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Relation of Wheat Yield with Parameters Derived from a Spectral Growth Profile

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ABSTRACT

An attempt has been made to generate crop growth profiles using multi-date NOAA AVHRR data of wheat-growing season of 1987-88 for the districts of Punjab and Haryana states of India. A profile model proposed by Badhwar was fitted to the multi-date Normalised Difference Vegetation Index (NDVI) values obtained from geographically referenced samples in each district. A novel approach of deriving a set of physiologically meaningful profile parameters has been outlined and the relation of these parameters with district wheat yields has been studied in order to examine the potential of growth profiles for crop-yield modelling. The parameter 'area under the profile' is found to be the best estimator of yield. However, with such a parameter time available for prediction gets reduced. Combination of different profile parameters shows improvement in correlation but lacks the consistency for individual state data.

Introduction

Profile of spectral development of a crop, as monitored through a vegetation index derived from remotely-sensed data, offers unique advantages in crop identification and growth stage estimation. Its implication for crop-yield modelling have, however, not been fully explored. Observations from ground-based experiments under controlled conditions indicate that spectral index of the crop canopy at any given point of time is a measure of the total green biomass. This simplistic description, when extended to the entire temporal domain of the crop growth, reveals the growth and decay of the canopy as affected by various factors. Some of these insights can be gained in terms of holistic profile parameters having direct analogy to physiologically significant processes. For example, maximum leaf-area index (LAI) during peak vegetative growth is analogous to peak value of the crop growth profile curve. Rate of senescence can be thought of as average slope of the profile in post-heading time domain. Having formed a set of such analogous parameters derived from the crop profile, it is obvious that direct utility of the profile for crop-yield modelling can be explored. Holistic nature of this approach makes it conceptually more sound than that involving single-date spectral indices which rely solely on acquisitions within a narrow critical period of maximum vegetative growth phase. Also the single-date indices cannot account for the yield variabilities in the crucial post-heading phase. Of course, the holistic approach demands more data and leaves less duration for prognosis.

Mathematical modelling of temporal-spectral profile of crop has been proposed by Badhwar (1980) and its utility for crop discrimination and growth-stage estimation have been demonstrated by Badhwar (1982, 1984) and Henderson and Badhwar (1984). Idso *et al.* (1980) derived rate of senescence from the post-heading spectral data and reported good correlations with grain yield. Integrated radiance ratio for a certain growth period which takes into account the effect of leaf area duration has been used along with accumulated mean daily temperature for deriving a multilinear relation for rice yield (Patel *et al.*,1985, Ravi *et al.*, 1988). Gupta and Dubey (1987) used rate of senesence alongwith maximum vegetation index and time-integrated vegetation index as independent parameters in a linear multiple regression relation with yield and found that the relation gave reasonably close estimates of yield on independent data set for diverse varieties of wheat crop. A technique for fitting NIR/Red ratio vs. days-after-sowing for ground experiments data was developed by Dubey (1987) and growth stage estimation was attempted by Sharma and Navalgund (1988).

The studies on large area crop-growth profiles are few and far between, and the direct utility of growth profiles for yield estimation remains totally unexplored. The studies cited above are based on specific time domains of crop growth instead of exploiting the analytical presentation of growth profile.

A study was conducted to explore the feasibility of developing crop-growth profiles for large areas using NOAA AVHRR data and to evaluate their potential for yield estimation for wheat crop in a largely wheat-dominated region, like Punjab and Haryana states of India. Specifically the study aimed at:

a) Modelling crop-growth profiles using Normalised Difference Vegetation Index (NDVI) values computed on sample segment basis, from geometrically corrected NOAA images for various districts of the study area, using the analytical form proposed by Badhwar.

b) Assessing the potential of crop-growth profiles for yield estimation using a novel concept of deriving a set of profile parameters bearing close analogy to important plant processes.

Profile Model and Derived Parameters

Time sequence of a typical spectral index (NIR/Red, NDVI, greenness) for the entire growth cycle of a crop suggests a continuous curve showing distinct rise and fall, much like a bell-shaped curve. Badhwar (1980) suggested an analytical function to describe this temporal behavior of spectral index. This function represents the growth profile of a crop as it describes the rise and decay of canopy green biomass through appropriate coefficients α and β, and has the following form :

$$G(t) = G_0 (t/t_0)^{\alpha} \quad \exp\beta \; (t_0^2 - t^2) \qquad (t > t_0) \qquad (1)$$

$$G(t) = G_0 \qquad (t \leq t_0)$$

where G_0 refers to spectral index for soil background, t_0 is the date of spectral emergence and G(t) is the spectral index at time t expressed in days after sowing or Julian date.

The above profile model has four free parameters namely G_0, t_0, α and β. While first two parameters represent only soil background and sowing conditions, the parameters α and β bear a physical interpretation in terms of development and maturity of the canopy and hence should have relevance to yield formation.

