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Crop Emergence Date Determination from Spectral Data

The unique temporal spectrum of wheat and barley were used to determine emergence (spring green-up) day of those crops.

Abstract: *An analytic method of estimating the emergence (spring green up) of a given crop is proposed. The method relies on the hypothesis that in the region* ($\lambda = 0.70 - 1.35\ \mu m$) *a given crop, after emergence, has a unique spectral profile in time. This profile, for wheat, can be described by the functional form*

$$\rho(t) = \rho_s(t_0)\left(\frac{t}{t_0}\right)^{\alpha} \quad \text{Exp}\left\{ \beta t_0^2 \left[1-(t/t_0)^2 \right]\right\} t \geq t_0\ \alpha, \beta > 0$$

where $\rho(t)$ *is the reflectivity at time* t, $\rho_s(t_0)$ *is the soil reflectivity at the emergence day,* t_0, *and* α *and* β *are crop specific constants. If the crop emerges late (or early) relative to a reference standard (determined for a given segment), the profile is displaced, but has the same shape. Thus, given the constants* α *and* β *of the reference profile and a sufficient number of Landsat observations of reflectivity,* $\rho(t_i)$, *at specific times,* t_i, *one can determine the emergence date of a field. This information can be of use in spectral separability of crops.*

Introduction

A considerable effort has been made in LACIE (Large Area Crop Inventory Experiment) to develop algorithms for signature extension. In this approach, the aim is to apply training statistics derived from one segment (5 n.mi by 6 n.mi) to many widely separated segments. To date, this effort has not been very successful. Indeed, one finds that training statistics developed from one part of a LACIE segment do not necessarily extend to other parts of the same segment. One of the largest sources of reflectivity variation in a crop is caused by the fact that there exists a distribution in the planting date of the fields in the segment. This obviously leads to a distribution of the emergence date because the reflectivity is a function of the biostage (which is a function of growing degree days, etc.) of the plant.

In the winter wheat regions, the emergence date referred to here is what is normally called the spring green-up and it is the distribution in the spring green-up times that is important.

It is, therefore, not surprising that the statistics of spectral data developed from different parts of the LACIE segment are different. Thus, if a technique to estimate the emergence (green-up) day of a pixel (1.1 acre in size) can be developed from the Landsat data, it will in all likelihood allow a standardization of these data. This can provide several benefits such as identification of crop types from multitemporal data.

In this paper, a possible method to esti-

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mate the emergence day, which has been developed from the field research data and has been verified in several LACIE segments in North Dakota and Minnesota, is suggested.

METHOD AND JUSTIFICATION

The reflectivity of a growing crop is an integrated response of a rather large number of factors. The importance of a fundamental understanding of plant canopy reflectance has long been recognized, and impressive progress has been made in this direction in the past decade (Allen and Richardson, 1968; Allen, 1969; Allen, 1970). These efforts have generally used the Kubelka-Munk theory (or its variations) and involve the concept of effective optical constants of the leaf. Measurements taken on single plant leaves do not permit reliable predictions of groups of plants. Moreover, due to low density of many individual plants, especially near the emergence date, the underlying soil surface affects the measurements. Even when the vegetation cover is 100 percent, edge problems, introduced between rows in cultivated fields, distort the reflectivity measurements.

The reflectance, ρ, of an area can be expressed as

$$\rho = f_v\rho_v + (1 - f_v)\,\rho_s \qquad (1)$$

where f_v is the fractional area occupied by the vegetation with reflectivity ρ_v, and ρ_s is the soil reflectivity. (This assumes that shadows effects are negligible.) All of these quantities are, obviously, functions of time. Detection of any crop by remote measurement of reflectance is based, in general, on analysis of multitemporal data. In an approach such as Allen and Richardson's (1968), it would be necessary to measure the optical constant of leaves at different times. This is not very practical. Our approach, in this paper, is essentially empirical. The amplitude of reflected radiation is determined by a characteristic linear dimension of the scattering entity and, in general, increases with decreasing size (Kortüm, 1963). The spectral reflectance, in the infrared of a healthy plant in which the scattering entities are plant cells, is known to rise, peak, and fall as a function of time. Such a distribution can be well described by the function

