



Research Article

Evaluating the Effect of Irrigation on Crop Evapotranspiration in Wheat (*Triticum aestivum* L.) by Combining Conventional and Remote Sensing Methods

S. CHATTARAJ¹, D. CHAKRABORTY^{1*}, R.N. GARG¹, RAVENDER SINGH¹, G.P. SINGH², V.K. SEHGAL¹, R.N. SAHOO¹, S. SINGH¹, V.K. GUPTA¹ AND DEEP CHAND¹

¹Division of Agricultural Physics, Indian Agricultural Research Institute, New Delhi - 110 012

²Division of Genetics, Indian Agricultural Research Institute, New Delhi - 110 012

ABSTRACT

Seasonal and growth stage-specific crop evapotranspiration (ET) in three varieties (DBW-17, PBW-502 and HD-2987) of wheat were estimated from a 2-year field study at the agricultural farm of the Institute. A field water balance was used with precise measurements of all the components to compute ET in wheat under adequate (ET_c) and limited (ET_a) irrigation treatments. Plant growth was monitored through leaf area index and the effect of water stress under limited irrigation was monitored through thermal remote sensing. Results indicated significant difference in crop ET, both seasonal and stage-specific. Peak ET_a and LAI in limited irrigation were obtained at flowering (80-95 DAS) stage, compared to milking stage (90-105 DAS) in adequate irrigation treatments. The LAI was significantly related to Normalized Difference Vegetation Index (NDVI) but saturated at LAI>3.5, indicating limitations of using NDVI for retrieving crop LAI.

Key words: Crop evapotranspiration, Canopy air temperature difference, Normalized difference vegetation index, Leaf area index, Irrigation, Wheat

Introduction

In India, wheat growing season is spread over winter-spring months (November to March) with the seasonal water requirement between 180 and 420 mm (Balasubramanian and Palaniappan, 2001). It is well-established that availability of water at various critical growth stages is crucial for the growth and development of the crop with a direct bearing on its production.

The over-exploitation of ground water resource has brought in several consequences including the uncertainty of sustenance in rice-

wheat production system. It is anticipated that the total demand for fresh water in the year 2050 would be 1447 BCM as compared to 634 BCM in the year 2000 (Sondhi, 2001). On the other hand, potential productivity in wheat is not appreciated partly due to poor irrigation management, especially in semi arid regions of India. Matching water supply and demand calls for determination of growth stage-specific crop water requirement, which becomes increasingly important for productivity and sustainability of any irrigation scheme. Nearly 99% of water uptake by plants from soil is lost through evapotranspiration (ET), and hence the measurement of actual crop evapotranspiration (ET_a) on a daily scale over the whole vegetative cycle can be assumed as

*Corresponding author,
Email: debashis@iari.res.in

equivalent to the water requirement of the given crop.

Any attempt to improve water use efficiency must be based on reliable estimates of ET_c as the correct knowledge of ET_c allows improved water management by adjusting the volume and frequency of irrigation to meet the crop requirements and to adapt to soil characteristics. Thermal remote sensing has proven capability in characterizing crop growing condition, and stress, if any, at any period of its growth. Optical remote sensing based vegetation assessment may be used for predicting stage-specific water requirements of the crop by linking to the crop growth parameters. The present study has therefore been planned to estimate the growth stage-specific crop evapotranspiration in wheat through a combined conventional-remote sensing approach in wheat in a semiarid region of Delhi.

Materials and Methods

A two-year field experiments on wheat (*Triticum aestivum* L.) were conducted during *rabi* season (November-April) of 2009-10 and 2010-11 in the Experimental Farm, Indian Agricultural Research Institute, New Delhi (28°35' N latitude, 77°12' E longitude and altitude of 228.16 amsl). The climate is subtropical, semi-arid with dry hot summer and cold winter. During the season, the mean daily temperature was 17.8 and 17°C during 1st and 2nd year, respectively; while RH was 64.5 and 50.2%. Total rainfall during the growing period was only 14 mm in the 1st year but was 49.7 mm during the 2nd year. A major amount of the rain concentrated in November in both the years. Duration of bright sunshine hours was also more during 1st year (5.6 hrs) than that in 2nd year (5.0 hrs) for the season. The soil is typic Haplustept, with sandy clay loam texture, medium to weak angular blocky structure, non-calcareous and slightly alkaline in reaction. The available water content in soil varies from 8-15 % (v/v) in surface and 11-15 % (v/v) in the subsurface.