Is it possible to derive additional 'relevant parameters' from the growth profile model? A review of physiological processes suggests that grain yield formation, broken in terms of various yield components, is a process occurring over a major portion of the crop-growth cycle, extending from pre-anthesis period to maturity (Evans, 1980). Many of the well-established canopy-related determinants of yield like leaf-area duration, maximum leaf-area index and rate of senescence reflect this basic nature. These determinants obviously restate the importance of photosynthesis for yield formation. In the present study a set of profile-derived parameters having close physiological analogy with basic yield determinants is proposed. The proposed parameters and their analogues are as follows:

i) Peak value of profile (G_m) at the time of peak occurrence (t_m), analogous to maximum leaf area index

ii) Area under the curve (AREASUM). analogous to total photosynthesis for the entire duration of canopy

iii) Full width at half maximum of the profile (FWHM), analogous to the photosynthetic duration and to some extent related to AREASUM and the rise and fall time of the profile

iv) Average slope in post-heading period (SLOPE), analogous to rate of senescence

Graphical representation and formulae for derivation of these parameters are given in Fig.1.

The free parameters as well as derived parameters reduce the multidimensionality of the temporal data while capturing the essence of crop growth and development. Since many of the climatic variables and agronomic practices manifest themselves in canopy development, these parameters have potential to account for the cultural and environmental inputs. Also being closely related to

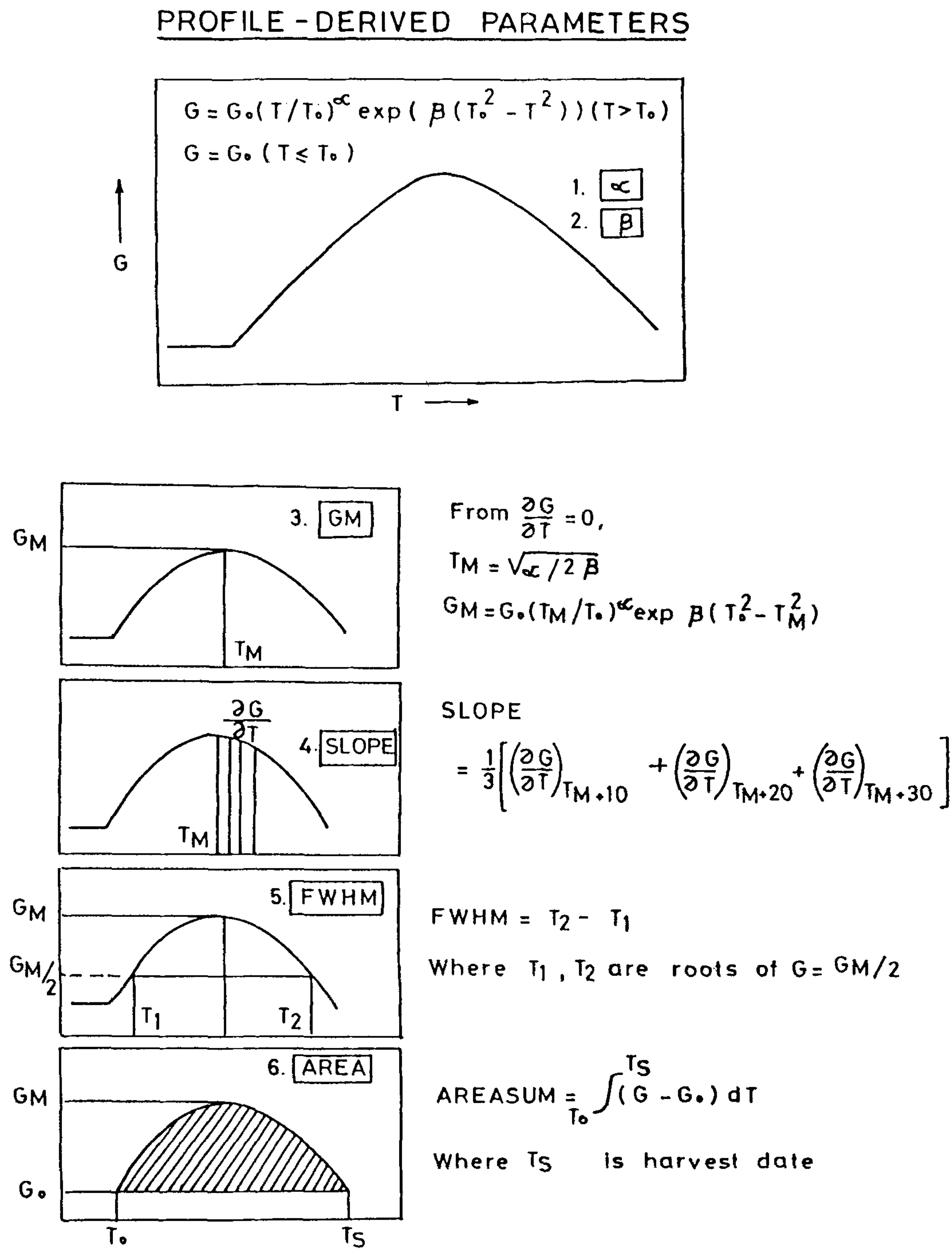

Fig. 1. Graphical presentation of profile derived parameters

crop growth variables, the relations based on these variables are likely to be stable over larger geographical area (Badhwar, 1982).