$$\rho_v(\mathrm{t}) = At^{\alpha} \exp\,(-\beta t^{\gamma}) \qquad (2)$$

where t is the time and α, β, and γ are crop specific constants. (Deirmendjian (1964) had suggested a similar distribution for water drop size in clouds to explain the reflectivity from clouds.) Since the reflectivity at emergence (green-up) day $t = t_0$ must equal the soil reflectivity $\rho_s(t_0)$, the constant, A, can be replaced with the soil reflectivity, and Equation 2 can be rewritten as

$$\rho(t) = \rho_s(t_0)(t/t_0)^{\alpha} \exp\,[\beta t_0^{\gamma}\,\{\,1 - (t/t_0)^{\gamma}\}]$$

In light of Equation 1, however, this is an obvious simplification. Using Equations 1 and 2, we can write

$$\rho(t) = \mathrm{A}f_v\,(t)\,t^{\alpha}\,\mathrm{e}^{-\beta t\gamma} + (1 - f_v)\,\rho_s(t) \qquad (4)$$

where the form of $f_v(t)$ is not known. In the spring wheat regions of North Dakota and Minnesota, one finds that $f_v(t) \rightarrow 1$ very rapidly as the season progresses ($\leq$18 days). (In winter wheat region $f_v(t)$ is measured after spring green-up.) If one assumes that $f_v(t) = 1$ and (thus, restricts the analysis to days after emergence when vegetation cover is essentially 100 percent) no edge effects are present, then Equation 4 reduces to Equation 2. Equation 4 can be easily interpreted. Before the crop emerges, one sees the soil reflectivity, which is essentially constant, within the measurement errors, as a function of time except for a period of days following rainfall when soil reflectivity is modified by surface moisture conditions. As the plant grows, less soil is exposed and, hence, soil reflectivity becomes a less important component in the spectral reflectance than does the vegetative canopy. The highest reflectance in the infrared region is reached in mid season, at the time of maximum green biomass (jointing-heading) for wheat, and then begins to decrease and approaches, in principle, the soil reflectance value. Now, by our basic hypothesis, if the emergence, say, is delayed or advanced from t_0 to $t_0 + \tau$, Equation 2 becomes

$$\rho(t + \tau) = \mathrm{A}(t + \tau)^{\alpha}\,\mathrm{e}^{-\beta(t+\tau)^{\gamma}} \qquad t + \tau > 0 \qquad (5)$$

where τ is the relative shift in the emergence (green-up) date from t_0 and can be positive or negative.

It should be noted that crop development and, hence, the reflectivity is not independent of environmental conditions and, in particular, depends on soil moisture conditions and ambient temperature. The parameters α, ρ, and γ thus depend on the growing conditions and are not fixed for all time. In the particular application in LACIE, these parameters are to be determined for each segment. There is, however, experimental evidence to indicate that the functional form of

Equation 5 still gives an adequate description of the data.

In the next section, the field data (from helicopter-mounted and truck-mounted instruments) on the reflectivity in the 0.76-0.90 μm band from Williston, North Dakota and Garden City, Kansas for wheat is presented and show that the hypothesis of a relative shift is a reasonable one. It is then applied to Landsat data for LACIE segments in North Dakota and Minnesota.

DATA ANALYSIS

Figure 1 shows a plot of the wheat bidirectional reflectivity factor in the 0.76-0.90 μm range as a function of time (calendar days) from the tillering to the harvest stage when the ground cover was nearly 100 percent. The data, taken from the work of Bauer *et al.* (1977), are for the Williston, North Dakota site. These data were taken from a truck-mounted spectrometer on clear days. If we fit, using the least-squares method, Equation 5 to the 1976 data, we find that

$$\rho(t) = 63.18\,(t + \tau)^{\alpha}\, e^{-\beta(t+\tau)^2} \qquad (6)$$

where $\alpha = 0.467 \pm 0.005$, $\beta = 1.524 \pm 0.010$ and $|\tau| = 1.429 \pm 0.002$. Here, we expressed the calendar time, t, in units of 100 days, i.e., day 150 is expressed as 1.5. The fitted profile is shown by the curve (A). There are ten data points and four free parameters. The residual, χ^2/degrees of freedom (6) is 0.213, which is an extremely good fit.

