A better approach would be the integration of the index with time, thus taking into account not only the value of ND but also its persistence during the grain-filling period.

This approach resembles that suggested by Watson *et al.* (1963). They proposed that leaf area duration (LAD = the integral of green LAI with respect to time over the interval from heading until maturity) could be used as a predictor of final wheat yield. Instead of using green LAI for calculating LAD, however, we substituted smoothed daily values of the radiometric index ND, from which we subtracted a baseline value that was equivalent to ND for a dense, totally senescent canopy. Our rationale for subtracting a baseline was to minimize the contribution of non-photosynthesizing canopy and background soil elements to the index. It also provided an objective method for establishing dates of canopy senescence and termination of the integration. The baseline was determined empirically for high-yielding crops at the end of the season for Produra wheat (in 1977, 0·422; in 1978, 0·337), Briggs barley (0·285), and Anza wheat (0·308). A single baseline was then used for each year and each cultivar. We suspect that variation in the baseline will be minimal for a given cultivar from year to year. The differences in the baseline between the 1977 and 1978 Produra wheat were attributed primarily to different row orientation. The 1978 east–west canopy configuration permitted deeper penetration of the specular component of irradiant flux at 09.30 hours, with the result that more soil was illuminated and the ND was lower (Jackson *et al.* 1979).

We then summed the smoothed daily values of ND minus the baseline for each plot, beginning with the day when 50 per cent of the plants were heading [Feekes scale, 10·5; entire ear out of sheath, flowering about to commence (Large 1954) and continuing until the canopy was totally senescent (i.e. the index dropped below the baseline). When the integrated index values were plotted versus final yield for Produra wheat (figure 2), we found the data were well described by the exponential relation

$$Y = 68 \exp(0{\cdot}1081X) \tag{1}$$

with $r_{y \cdot x} = 0{\cdot}94$ and $S_{y \cdot x} = 51$ g/m^2, where X is the accumulated positive values of ND minus the baseline and Y is the final yield in g/m^2. Furthermore, data for Briggs barley and Anza wheat also fell within the same range, implying that a similar predictive approach may be applicable to other small grains as well.

The three circled data points in figure 2 were not included in the analysis since they represent the index values for fields which were heavily damaged by birds during the soft-dough stage of kernel development. Each of these, however, received 20 cm more irrigation than our highest yielding Produra field in 1978 (656 g/m^2) and our pre-bird-damage observations of head weight and persistence of green leaf area lead us to believe that their yield would have approached 700 to 800 g/m^2.

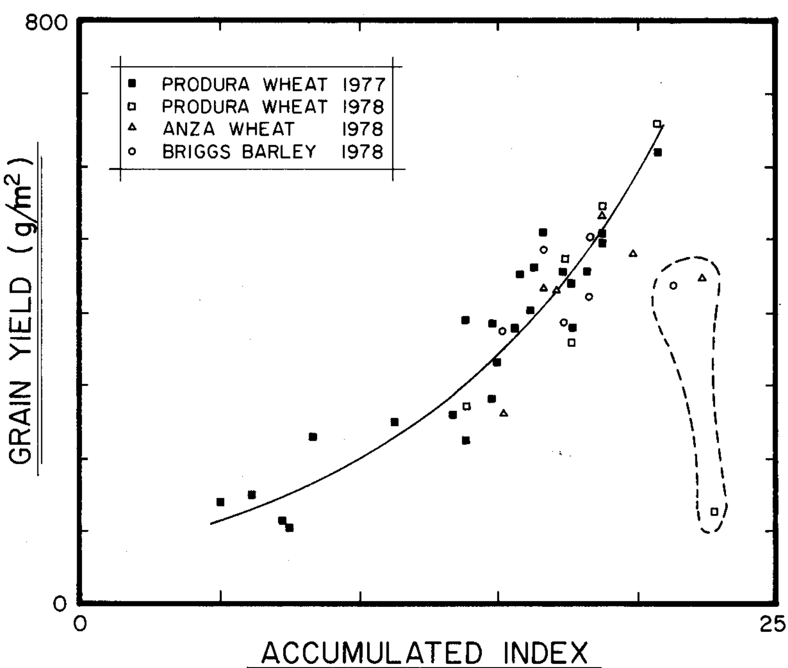

Figure 2. Grain yield (dry weight) versus the accumulated daily values of the radiometric index from heading until senescence. Circled data points are from three fields in which birds damaged up to 88 per cent of the heads. The curvilinear relation was calculated for 29 non-damaged Produra wheat fields.

A residual analysis (Neter and Wasserman 1974) of the data from undamaged plots showed that model performance was not affected by yield (103 to 656 g/m^2), planting rate (67 to 137 kg/ha), or total water received (20 to 70 cm). The model performed equally well in predicting 1977 and 1978 yields, even though the 1978 crop was planted 2 weeks later and received three times more winter rainfall. Furthermore, our data imply that the fundamental principles involved in this model may be applicable to other grain crops as well.

The performance of this model is optimum when it starts at a specific phenological event. In our case, we chose stage 10·5, heading, but analysis of our data has shown that equally good predictions could have resulted from starting 5 days earlier or 10 days later; however, the coefficients of equation (1) would have been different. A sensitivity analysis was employed to evaluate the performance of equation (1) when the actual date of heading could not be specified accurately. Our results showed predictions for low yielding plots were most insensitive to errors of this kind. For example, we found that an error of ± 5 days in determining the date of heading would lead to only a 25 g/m^2 error in fields with a 100 g/m^2 yield, an important consideration if this technique is to be applied in marginal agricultural regions. For high yielding fields, however, the date must be specified with greater accuracy. A ± 2 day error in a field yielding 600 to 700 g/m^2 would lead to a predictive error of ± 100 g/m^2, whereas an error of ± 5 days would lead to an intolerable 200 to 300 g/m^2 error in predictions. Another relevant limitation is that such spectral models have a sun-angle dependence that makes them unique to a specific crop geometry, time, latitude and season (Duggin 1977, Jackson *et al.* 1979, Kimes *et al.* 1980). Work is under way at our location to make these spectral measurements more independent of these variables.

Substitution of a radiometric index in lieu of LAI for yield prediction had several advantages. Perhaps the most important is the ease and rapidity with which measurements can be made in the field, eliminating the cumbersome and variable LAI determinations and making it feasible to survey many fields within a very short time. In addition, use of a remote, non-destructive technique with little input of ground data implies the potential for adapting this approach to aircraft or satellite surveillance systems for predicting yield over broader regions.

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