Selection of Study Area and Data

The study area comprising of Punjab and Haryana states (latitude 27°-32°30' N, Longitude 73°50'-78° E) represents major wheat-growing region of the country with wheat accounting for the single largest crop in the region. These areas, having single dominant crop as wheat, have virtually served as test bed for various studies on acreage and yield estimation using remotely sensed data (Sahai and Dadhwal, 1990). Wheat crop accounts for 64.5 percent of geographical area and 78 percent of net sown area during Rabi season (November - April) in Punjab (Mahey *et al.*, 1990), the corresponding figures being 40 and 66 percent respectively for Haryana (Dadhwal *et al.*, 1991). Gram, mustard, sugarcane and barley are the other crops in these states. Favourable conditions of climate, soil and physiography alongwith assured means of irrigation have endowed this region with high wheat yields. The state of Punjab records the highest wheat yield in the country. Southern districts of these states lie in close vicinity of Thar desert and thus have considerably low yields. The study area thus offers a wide range of yield values, encompassing a range of nearly 20 - 45 quintals per hectare. Wheat crop is sown during a period starting from last week of October to whole of November in Punjab and in the month of November with Nov 21 as median date of sowing in Haryana (Dadhwal *et al.*, 1991). Heading/flowering stage of the crop occurs around end of February and the harvesting is done during the second half of April.

Multi-date NOAA-9 AVHRR Visible and Near Infrared channel data acquired during 1531-1557 hours IST (Indian Standard Time) for Punjab and Haryana states was used in the present study. The reason for selecting NOAA data was the high frequency of data availability, reduced data load for digital processing and the previous experience (Potdar and Sharma, 1988) indicating relationship of yield with NOAA-NDVI. Relatively large synthetic field sizes in these states permit the use of coarser spatial resolution data like NOAA-AVHRR, instead of requiring medium resolution data like Landsat or IRS (Indian Remote Sensing Satellite). The browse data products of all the available dates during wheat-growing season (Nov 87 - April 88) were screened for cloudiness. Due to its wide swath, NOAA data shows large panoramic distortions and view angle effects at the edges. Hence all efforts were made to select the dates with area of interest lying in the scene centre, i.e. within ±30° scan angle. However, this was not possible for 3 dates due to non-availability of data. The dates of NOAA acquisitions selected in this study are listed in Table 1.

Methodology

Multi-date Normalized Difference Vegetation Index (NDVI) for each district was obtained from one random sample of size 10 x 10 pixels in each district while maintaining the geographical

Table 1. Acquisition Dates of NOAA AVHRR Data

S.No.	MONTH	DATE	YEAR
1.	November	28	1987
2.	December	16	1987
3.	-do-	19	1987
4.	January	19	1988
5.	-do-	31	1988
6.	February	08	1988
7.	-do-	23	1988
8.	March	21	1988
9.	April	29	1988

reference of the samples on all the multi-date NOAA scenes combined with a common referencing scheme. Profile parameters for each district were computed from the NDVI profile and these were related to district yields. Flow-chart of methodology is given in Fig. 2 and the details of major steps are described in the following sections.

Geometric Correction of NOAA Images

Raw NOAA tapes were reformatted and bulk correction was carried out on the visible/near infrared channels on VIPS 32 Image Processing System using the relevant programs in software library. Bulk correction removes the systematic geometric distortions like panoramic distortion, earth curvature and earth rotation effects. A nearest-neighbor resampling option with 1-km pixel height was used for all the dates.

Since high registration accuracies of the order of 1-2 pixels were aimed at for coincident location of samples on multi-date images, the geometric corrections implemented through bulk-correction software were not adequate. Hence accurate geometric rectification using 1 : 1 million-scale Survey-of-India map was carried on each of the subscenes covering area of interest. This involved selection of ground control points (GCPs), generation of map-to-image transformation model and image rectification using inverse model.

Due to coarse resolution, selection of GCPs is relatively difficult on NOAA images. To facilitate easy location of GCPs, a colour composite using first two bands (visible/NIR) and corresponding NDVI image was generated. Using this colour composite as well as original display of individual images, about 15 GCPs were located in Punjab/Haryana and adjoining areas. The model computed from these GCPs was used to display the relative error directly on the video terminal as a line drawn between actual GCP and its computed position. Based on this visual display, the GCPs showing large errors were screened out.

A map-to-image coordinate transformation model was computed using the final screened set of GCPs (8-10 numbers). Inverse of this model was used for rectification of the image. The options for image rectification were 128 x 128 pixel grid and nearest neighbour sampling. The procedure, based on the relevant softwares available in VIPS 32 library, was repeated for all the ten subscenes covering nine dates of data acquisition.