If one assumes that Equation 6 applies to the same site in 1974 and 1975 with the only free parameter being, τ, the relative shift in the emergence day, we find that for the 1974 data set $|\tau| = 1.406 \pm 0.003$, indicating a shift

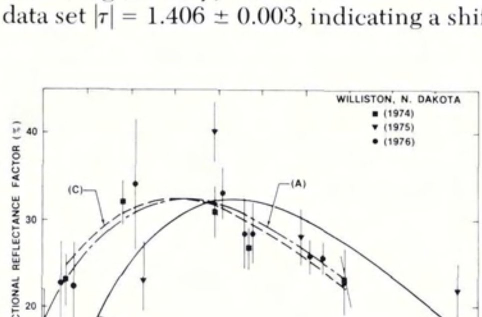


FIG. 1. A plot of the bidirectional reflectance factor of spring wheat for the wavelength interval range of 0.76 to 0.90 μm as a function of calendar days at Williston, North Dakota for 1974, 1975, and 1976. The lines A, B, and C are best fit curves to these data points.

of (2.3 ± 0.4) days. A similar analysis of 1975 (a fairly wet year) shows $|\tau| = 1.549 \pm 0.002$ and a consequent shift from 1976 of (12.0 ± 0.25) days. Table 1 summarizes the results of the fit for this site. In column 7, we have also noted the relative shift as noted by a ground observer for these years. We find a good agreement between the ground observations and our calculations. We have also found that a value of $\gamma = 2.04$ would lead to a slightly better fit. However, a value of $\gamma = 2$ is more convenient to use and the LACIE segments do not have enough data to determine five free parameters reliably.

Figure 2 shows field measurements of bidirectional reflectance factor as a function of time for the Garden City, Kansas site for the three years 1974, 1975, and 1976. The data are plotted after the spring green-up only. First, one wants to know if the same Equation 6 developed for North Dakota can be applied to winter wheat region of Garden City, Kansas. To test this we fitted the Kansas data to the form

$$\rho(t) = \eta\{63.18(t + \tau)^{0.467} \exp[-1.524\,(t + \tau)^2]\} + \xi$$

where η and ξ are multiplicative and additive real constants, respectively.

One finds that $\eta = (1.058 \pm 0.001)$, $\xi = (7.57 \pm 0.025)$ and $\tau = (0.886 \pm 0.003)$ with residual χ^2/degrees of freedom (12) of 0.827, which is again a very good fit.

The results of fits for 1974 and 1975 are shown by curve C and curve B, respectively, in Figure 2. Table 1 also summarizes these results. One again finds that in 1975 the crop emerged (13.9 ± 0.5) days later than the 1976 crop, consistent with the ground observations.

Therefore, at least for Williston, North Dakota and Garden City, Kansas, the spectral profiles are the same, except for a possible normalization difference. Next, the effect of variety and nitrogen fertilizer application to this spectral profile were examined. Figure 3a is the plot of bidirectional reflectance factor as a function of calendar days for four different cultivars of wheat in Kansas in 1976; Centurk, Satanta, Scout, and Eagle. The data are taken from crop spectra from the LACIE Field Measurements Project by Bauer *et al.* (1978) and refer to the mean bidirectional reflectance factors. Since the errors of these measurements are similar to those shown in Figure 2, it is apparent that these profiles are similar and essentially indistinguishable from curve (A) in Figure 2. Similar results are seen for the spring wheat cultivars of Waldron and Olaf in North

TABLE 1. A COMPARISON ON PREDICTED AND OBSERVED SHIFT

Year	Parameter A	Parameter α	Parameter β	$\lvert\tau\rvert$	Predicted Shift	Observed Shift	χ^2/degree of freedom
Williston, North Dakota							
1974	—	—	—	1.406 ± 0.003	2.3 ± 0.4	2	0.503
1975	—	—	—	1.549 ± 0.0014	12.0 ± 0.25	14	2.115
1976	63.18 ± 0.56	0.467 ± 0.0042	1.524 ± 0.009	1.429 ± 0.002	—	—	0.213
Garden City, Kansas							
1974	—	—	—	0.858 ± 0.006	2.8 ± 0.5	3	0.721
1975	—	—	—	1.025 ± 0.002	13.9 ± 1.0	14	1.994
1976	66.84	0.467	1.524	0.886 ± 0.003	—	—	0.828

