Observing long-term changes in rice phenology using NOAA–AVHRR and DMSP–SSM/I satellite sensor measurements in Punjab, India

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The paper reports a unique observation from remote sensing records that the temporal rice growth pattern in terms of time of emergence and peak vegetation stage has been advanced by 3–4 weeks in Punjab, India from 1981 to 2000. Analysis was carried out using multi-temporal remote sensing data from the optical sensors such as Advanced High Resolution Radiometer (AVHRR) and the passive microwave sensors such as Special Sensor Microwave Imager (SSM/I) onboard NOAA and DMSP series of satellites respectively. The rice growth characteristics were quantified by Badhwar and Gaussian model fitting on seasonal Normalized Difference Vegetation Index (NDVI) covering the monsoon period (kharif season) for six years. The observed time of peak vegetation stage of rice estimated from the average growth profile of years 1981–82 was 4 September, which advanced to 8 August in years 1999–2000. This change in phenology was further confirmed using Basist Weiteness Index (BWI) data derived using multi frequency approach. The BWI data representing surface moisture/water fraction were found to reach maximum in the middle of July in 1988, compared to middle of June in 1998. Temporal trends in mean BWI of Punjab during May–June also indicate a shift in crop growth profile and gradual increase in area flooded with water for rice transplanting with time.

Keywords: Crop, phenology, remote sensing, microwave.

QUANTIFICATION of human-induced land use/cover changes and their impact on regional climate is an important area of global change research. It has been demonstrated that large-scale changes in crop irrigation and deforestation appreciably affect climate. Remote sensing-based studies have been used to highlight the effect of changing vegetation phenology, global net primary productivity, and global land use/cover on climate. Indian agriculture has undergone significant change for the past several decades. Pandya et al. have reported increase in vegetation activity over the years in India using NOAA–AVHRR-derived fraction of absorbed photosynthetically active radiation data. Amongst the major changes in Indian agriculture has been the introduction of irrigated rice in the semi-arid northwest Indian region. Punjab has witnessed significant change in cropping pattern during the last few decades. Increase in rice area is of particular significance. Rice–wheat rotation followed in Punjab leaves little time for land preparation for wheat after rice. This has resulted in a shift of the rice calendar. The cropping pattern shifts are generally described in terms of crop dominance only, while equally important changes in phenology are much less studied, as they are not captured in crop statistics information. Multi-temporal remote sensing data are well suited to study crop phenology. Satellite remote sensing in optical wavelengths is sensitive to changes in photosynthesis and biomass, while microwave remote sensing can detect surface soil–moisture conditions. In this study we have investigated the synergistic use of coarse resolution optical and microwave data in detection of (a) shift in rice crop phenology using six-year Normalized Difference Vegetation Index (NDVI) temporal profile from the period 1981 to 2000 and (b) changes in flooded-field condition associated with rice crop using seven year Basist Weiteness Index (BWI) data from the period spanning 1988 to 2000.

The State of Punjab, with a geographical area of 50,362 km², occupies a special place in Indian agriculture. It contributes around 70% of wheat and 50% of rice in the national pool of foodgrains. It lies between 29°33′–32°31′N lat. and 73°53′–76°55′E long. The climate is dominantly sub-tropical, semi-arid and monsoon-type. Most of the soils of Punjab, which are part of the Indo plains are derived from alluvium, and are deep. The soil texture varies from sandy to fine silty, with majority belonging to coarse loamy (62.3%) and fine loamy (19.5%). Punjab is a vast expanse of flat alluvial land, except Siwalik hills in the North; fluvial carvings and deposits of the three major rivers (Ravi, Beas and Sutlej) in the central Punjab and sand dunes in the southwest.