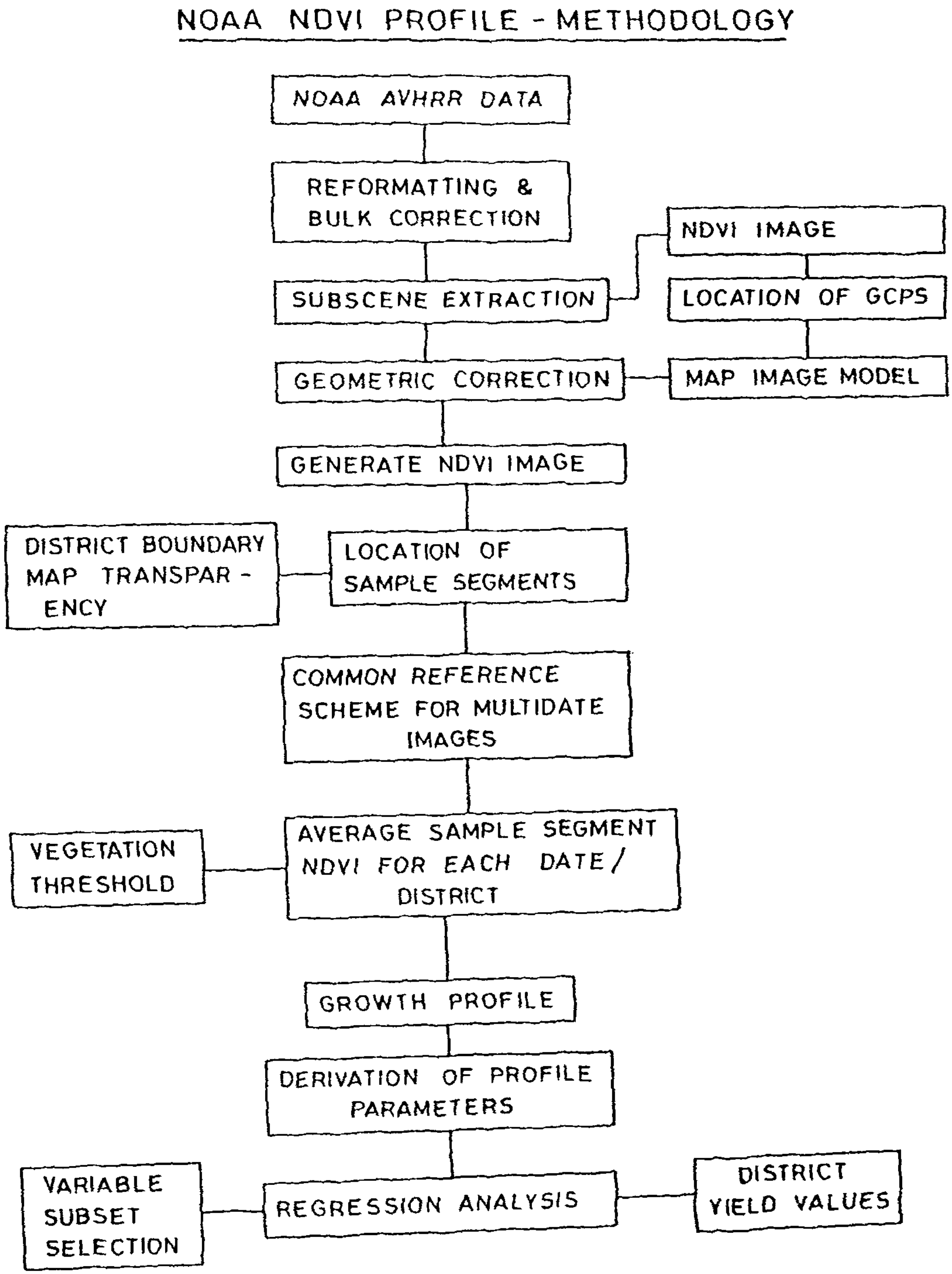

Fig. 2. Methodology flowchart

Location of Sample Segments

Using the corrected two-band NOAA subscene of study area, NDVI image was generated using the following transformation:

$$NDVI = \frac{(R2 - R1) \times 127.5}{(R2 + R1)} + 127.5$$

where R1 and R2 refer to channel counts in visible (0.58 - 0.68 μm) and near infrared (0.725 - 1.1 μm) bands of AVHRR. This essentially scales NDVI values linearly over 0 - 255 range from the original range of -1 to +1. The computations are implemented using the ratioing software in one step, using the following simplification of the above scaling:

$$\text{scaled NDVI} = \frac{127.5 \times R2}{R1 + R2}$$

A colour composite image using two-band image file and NDVI image was generated. A transparency showing district boundary map of Punjab/Haryana was prepared using a base map and Optical Reflecting Projector at a scale matching closely to the displayed image. This transparency was physically overlaid on one of the displayed subscene (8/2/88) and one random sample of size 10 x 10 pixel was located in each district. Top left hand corners of these sample segments were noted alongwith a few reference points in the image. For the remaining nine images, the location of sample segments in terms of scanlines/ pixels was computed by a uniform referencing scheme with respect to location of a common reference point in each image.