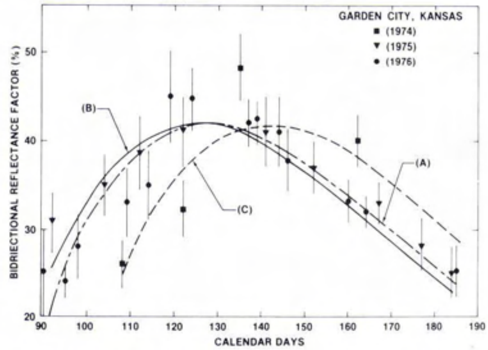


FIG. 2. A plot of the bidirectional reflectance factor of winter wheat beginning at spring green-up for the wavelength interval of 0.76 to 0.9 μm as a function of calendar days at Garden City, Kansas for 1974, 1975, and 1976. The lines *A*, *B*, and *C* are best fit curves to these data points.

Dakota. In Figure 3b, the bidirectional reflectance factor for spring wheat in North Dakota is plotted with and without nitrogen fertilizer application. It is again clear that the two curves in this wavelength band are similar.

It is thus shown that (a) Equation 6 describes the reflectivity as a function of time very well; (b) the wavelength band 0.76-0.9 μm is relatively insensitive to the cultivar of wheat and the application of nitrogen fertilizer; and (c) it can be used to deduce the emergence date of wheat and thus produce an approximate crop calendar. Environmental conditions such as lack of soil mois-

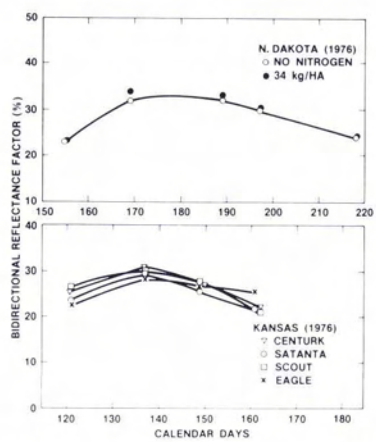


FIG. 3. A plot of the bidirectional reflectance factor in the wavelength interval of 0.76 to 0.9 μm as a function of calendar days. The lower graph is for Kansas in 1976 for four different cultivars of winter wheat and the upper graph is for North Dakota in 1976 for the effect of application of nitrogen fertilizer on spring wheat.

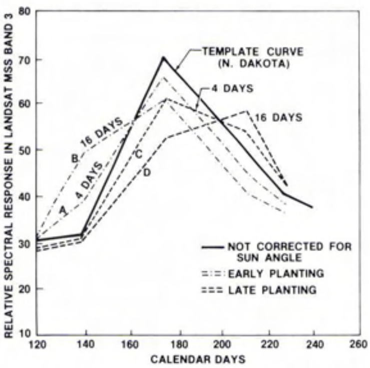


FIG. 4. A plot of the spectral response in Landsat band 3 (wavelength interval of 0.7 to 0.8 μm) as a function of date. Curves A and B are for wheat planted 4 and 16 days earlier relative to the template curve E and curves C and D are for wheat planted 4 and 16 days later relative to E.

ture and high temperatures, which are known to speed up the rate of crop development, have not been examined with the data sets available. In the next section, we apply

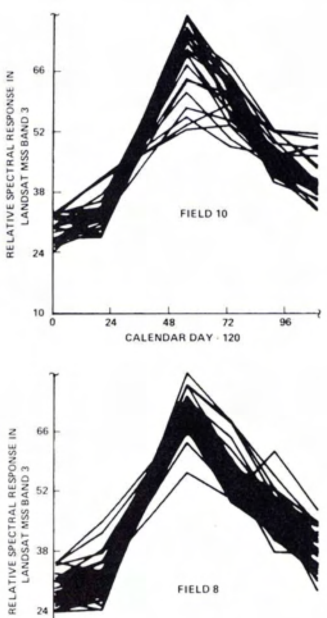


FIG. 5. Plots of the observed spectral response of two spring wheat fields in the crop year 1976-1977 in North Dakota as a function of date. Each curve is for one pixel in the field. A ground observer noted that on calendar day 122 (plotted as day 2 on the graph) no wheat emergence had taken place.