Crops show a characteristic temporal spectral behaviour due to growth and senescence. It has been observed in a number of investigations that the profile of spectral development of a crop, as monitored through a vegetation index derived from remotely sensed data, offers unique advantage in growth stage and yield estimation. The time of crop emergence and senescence is of particular importance because of their considerable influence on the spatial and inter-annual variability of terrestrial carbon cycles. Large-scale carbon cycling models requires a regional-scale phenology model to capture mean phenological changes related to average environmental conditions for each grid. NDVI data derived from NOAA–AVHRR sensor under Pathfinder project were used to model the rice growth profile over homogenous rice-dominated agricultural grid (0.5°×0.5°), covering parts of Punjab (75.5–76°E and 30.5–31°N). Ten-day maximum value composite NDVI data of kharif season (from first week of June to November) were analysed for six years, viz. 1981, 1982, 1992, 1997, 1998, 1999.
1996, 1997 and 1999 and 2000. NDVI data used in the analysis were provided by Goddard Space Flight Center, Distributed Active Archive Center, USA.

Originally, the concept of NDVI was developed to exploit the spectral properties of leaves of green plants, which absorb incoming radiation in red wavelength of the optical spectrum (AVHRR red channel: 0.62–0.70 μm) and strongly reflect light in the near-infrared wavelength (AVHRR NIR channel: 0.74–1.1 μm). NDVI is derived using the red reflectance ($r_r$) and near-infrared reflectance ($r_n$) as:

$$\text{NDVI} = \frac{(r_n - r_r)}{(r_n + r_r)} \text{ (when } r_n > 0 \text{ and/or } r_r > 0),$$

$$\text{NDVI} = 0 \text{ (when } r_n, r_r = 0).$$

The reflectance of vegetation in red ($r_r$) is governed by the chlorophyll absorption and the reflectance in near-infrared ($r_n$) is due to the phenomenon of total internal reflectance occurring within the leaf. There is decrease in $r_r$ and increase in $r_n$ and NDVI as the crop grows. NDVI has low values ranging from -0.2 to 0.1 for snow and bare soil, glaciers, rocks, and rises to around 0.2 to 0.8 for green vegetation. NDVI is an estimator of fraction of absorbed photosynthetically active radiation used by leaves in photosynthesis. NDVI is frequently used by various researchers in modelling biospheric processes and climate. Earlier studies using long term NDVI data have revealed large-scale inter-annual variations in global vegetation activity related to climate. NDVI anomalies in semi-arid tropics have been reported to correlate well with equatorial Pacific sea surface temperature anomalies associated with El Nino southern oscillation phenomenon.

NDVI datasets have also indicated a warming-driven greening trend consistent with the observation of increased amplitude of the seasonal cycle of atmospheric CO$_2$ data from the North.

Various NDVI datasets are available with different spatial and temporal resolutions with different temporal periods. The NOAA–AVHRR sensors cover long-term time series NDVI datasets from 1981 to the present. Other NDVI data are also available from Landsat-Thematic Mapper (1984 to 2003), EOS-MODIS (2000 to the present) and SPOT–VEGETATION data (1998 to the present). Pettorelli et al. have reviewed in detail different satellite-derived NDVI datasets and their environmental applications. The NOAA–Pathfinder AVHRR Land (PAL) NDVI data product at 8 km resolution is a well-calibrated dataset for long-term studies. The pathfinder NDVI dataset is corrected for Rayleigh scattering and ozone absorption using radiative transfer model by Gordon et al. Inter sensor calibrations have been accounted by fitting a time-dependent calibration algorithm for each channel to normalize the instrumental degradation of each satellite of the NOAA series flown from period 1981.