Computation of Average NDVI

Average NDVI for each of the sample segments was derived directly as average digital count of NDVI image file using appropriate thresholds for vegetation. No attempt was made to derive thresholds for wheat crop, because due to multiple dates, thresholds would not have been uniform. Hence the average NDVI values were computed from the vegetation pixels obtained by thresholding technique. Lower threshold was set as boundary of vegetation/non-vegetation pixel values and upper threshold was derived arbitrarily for maximum vegetation period (Feb. data). Since wheat is the major crop of the region, the vegetation profile derived using this approach will largely represent the wheat crop. Barnett and Thompson (1983) have shown that the assumption is valid in regions having more than 60% area under a specific crop.

Profile Model and Relation of Parameters with Yield

Average NDVI for each of the nine dates was compiled against days-since-Nov. 15 (average normal date of sowing in Punjab) for all the 24 districts. Profile model given in equation (1) was fitted using partial differential correction procedure. As discussed earlier, a set of parameters was derived from the profile based on analogous agronomic variables. Apart from α and β which are obtained during model fitting, other parameters were computed from the profile equation using the appropriate formulae outlined in Fig. 1.

The district wheat yields for 1987-88 were obtained for Punjab and Haryana from the respective State Directorates of Agriculture. Linear regression analysis of the above parameters with yield was performed separately for each state and on the combined data set. To select the best subset of variables for regression with yield; all the six parameters were subjected to selection procedure using leaps-and-bounds technique followed by detailed multiple regression analysis.

Results and Discussion

Accuracy of geometric correction of NOAA images was evaluated from transformation model. Multi-date NOAA-NDVI values were fitted to growth profile function and the proposed parameters were derived. Since the main aim of the study was to explore the potential of the approach using single-year data, rigorous statistical analysis considering multicolinearity and significance of regression coefficients was not carried out.

Geometric Correction of NOAA AVHRR Data

The details of geometric correction using GCPs is given in Table 2. It is evident that accuracy of the model-predicted values is about ±3 pixels with maximum RMS error ranging from 0.8 pixels for Dec. 16 data to 8.2 pixels for April 29 data. The low contrast in April 29 scene was the reason for the large error as GCPs could not be located accurately. The average error of ±3 pixels was marginally acceptable in this case because of significant contiguity of featrues in the study area.

Growth Profile

Initial values of α and β were computed from a typical scatter plot.

Table 2. Results of Geometric Correction

S.No.	Scene	No. of GCPs	Est. Res. Error (pixels) MAX.	MIN.
1.	28.11.87	8	3.877	0.128
2.	16.12.87	9	0.805	0.031
3.	23.12.87	10	2.958	0.359
4.	19.01.88	10	1.876	0.337
5.	31.01.88	8	2.172	0.042
6.	31.01.88	8	1.986	0.198
7.	08.02.88	9	2.436	0.343
8.	21.03.88	10	2.593	0.215
9.	23.02.88	8	2.893	0.315
10.	29.04.88	8	8.235	0.132

Parameter G_0 was assigned an arbitrary but constant value so as to give, in general, a reasonable estimate of t_0. Assumption of constant G_0 has also been advocated by Badhwar (1982). Growth equation proposed by Badhwar was fitted to all the data sets. The values of α, β, t_0 and G_0 alongwith number of data points used for fitting the function are listed in Table 3. Out of 12 districts in each state, the model could be fitted to only 10 districts. For the remaining two in each state, number of data points was less than 5 and hence fitting procedure did not

Table 3. Coefficients of Growth Profile

a) Punjab

S.No.	District	α	β (x 10^{-4})	T_0	N
1.	Amritsar	1.362	09.28	11.35	8
2.	Kapurthala	1.204	04.86	10.34	8
3.	Jalandhar	1.721	10.64	15.60	9
4.	Ludhiana	1.853	11.57	15.74	9
5.	Ropar	0.740	05.55	05.65	9
6.	Patiala	2.103	13.98	18.00	9
7.	Sangrur	2.289	14.61	20.48	9
8.	Firozpur	1.593	11.27	12.35	9
9.	Faridkot	2.104	12.00	19.49	9
10.	Bhatinda	6.920	30.01	53.40	9

b) Haryana

S.No.	District	α	β (x 10^{-4})	T_0	N
1.	Karnal	2.832	24.25	22.6	9
2.	Sonipat	3.506	20.17	31.2	8
3.	Faridabad	18.35	103.17	63.5	5
4.	Jind	2.454	16.03	24.8	8
5.	Kurukshetra	2.394	13.73	23.1	9
6.	Ambala	0.965	5.54	10.2	9
7.	Hisar	2.031	14.07	23.4	8
8.	Bhiwani	3.131	20.69	27.7	7
9.	Rohtak	3.492	22.71	32.4	8
10.	Sirsa	3.642	23.20	35.6	9

To refer to Bhadwar Model, with G_0 = 0.03

converge to a solution after preset number of iterations. The typical plots of NDVI vs. Days since Nov. 15 are given for Karnal (Haryana) and Ludhiana (Punjab) districts in Fig. 3, respectively. The scatter plots show large scatter of NDVI value in post-heading period as compared to general trend of the values. This can be traced back to drastic change in the radiance values due to geometric