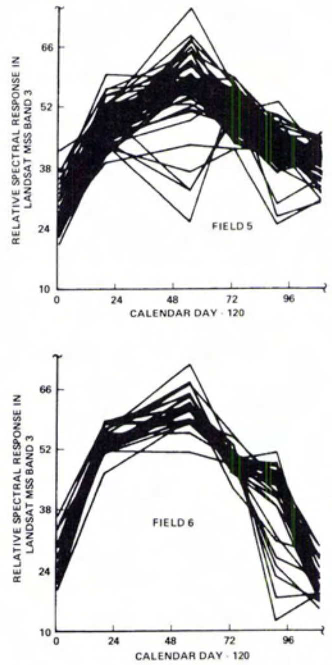


FIG. 6. Landsat spectral response as a function of date for field 5 which showed emergence on day 121 (plotted as day 1) and field 6 which showed still earlier emergence than field 5.

these results to the Landsat data from LACIE segments in North Dakota and Minnesota.

ANALYSIS OF LANDSAT DATA

If curve (A) in Figure 1 is treated as a continuous curve but sampled at 18-day intervals, as is the case with the Landsat data, we would expect a curve such as in Figure 4 (curve E), where the various sampled points are connected by straight lines. If the crop was planted earlier (or later) relative to the curve (A) in Figure 1 but again sampled at an 18-day interval, we expect to see curves (A), (B), (C), and (D), which are for 4 days earlier, 16 days earlier, 4 days later, and 16 days later, respectively.

In the crop year 1976-77, for each LACIE "blind" site there are 15 special fields which are known to be wheat. For these special fields information on the plant height, percentage ground cover, row spacing, and any unusual aspects (such as weeds, drought, etc.) were noted each 18 days coincident with the Landsat overpass. These fields, then, provide a way of determining the form of the function $\rho(t)$ in the segment. Figure 5(a) is a plot of the radiance values in Ch3 ($\lambda = 0.7 - 0.8$ μm) (uncorrected for sun zenith angle) versus time on field 10 in segment

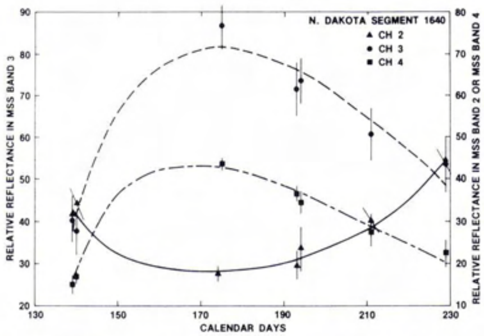


FIG. 7. The mean spectral response of field 10 (and/or 8) as a function of date in Landsat Ch 2, Ch 3, and Ch 4 and the results of the fitting Equation 5 to the data. Note the change of scale.

TABLE 3. PREDICTED EMERGENCE DATE FOR FIFTEEN FIELDS IN SEGMENT 1640 (NORTH DAKOTA)

Field No.	Emergence Date
1	131.9 ± 1.47
2	129.6 ± 1.66
3	136.7 ± 0.14
5	129.6 ± 0.50
6	127.4 ± 0.53
7	136.5 ± 0.20
8	137.3 ± 0.10
9	138.0 ± 0.30
10	137.3 ± 0.28
11	137.6 ± 0.18
12	137.3 ± 0.50
14	137.8 ± 0.17
15	135.8 ± 0.30

1640, (Barnes, North Dakota) where the first acquisition day 121 data are plotted as day 1. This particular field showed no sign of emergence (as noted by an observer in the field) on the first acquisition day. In this segment there were ten other fields which were also identified by the field observer not to have emerged on the first acquisition day. All of these showed the same profile. Another example of this situation is shown in Figure 5(b) which is for field 8. The remaining five fields had heights of 1 inch and 3 inches on day 121 and, from the discussion above, one would expect to see a shape similar to curve (*B*) and curve (*A*), respectively, in Figure 4. Figures 6(a) and 6(b) are plots of CH3 versus time for field 5 (1 inch plant heights) and for field 6 (3 inch plant height). The shape (Figure 6) of the curve is similar to patterns *A* and *B* in Figure 4. This again suggests that the shift hypothesis is a reasonable one.