Experimental details

Crop: Wheat (*Triticum aestivum* L.)

Varieties: DBW-17, PBW-502 & HD-2987

Design: Strip plot (six treatments: three varieties each under adequate and limited irrigation with three replications)

Date of Sowing: 24-11-2009 (1st year, 2009-10) and 24-11-2010 (2nd year, 2010-11)

Date of Harvesting: 10-04-2010 (1st year) & 19-04-2010 (2nd year)

Plot size: 5 m x 6 m

Spacing: 22.5 cm (Row to Row)

Fertilizer dose: 120 Kg N, 80 Kg P₂O₅ and 60 Kg K₂O ha⁻¹ dose (1/2 of N as urea plus full dose of P₂O₅ and K₂O as SSP and MOP as basal dose at the time of sowing + rest of the N (as urea) as top dressing in two installments, one at 35 days after sowing (DAS) and another at 78 DAS.

Irrigation was given in measured amount at adequate (60 mm) and limited (40 mm) application in plots with the help of Parshall flume. Total five (5) and four (4) irrigations were given throughout the growing period in plots under adequate and limited irrigation, respectively. The irrigation details are given below:

	2009-10	2010-11
1 st irrigation	16-12-2009 (22 DAS)	18-12-2010 (24 DAS)
2 nd irrigation	20-01-2010 (57 DAS)	20-01-2011 (57 DAS)
3 rd irrigation	19-02-2010 (87 DAS)	*irrigation escaped in all plots
4 th irrigation	16-03-2010 (113 DAS)**	16-03-2011 (113 DAS)**
5 th irrigation	28-03-2010 (125 DAS)	28-03-2011 (125 DAS)

* Irrigation was escaped due to prevalence of rain on 83 (4.00 mm), 84 (17.1 mm) and 89 (15.4 mm) DAS during 2010-11

**Only in plots under adequate irrigation treatment

All the recommended agronomic practices were followed.

Soil Water Monitoring

The soil water balance method (Hanks and Ashcroft, 1980) was used to measure crop evapotranspiration (ET_c)

$$ET_c = P + I - D - R - \Delta S \quad \dots(1)$$

where P and I are precipitation and irrigation, D is deep percolation below the root zone (or an upward flow i.e. capillary rise, if negative, into the root zone), R is runoff and ΔS is the change in soil profile water storage (end-of-period value minus beginning-of-period values), determined for each period between two consecutive soil water measurement days.

For monitoring soil water, neutron probe access tubes were permanently installed to a depth of 1.5 m in each plot. The soil water content was monitored at a counting rate of 60s at regular intervals (depending on the irrigation and subsequently soil water depletion rates) using the neutron moisture meter (CPN 503 DR HYDROPROBE MOISTURE GAUGE, USA) for each 30-cm layer with overlapping depth increments (5-35, 30-60, 45-75, 60-90 and 75-100 cm depths). Gravimetric method was employed for water content at 0-5 cm depth. The probe was calibrated before use in the same field. The cumulated depletion was calculated during entire crop growth period by integrating the depletion for each depth (0-5 cm for evaporation and other depths were taken for root water extraction calculation) over the whole profile. The soil water fluxes at the upper and lower boundaries of root zone were computed following the procedure outlined by Stibbe (1975):

$$\bar{E}_r = \left[\frac{1}{t_2 - t_1} \int_z^{z_r} \theta_z \cdot dz \right] \pm \bar{v}_z \pm \bar{v}_r \quad \dots(2)$$

where, \bar{E}_r = rate of root water extraction in mm day⁻¹; the first term on the right hand side of the equation is the rate of total soil water depletion in the root zone (up to depth z_r) per unit time and

the second term is the flux; \bar{v}_z and \bar{v}_r are the fluxes at the upper and lower boundary of the root zone. The upper boundary of root zone was taken as 5 cm (contributor for evaporation), and lower boundary was changing according to root growth till the root attained its maximum development (90 cm on 80 DAS). The rooting depth was simulated through a sigmoidal model developed by Gajri (1980) for wheat as given below:

$$RD_t = \frac{D_m}{1 + \exp\left(4.31 - \frac{7.82t}{t_m}\right)} \quad \dots(3)$$

Where, RD_t = depth of root zone at a given day since planting (cm); D_m = maximum depth of root zone (cm); t_m = days after sowing when the maximum root zone depth D_m is reached.