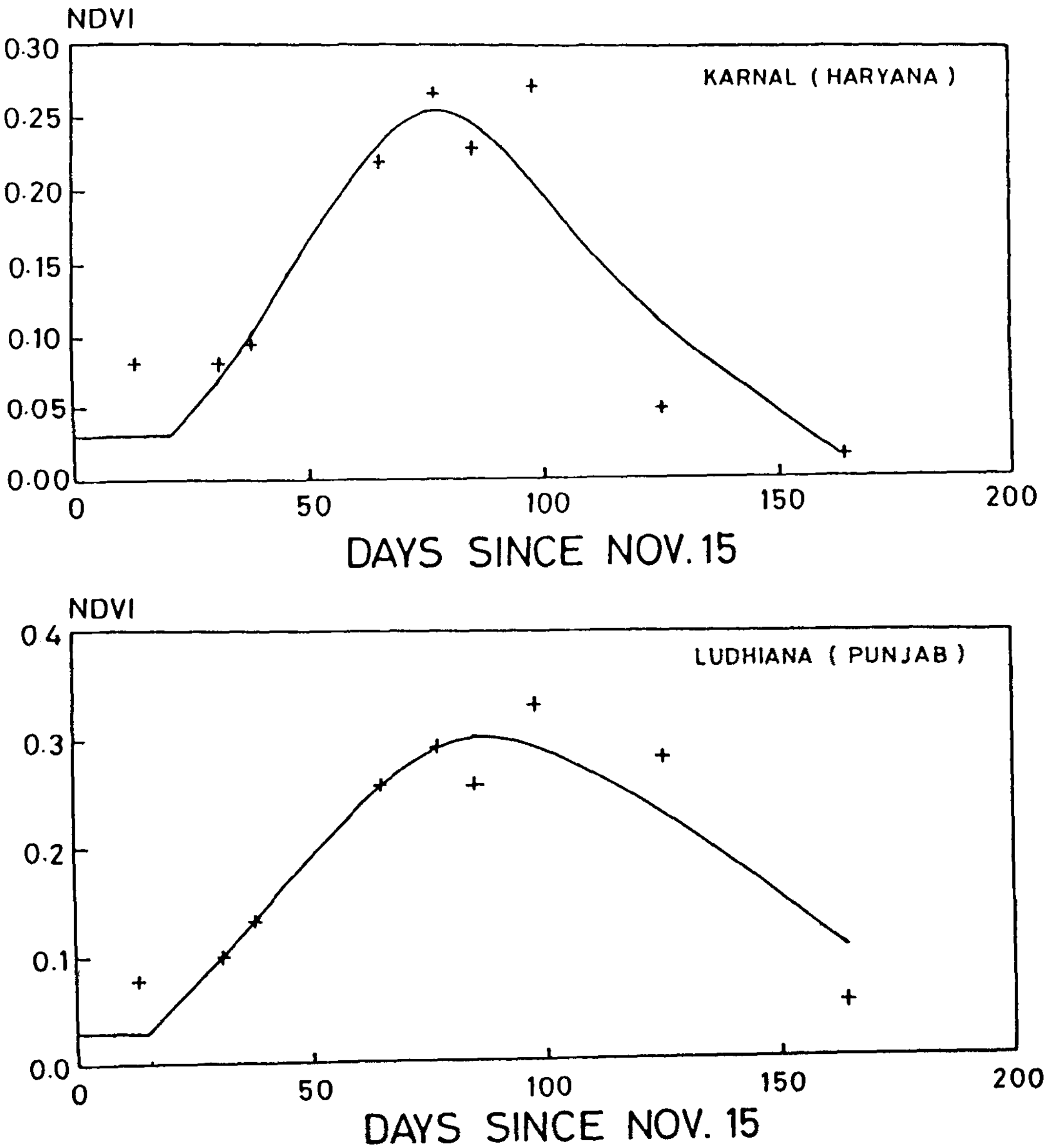

Fig. 3. Crop growth profiles

distortion and effect of atmospheric path radiance for a study area lying on extreme side of the original scene combined with the effect of atmospheric path radiance. The model coefficients for districts of Haryana, are in general higher than those for Punjab. Also α and T_0 show a similar trend. Larger than normally expected values of T_0 for Haryana are due to Nov. 15 as assumed date of sowing. Anomalous values of α and β are observed for Ropar (Punjab), Ambala (Haryana), Bhatinda (Punjab) and Faridabad (Haryana). Permanent forest vegetation on hilly terrain may be the reason for low values in the former two districts and sparse vegetation in semi-arid tract may account for higher values in the last two districts.

Profile Parameters and their Relation with Yield

Different parameters were derived from profile using the formulae given in Fig. 1. These parameters viz peak value of profile (G_m), time of peak value (t_m), average slope of profile in post-heading period (SLOPE), full width at half maximum (FWHM) and total area under the curve (AREASUM) are given in Table 4. In general, profile parameters G_m and AREASUM are higher for Punjab as compared to Haryana. Anomalous model coefficients in four districts mentioned previously affect slope and FWHM but have no significant influence on G_m and AREASUM.

Alongwith α and β the relation of these parameters with yield was studied using linear regression technique. The correlation matrix for these parameters is given for combined data set in Table 5. It is evident from the correlation matrix that, amongst themselves, parameters α and β are highly correlated followed by FWHM and slope. The correlation of these parameters with yield is consistent in terms of sign only and for α, slope, AREASUM and G_m.