To analyse the crop growth parameters, viz. time of emergence and peak period, temporal modelling of the NDVI data was carried out by two approaches. In the first approach, a nonlinear growth function was fitted as described by Badhwar:

$$\text{NDVI} (t) = \text{NDVI}_0 (d(t_0)^a \exp(-\beta (t^2 - t_0^2)) \text{ for } t > t_0., \quad (2)$$

$$= \text{NDVI}_0 \text{ for } t \leq t_0,$$

where NDVI (t) represents the crop greenness at time t, NDVI$_0$ is the soil NDVI at the spectral emergence day (t$_0$), and a, β are crop-specific constants ($a > 0$ and $\beta > 0$). In the second approach, the temporal growth pattern was fitted using Gaussian function:

$$\text{NDVI} (t) = \text{NDVI}_m \exp\left(-\left(t - t_m\right)^2/2\sigma^2\right), \quad (3)$$

where NDVI$_m$ is NDVI at peak vegetative stage (t$_m$) and $\sigma$ represents the width of the profile. The above model fittings were carried out after the scaled NOAA-AVHRR NDVI (in Digital Number (DN)) were converted to crop NDVI as:

$$\text{NDVI} = (\text{NDVI}_0 - 128.0) \times 0.008. \quad (4)$$

Optical remote sensing data are not sensitive in detecting the low NDVI at the time of crop emergence, at the same time passive microwave radiometers show enhanced sensitivity in detection of surface water fraction available at the time of field preparation during rice transplanting. We have used SSM/I sensor data flown on-board a series of Defense Meteorological Satellite Program (DMSP) platform, to study changes in surface wetness conditions. SSM/I is a seven-channel passive microwave radiometer operating at four frequencies (19.35, 22.235, 37.0 and 85.5 GHz) and dual-polarization (except at 22.235 GHz which is V-polarization only). Multiple frequencies available on the SSM/I instrument have different responses to the liquid water on land, and this response across the microwave spectrum indicates the percentage of the ‘radiating surface’ that is water. Wang and Schmugge developed a model for computing the emissivity of wet surface based on the dielectric constant of water. As the fractional amount of wet surface increases, its emissivity decreases. The lowest emissivity occurs when the surface becomes saturated with water, as in the case of flooded land. The reduction in soil emissivity (from dry to wet condition) is large when observed in low frequencies (19.35 GHz) compared to high frequencies (85.5 GHz). The relative change in emissivity between two or more frequencies is approximated as:

$$\Delta \varepsilon = \beta_1 \left[\varepsilon_f(t) - \varepsilon_d(t)\right] + \beta_2 \left[\varepsilon_d(t) - \varepsilon_f(t)\right], \quad (5)$$

where $f_1, f_2,$ and $f_3$ represent the 19, 37 and 85 GHz vertical channels respectively, and $\beta_0, \beta_1$ are proportionality constants. To quantify the surface wetness condition, Basist et al. have defined BWI as:
Table 1. Growth profile of rice using NOAA Pathfinder AVHRR Land NDVI data based on Badhwar model. Time (t) is considered from 1 May for fitting profile parameters.

<table>
<thead>
<tr>
<th>Year</th>
<th>NDVI_b</th>
<th>t_0</th>
<th>Alpha</th>
<th>Beta (10^{-4})</th>
<th>t_m</th>
<th>r</th>
<th>N</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981–82</td>
<td>0.02891</td>
<td>48.4825</td>
<td>5.4321</td>
<td>1.6778</td>
<td>127.26</td>
<td>0.9728</td>
<td>14</td>
<td>0.0422</td>
</tr>
<tr>
<td>1996–97</td>
<td>0.06565</td>
<td>35.6168</td>
<td>3.2866</td>
<td>1.3913</td>
<td>108.58</td>
<td>0.9880</td>
<td>14</td>
<td>0.0284</td>
</tr>
<tr>
<td>1999–00</td>
<td>0.01514</td>
<td>25.0482</td>
<td>3.9636</td>
<td>1.9733</td>
<td>100.22</td>
<td>0.9798</td>
<td>14</td>
<td>0.0416</td>
</tr>
</tbody>
</table>

Table 2. Growth profile of rice using NOAA Pathfinder AVHRR Land NDVI data based on Gaussian model. Time (t) is considered from 1 May for fitting profile parameters.