The analysis carried out on the field measurement data cannot, however, be directly applied to these Landsat data, the reason being that the Landsat data needs to be corrected for sun angle and atmospheric effects. The correction for sun angle, θ, is simply given by corrected channel value = raw channel value/cos (θ). The correction, for atmospheric effects, however, is not straightforward. A number of methods have been suggested; however, since their reliability is not known, no correction is applied. This should not, however, seriously affect the analysis of a given LACIE segment if one chooses acquisitions which are free of haze and clouds. In Figure 7, we show a plot of mean radiance in Ch 2, Ch 3, and Ch 4 as a function of time for field 10. These values have been corrected for the sun angle. The results of fitting Equation 5 are shown by the solid curve in Figure 7 and the fitted constants are given in Table 2.

The $|\tau|$ from each of these fits was also found to be consistent with a single value of 1.37 ± 0.03. Using the constants developed for Ch3 from field 10, we have calculated the emergence date of all 15 fields in segment 1640, which are given in Table 3. These are quite consistent with ground observations.

An application of the constants determined from segment 1640 to the 15 fields in six other segments in North Dakota and Minnesota results in a very satisfactory agreement between the calculated and observed emergence days. This supports the conjecture about the shift in profile shape due to emergence (green-up) date and indicates that there exists a unique profile at least for a local region.

In Figure 8 the Kauth-greenness in segment 1663 of all wheat and barley pixels is

TABLE 2. FITTED CONSTANTS FOR FIELD 10 IN SEGMENT 1640, NORTH DAKOTA

	A	α	β	χ^2/degree of freedom
CH 2	7.43 ± 4.72	−0.67 ± 1.54	1.76 ± 0.30	0.598
CH 3	134.42 ± 0.10	0.342 ± 0.026	−1.15 ± 0.01	0.860
CH 4	122.98 ± 0.10	0.192 ± 0.037	−1.41 ± 0.034	0.629

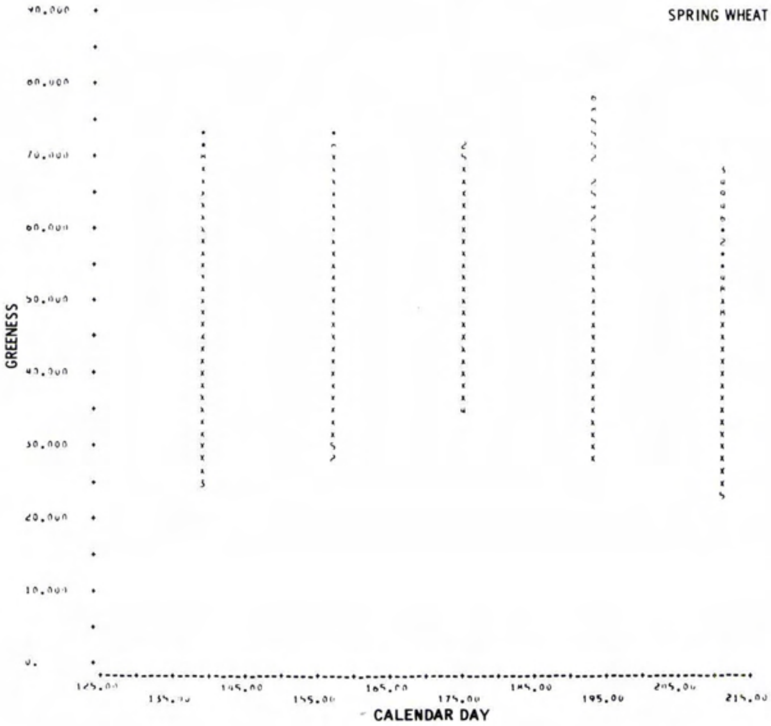
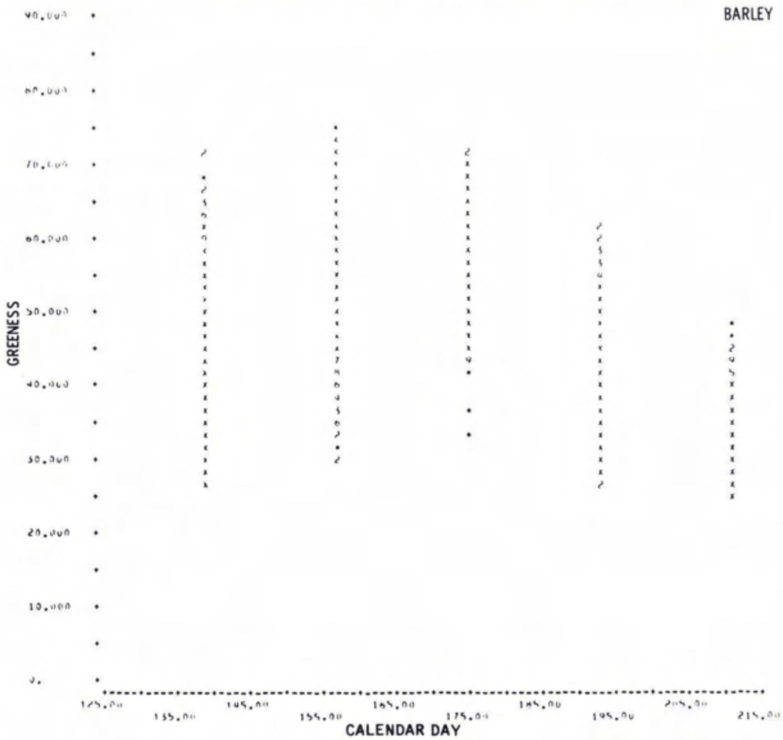