It is apparent that the parameter AREASUM is the single best estimator of yield. This parameter accounts for nearly 69% of variability in yield. The regression relation of yield with AREASUM is as follows:

$$Y = 18.045 + 0.700 * AREASUM \quad (r = 0.82, F = 37.9)$$

The scatter plot and regression line for the above relation are shown in Fig. 4.

Poor correlation for other parameters and inconsistencies may, to some extent, be attributed to inadequate sample size for each district. However, many of these parameters are nearly independent and have opposite signs of correlation coefficients. That means a suitable subset of these parameters will be more appropriate for regression analysis. To find the best subsets for regression, the technique of leaps and bounds (Anon, 1984) was used with R^2 criterion. The best variable subsets were used for further multiple regression analysis. The regression coefficients obtained by multiple regression analysis on the best subsets are given in Table 6. It is revealing that profile parameters, individually as well as in combination, account for significant

Table 4. Profile Parameters

a) Punjab

DISTRICT	TM*	G_m	FWHM**	SLOPE (-)	AREASUM**
Amritsar	85.7	0.2413	119	0.204	22.65
Kapurthala	111.3	0.2887	41	0.250	28.66
Jalandhar	89.9	0.2655	112	0.105	24.47
Ludhiana	89.5	0.3054	107	0.100	28.19
Ropar	81.6	0.1497	149	0.736	14.75
Patiala	86.7	0.2992	97	0.072	26.16
Sangrur	88.5	0.2896	96	0.053	24.03
Ferozpur	84.1	0.2923	108	0.167	27.03
Faridkot	93.6	0.2975	106	0.063	27.09
Bhatinda	107.4	0.2785	68	0.002	16.68

b) Haryana

Karnal	76.4	0.2599	75	0.0342	17.30
Sonipat	93.2	0.2460	82	0.0162	20.60
Faridabad	94.3	0.2811	36	0.0001	9.24
Jind	87.5	0.2150	91	0.0354	15.81
Kurukshetra	93.4	0.2785	98	0.0420	21.96
Ambala	93.3	0.1577	150	0.2455	13.70
Hisar	84.9	0.1617	78	0.0446	11.50
Bhiwani	86.9	0.2641	81	0.0224	18.83
Rohtak	87.7	0.2156	77	0.0151	13.83
Sirsa	88.6	0.1809	77	0.0124	10.99

* T_s (date of harvest) = 160 days (Punjab), = 150 days (Haryana)
* Days after sowing, ** in days

Table 5. Correlation Matrix for Profile Parameters

	α	ß	G_m	FWHM	SLOPE	ASUM*	YIELD
α	1.00						
ß	0.99	1.00					
G_m	0.20	0.17	1.00				
FWHM	-0.60	-0.59	-0.36	1.00			
SLOPE	0.35	0.36	0.41	0.59	1.00		
ASUM	-0.47	-0.49	0.72	0.16	-0.04	1.00	
YIELD	-0.29	-0.30	0.66	0.08	-0.04	0.82	1.00

* ASUM = AREASUM

Table 6. Results of Multiple Regression Analysis

PARAMETER	R	Ao	A1	A2	A3	A4	F
ASUM	0.82	18.045	0.700				37.9
ß, ASUM	0.83	16.214	0.035	0.759			19.1
α, ß, ASUM	0.836	15.760	-0.733	0.169	0.770		12.3
α, ß, Slope, ASUM	0.838	15.083	-0.794	0.189	2.336	0.782	8.9