<table>
<thead>
<tr>
<th>Year</th>
<th>NDVI_b</th>
<th>t_0</th>
<th>σ</th>
<th>r</th>
<th>N</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981–82</td>
<td>0.5331</td>
<td>128.64</td>
<td>37.47</td>
<td>0.982</td>
<td>14</td>
<td>0.0326</td>
</tr>
<tr>
<td>1996–97</td>
<td>0.5938</td>
<td>112.16</td>
<td>41.70</td>
<td>0.985</td>
<td>14</td>
<td>0.0304</td>
</tr>
<tr>
<td>1999–00</td>
<td>0.5738</td>
<td>103.22</td>
<td>35.71</td>
<td>0.978</td>
<td>14</td>
<td>0.0416</td>
</tr>
</tbody>
</table>

Figure 1. Average NDVI growth profile of rice-dominated grid estimated using NOAA–AVHRR NDVI data during kharif season and model fit over 0.5° grid covering Ludhiana district. Punjab. t_m, t_0, σ representing mean peak vegetative stage of crop during 1981–82, 1996–97 and 1999–2000 respectively.

The estimated model parameters of crop growth for Badhwar and Gaussian model are given in Tables 1 and 2 respectively. The observed mean and fitted profile for Badhwar is shown in Figure 1. The temporal NDVI patterns capture crop emergence, greening, peak vegetative phase and senescence. The NDVI composite over a ten-day period is affected by continuous clouds, varying solar and view zenith angles and other sources of variability such as vegetation anisotropy, etc. Since our objective was to infer long-term changes in rice phenology and avoid other error sources, the average NDVI profile for consecutive years, i.e., 1981–1982, 1996–1997 and 1999–2000 were analysed. The derived dates for the peak growth stages using Badhwar model were 4 September during 1981–82, 16 August during 1996–97 and 8 August in 1999–2000. Thus, there was a shift of 27 days in the occurrence of peak crop growth stage (t_m) from 1981–82 to 1999–2000 season. The dates derived using Gaussian model closely match those of the Badhwar model. This indicates that the type of model used to characterize crop growth behaviour does not significantly affect the result. Since the above profile was generated for a site belonging to the traditional rice-growing area, north of Ludhiana, Punjab, it can be assumed that the phenology represents the rice crop for all the years.

The wetness index was used to further confirm the above estimated shift in growth cycle. Since the transplanting of rice crop is associated with field-flooding, the BWI representing surface moisture changed significantly. The results of temporal trends in mean wetness computed for weekly composite sets with median dates at 17 May, 31 May and 7 June respectively, are shown in Figure 2. We have analysed the weekly wetness trends for the seven years spanning 1988 to 2002 to find out the earliest week, which is most affected due to shifting rice growth characteristic. The mean wetness index observed on 17 May was found almost constant over the years (slope = 0.13, r = 0.53). Increasing trend was found on 31 May (slope = 0.82, r = 0.88) and 7 June (slope = 0.99, r = 0.86). It can be inferred from the scatter in the time trend of surface wetness in Figure 2, that field preparation/puddling activities are now being initiated during the last week of May. Relative increase in the amount of wetness during these weeks over the years from 1988 indicated increase in area under flooding. It should be mentioned that the rice area in Punjab has increased from 1.18 Mha during 1981 to 2.61 Mha in 2001.

\[
BWl = \Delta e^T, \tag{6}
\]