The soil water evaporation (\bar{E}_v) (mm day⁻¹) from 0-5 cm of surface was measured by using following formula (Stibbe, 1975):

$$\bar{E}_v = \left[\frac{1}{t_2 - t_1} \int_0^z \theta_z \cdot dz \right] \pm \bar{v}_z \quad \dots(4)$$

Soil water fluxes in the root zone were determined numerically as given by Hanks *et al.* (1969) using the equation:

$$\bar{v} = \frac{\Delta h t_2 + \Delta h t_1 + \Delta z}{2 \times \Delta z} \times \bar{K} \quad \dots(5)$$

Where, \bar{v} = the soil water flux at boundary in mm day⁻¹; Δh = the pressure head difference the upper and lower boundaries at the time t_1 (at the beginning) and t_2 (at the end of period), in mm; \bar{K} = the unsaturated hydraulic conductivity at the boundary layer, associated with the volumetric moisture content at half of the period between sampling times, in mm day⁻¹; Δz = the thickness of the soil layer, in mm. The pressure heads of soil layers (a) and the unsaturated hydraulic conductivity at the boundary layer (b), associated with the observed volumetric moisture contents, were calculated using the following procedure (step by step):

(a) *Soil water retention characteristics*

At 0-816 cm suction range, the suction values corresponding to water contents (through neutron moisture meter) were determined using tensiometers following the procedure of Richards (1948). Soil water retention characteristics (up to 0.8 bar) were calculated in the field plots with the help of four tensiometers installed at 7, 22, 45, 75 and 100 cm soil depth and readings were taken on the same days of moisture measurements. To cover the full range of soil water characteristics, additional points were determined with soil samples utilizing pressure plate apparatus (Soil Moisture Equipment Corporation, USA) (Klute, 1986). The moisture retention curve (power form) was fitted well with R^2 values of 0.98, 0.97, 0.99, 0.99 and 0.99 respectively for 0-15, 15-30, 30-60, 60-90 and 90-120 cm soil depths.

(b) *Unsaturated hydraulic conductivity (K) at different moisture contents (θ)*

The K- θ relationship was determined by dividing the water content-pressure head relation into n number of equal water content increments, obtaining the pressure head 'h' at the mid point of each increment; and calculating the conductivity using the following equation (Jackson, 1972):

$$K_i = K_s \left(\frac{\theta_i}{\theta_s} \right)^c \frac{\sum_{j=i}^m [(2j+1-2i)\psi_j^{-2}]}{\sum_{j=1}^m [(2j-1)\psi_j^{-2}]} \quad \dots(6)$$

where K_i is the unsaturated hydraulic conductivity at wetness θ_i , m the number of increments of θ (equal intervals from dryness to saturation), ψ_j the suction head at the mid point of each increment in θ , j and i summation indices, and c an arbitrary constant (taken as 1; Jackson, 1972). Values of the unsaturated hydraulic conductivity at all depths of soil profile invariably increased with the increase in soil moisture contents.

The pressure heads of soil layers and the hydraulic conductivity at the boundary layer, associated with the observed volumetric moisture contents, were obtained by interpolation of the data obtained through soil moisture retention characteristics and equation (6).

Finally the rate of evapotranspiration (ET) is calculated as the sum of water extraction by roots and the evaporation from the soil surface:

$$ET_a = \bar{E}_r + \bar{E}_v \quad \dots(7)$$

Remote Sensing Derived Plant Growth and Water Status Parameters

Hand-held Field Spec™ 3 spectroradiometer having 25° Field of View (FOV) was used for spectral reflectance measurement of wheat in the field condition. The Analytical Spectral Device (ASD) covers the spectral range between 350 to 2500 nm with 1.4 nm sampling interval (350-1000 nm range) and 2 nm (1000-2500 nm range). Spectral reflectance was derived as the ratio of reflected radiance to incident radiance estimated by a calibrated white reference (Spectralon). The spectral data were processed and exported to Microsoft excel through ASD View Spec Pro software. Thereafter, Normalized Difference vegetation Index (NDVI) (Rouse *et al.*, 1974) was calculated as:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \quad \dots(8)$$

Spectral data were recorded eight times during 1st year (30, 61, 87, 95, 104, 112, 120, and 129 DAS) and nine times during 2nd year (31, 48, 71, 79, 94, 105, 113, 119 and 129 DAS).

A hand-held infrared thermometer (AG-42, Teletemp Crop., USA) with an 8° field of view, was used to measure canopy temperature (T_c) and canopy air temperature difference (CATD) around midday. The data for each plot were the mean of two readings, taken from third row of each plot, at an angle of ~ 45° to the horizontal, in a range of directions to shoot plant canopy.