* ASUM = AREASUM
Coefficients A_i refer to

$$Y = Ao + A1 * X1 + A2 * X2 + A3 * X3 + A4 * X4$$

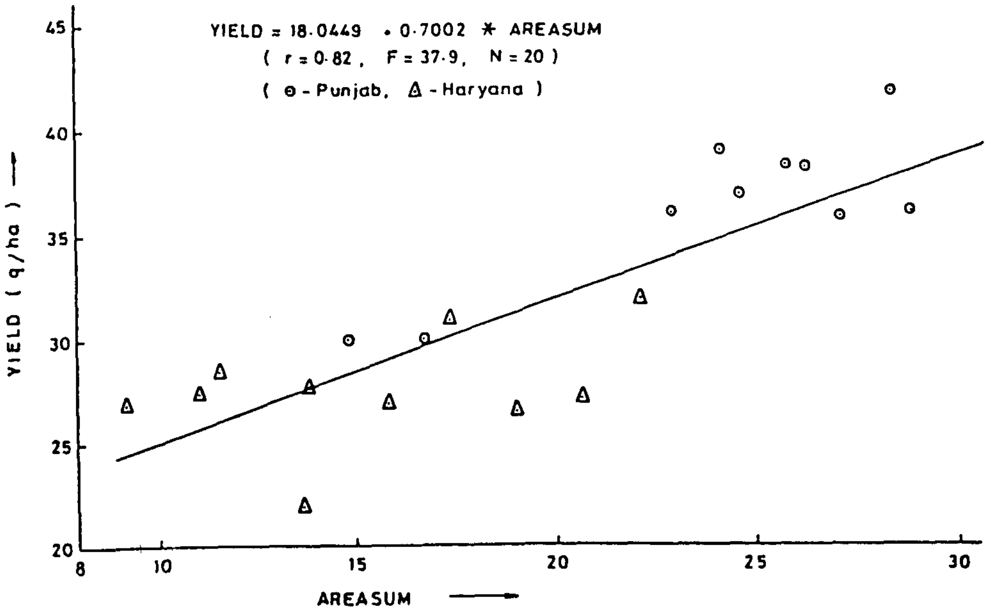

Fig. 4. Yield vs AREASUM for combined data set

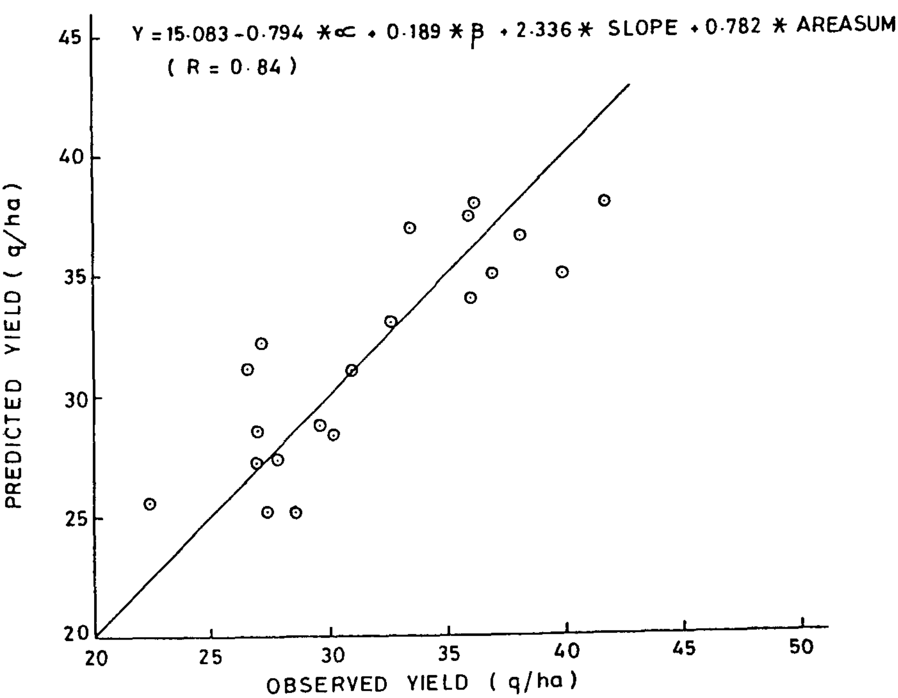

Fig. 5. Relation of yield with profile parameters - observed and predicted values for combined data set

amount of variability in yield. However the subsets of variables are not consistent for Haryana, Punjab and combined data set. The best subset of four variables for combined data set has the following linear relation with yield:

$$Y = 15.083 - 0.794 * \alpha + 0.189 * \beta + 2.336 * SLOPE + 0.782 * AREASUM \quad (R = 0.84)$$

Above relation shows only marginal improvement in correlation coefficient as compared to that based on AREASUM. This may be attributed to considerable multicolinearity amongst the profile parameters. Observed and predicted yield values for the above relation are shown in Fig. 5.

Conclusions

The study demonstrates the feasibility of deriving growth profiles for large areas using NOAA-AVHRR data. The approach of deriving a set of physiologically meaningful parameters from growth profile seems to offer a potential new technique for yield modelling. Results of the study are summarised below:

i) Using 8-10 GCPs it was possible to achieve a residual error of average 3 pixels (maximum) for the map-image transformation models.

ii) The model coefficients obtained by fitting Badhwar equation to data show anomalous values for some districts having hill forests or sparse vegetation.

iii) A set of six profile-derived parameters have been proposed and computed for each of the districts and related to yield. Apart from free parameters of the model, new parameters have been selected on the basis of their analogy to basic yield determinants.

iv) Relation of these profile parameters with district yields shows consistency only for slope and G_m. Individually the variable AREASUM i.e. 'area under the profile curve' shows high correlation with yield. This is a significant finding considering the large geographical distribution of districts.

v) A suitable subset of these variables was selected using leaps-and-bounds procedure using R^2 criterion. The combination of variables accounts for significant variability in yield.

The results presented in this study should be treated as only indicative in view of the drawbacks or unvalidated assumptions like inadequate sample size, off-nadir location of the study area, representation of specific crop (wheat) growth profile by a vegetation growth profile, inconsistencies of correlation coefficients and variable combinations.

While it is easy to rectify the problems related to data acquisition, further research is required to develop a suitable sampling design for obtaining a representative crop growth profile for a given administrative unit and to investigate the feasibility of incorporating crop discrimination algorithms for obtaining crop-specific growth profiles. Also, to arrive at a consistent subset of these parameters having stable relation with wheat yields, studies using data of different years are required.

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