where \( T \) is the surface temperature. The weekly composite BWI data from National Climatic Data Centre (NOAA/NESDIS) at 0.3° resolution were used in assessment of surface flooding. The weekly composting scheme is used to generate global gridded product from swath data at regular temporal period and to avoid the atmospheric influence in assessment of land surface wetness condition. The average surface wetness for the whole of Punjab for three pre-monsoon weeks, viz. (1) 14–20 May, (2) 28 May–3 June and 4–10 June was analysed for seven years (1988, 1992, 1995, 1997, 1998, 2000 and 2002). The temporal weekly profiles of surface wetness for Punjab during kharif season were analysed (April–August) for two representative years, viz. 1988 and 1998 separated by a decade.
increase in rice cultivation. High temporal data like AVHRR, irrespective of the coarse spatial resolution, could capture the dynamics of agricultural activities due to their high temporal resolution. SSM/I data though not designed for land surface studies have been found useful due to their inherent characteristic signature for regional soil moisture studies and flooding condition assessment. This study shows the potential of detecting the rice planting period mainly due to the puddling operation that changes the surface wetness significantly. This was mainly due to the large monoculture cultivation pattern of rice crop in Punjab. The potential of this sensor can be best utilized for agricultural study with an improved spatial resolution. There exist strong and convincing evidence that modification of land-cover properties affects partitioning of available energy and water, which can influence local to regional-scale climate. The large-scale modifications in land-cover properties such as increase in wetness and advancement in the onset of vegetation greenup in summer would result in extra evaporation and changes in atmospheric CO2 seasonality. A modelling study using appropriate land-surface model coupled with remote sensing-derived crop phenology and soil moisture is needed to quantify the integrated influence of increase in rice crop area and changes in phenology on regional climate.

IgG4-reactive low molecular weight antigens from *Setaria digitata* adult parasites have immunodiagnostic potential in lymphatic filariasis

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Development of sensitive as well as low-cost immunodiagnostics for detection of infected individuals would be an important step towards reaching the goal of lymphatic filariasis elimination by 2020. In an earlier study, using soluble antigens of adult *Setaria digitata*, we have shown that an antigen fraction in the molecular weight range 14 to 20 kDa can induce differential Th1/Th2 immune response in the PBMC of the endemic normal (EN) and asymptomatic microfilaremic (ASF) individuals residing in bancroftian filariasis endemic areas. In the present study, using 2D immunoblot we are able to show that two antigens of 17 and 18 kDa molecular weight and pI of 5–5.5 are recognized by the IgG4 isotype antibodies, a marker for active parasite infection, present in the sera of ASIN but not in that of EN individuals. Elevated antigen-specific IgG4 antibodies in the blood are the indicators of circulating parasite in infected individuals who do not have apparent clinical symptoms of filariasis. Thus, we suggest that these two antigens can be explored for the immunodiagnosis of lymphatic filariasis.

Keywords: IgG4 isotype immunoblot, immunodiagnosis, low molecular weight antigens, lymphatic filariasis, *Setaria digitata*.

LYMPHATIC Filariasis (LF) is recognized as one of the world’s most disabling diseases. The disease is caused in humans by infection with the filarial nematode *Wuchereria bancrofti*, *Brugia malayi* or *Brugia timori* and continues to be a major public health problem in many of the tropical countries. The World Health Organization has declared lymphatic filariasis to be the second leading cause of permanent and long-term disability worldwide and has targeted to eliminate LF globally by 2020. The disease manifests itself in a broad clinical spectrum. Individuals living in a filaria endemic area can be categorized on the basis of their clinical symptoms and parasitological as well as immunological profile into three broad groups, namely endemic normals (EN), asymptomatic microfilaremic individuals.

ACKNOWLEDGEMENTS. We thank Dr R. R. Navalgund, Director, SAC, J. S. Parthar, Group Director, Agricultural Resources Group and Dr S. Panigrahy, Head, Agro-ecology and Management Division, Ahmedabad for encouragement and guidance. We are grateful to Dr V. K. Dadhwal, Indian Institute of Remote Sensing, Dehradun for guidance. We also thank the National Climatic Data Centre (NOAA/NESSDIS) and Goddard Space Flight Center, Distributed Active Archive Centre for providing SSM/I wetness and NOAA-AVHRR data respectively.

Received 29 May 2006; accepted 5 August 2006

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CURRENT SCIENCE, VOL. 91, NO. 9, 10 NOVEMBER 2006 1221