Plant Growth Parameters

Field measurements of LAI were carried out using LAI-2000 Plant Canopy Analyzer (LI-COR, USA). The instrument was set to take four below and one above canopy measurements to estimate the LAI. Three to four LAI readings were recorded in each plot and were averaged to represent the plot LAI. The LAI data were recorded 12 times each during 1st year (35, 46,

62, 70, 79, 86, 92, 100, 106, 112, 120 and 128 DAS) and 2nd year (41, 48, 65, 72, 79, 86, 94, 102, 108, 115, 119, 129 DAS).

Two plants were randomly selected from each plot and cut at ground level. The plants were oven-dried at 65°C for 48 hours. Dry biomass produced was expressed as g m⁻². The data were recorded on 60, 87, 98, 109, 127 and 137 DAS during 1st year and 53, 66, 87, 99, 107, 119 and 147 DAS during 2nd year.

Grain Yield and Final Biomass

An area of 1 m² was harvested manually from each plot. After sufficient air drying, these samples were weighed to get the final crop biomass and the grain yields.

Statistical Analysis

Analysis of variance (ANOVA), computation of correlation coefficients, curve fitting, regression relations and validation indices were

carried out using MS Office Excel 2007 and SPSS (Version 13.0) packages. Treatment differences were expressed with least significant difference at 5% probability level. The required graphs were drawn using MS Excel/Power Point software packages.

Results

Soil Water Distribution

(a) Soil water profile distribution under adequate irrigation

Following irrigation, soil water content was recorded at 180-220 mm on 60 DAS, and sharply decreased thereafter to reach at 141-172 and 127-160 mm m⁻¹ of soil during 1st (Fig. 1a) and 2nd (Fig. 1b) year, respectively. Profile water depletion was maximum in HD-2987 (65 and 75 mm in 1st and 2nd year, respectively), followed by PBW-502 (65 and 67 mm) and DBW-17 (44 and 59 mm). A similar pattern of soil water depletion

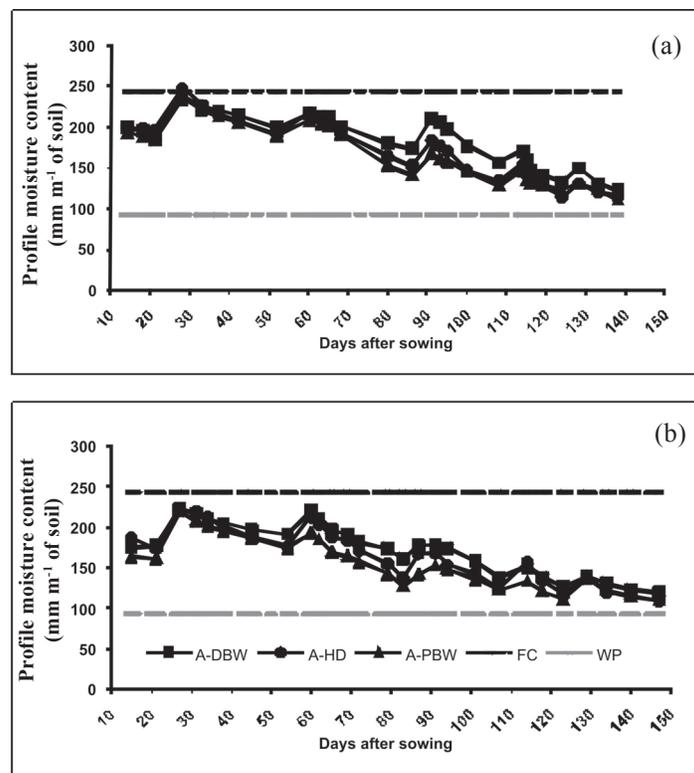


Fig. 1. Profile moisture content (mm m⁻¹ of soil depth) during (a) first (2009-10) and (b) second year (2010-2011) crop growth periods of DBW-17, HD-2987 and PBW-502 varieties of wheat under adequate irrigation regimes (standard error of mean varied between ±10% of mean value for all treatments)

was observed during next irrigation cycle, although the difference between DBW-17 and other varieties reduced in 2nd year. The subsequent irrigation (87 DAS in 1st year) was escaped in 2nd year, due to rain at 86 and 90 DAS (21 and 15.4 mm, respectively), bringing a gradual increase in profile moisture content. The variety, DBW-17 maintained higher profile water content till the next irrigation at 112 DAS. The moisture content change was low (24 to 38 mm m⁻¹ of soil) in rest of the periods with reduced variation.