FIG. 8. A plot of greenness, defined as -0.238 Ch 1 $-$ 0.660 Ch 2 + 0.577 Ch 3 + 0.381 Ch 4, for wheat and barley in segment 1663. The graph marked *C* are the raw data and graph marked *D* are the data adjusted for the emergence date. * stands for one pixel and x for $\geq$10 pixels. Each graph contains approximately 5000 pixels.



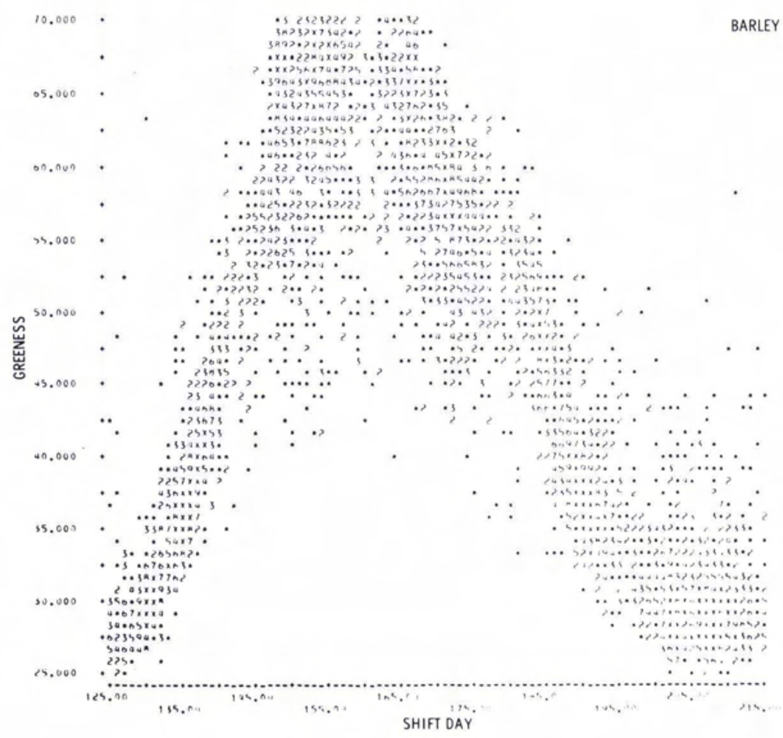


FIG. 8—*Continued*

plotted. The graphs marked A are uncorrected for the emergence day variation, whereas those marked B are corrected for this variation. The results clearly show that a large fraction of variation in greenness was indeed caused by the emergence day variation, and the corrected temporal profiles for wheat and barley are similar.

Conclusion

It has been shown that wheat and barley have unique temporal spectrum describable by a modified gamma function. This profile can be used to determine the emergence (spring green-up) day of a given crop. The present method should be applied in an approximately "normal" year. Segments with severe drought, etc., have yet to be studied. In future work, data should be corrected for atmospheric effects.

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