(b) Profile moisture distribution under limited irrigation

Soil water content under limited irrigation was always well-below field capacity, and reached close to wilting point at later stages forcing mild water stress to the crop (Fig. 2). In 1st year, the pattern and rate of decrease were similar for the

varieties till 3rd irrigation cycle. But in 2nd year, the water content profiles were distinct at CRI-irrigation onwards, where maximum depletion (21-60 DAS) was recorded in HD-2987 (76 mm), followed by PBW-502 (69 mm) and DBW-17 (64 mm). The 3rd irrigation was avoided due to rainfall and moisture content reached to near wilting point, and thereafter remained at nearly the same level. Plant water uptake after the final irrigation was negligible.

Crop Evapotranspiration under Adequate (ET_c) and Limited Irrigation (ET_l) Conditions, Root Water Extraction (E_r) and Soil Evaporation (E_s)

Seasonal mean daily (Penman–Monteith) reference evapotranspiration, ET_0 was higher in 1st year (2.74 mm d⁻¹) than the 2nd year (2.36 mm

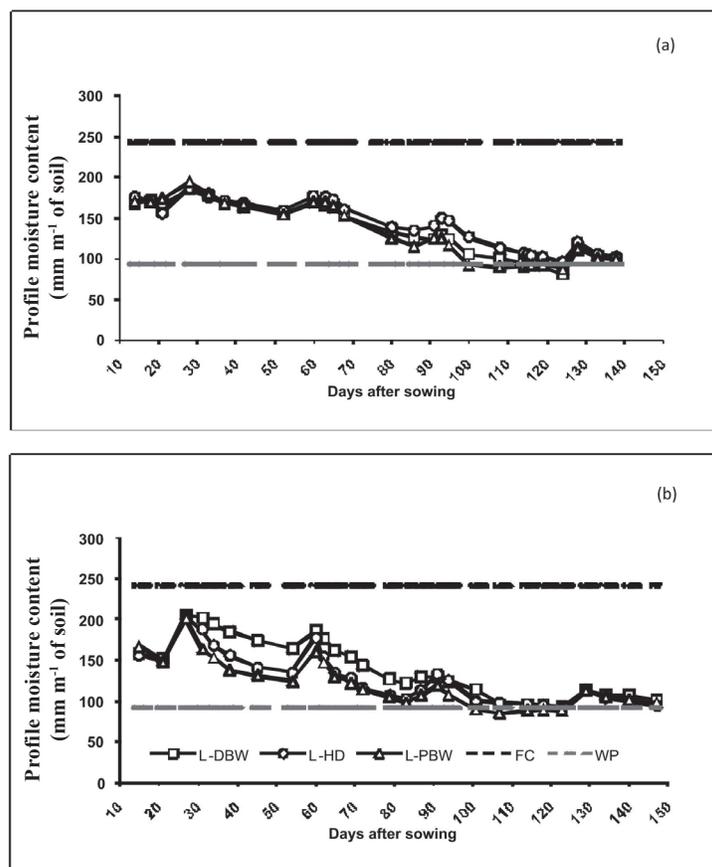


Fig. 2. Profile moisture content (mm m⁻¹ of soil depth) during (a) first year (2009-10) and (b) second year (2010-2011) crop growth periods of DBW-17, HD-2987 and PBW-502 varieties of wheat under limited irrigation regimes (standard error of mean varied between $\pm 10\%$ of mean value for all treatments)

d⁻¹) and so the seasonal total ET₀ (378.1 and 347.5 mm in 1st and 2nd year, respectively).

(a) Under adequate irrigation

Compared to 2nd year, initial (up to 60 DAS) ET_c values were significantly higher in 1st year in DBW-17 (36%) and PBW-502 (33%), but similar in case of HD-2987 (Fig. 3). Mean E_r was 33% higher in 1st year than that in 2nd year in DBW-

17, but marginal in case of other two varieties. The maximum E_v during this period was recorded as 0.4, 1.3 and 1.2 mm d⁻¹ in DBW-17, HD-2987 and PBW-502, respectively in both the years of study. The peak ET_c (75-115 DAS) was higher in 1st year by 8, 11 and 15% in DBW-17, HD-2987 and PBW-502, respectively, while E_r was higher by 25, 6 and 12% in respective varieties. During same period, E_v had fallen from initial higher

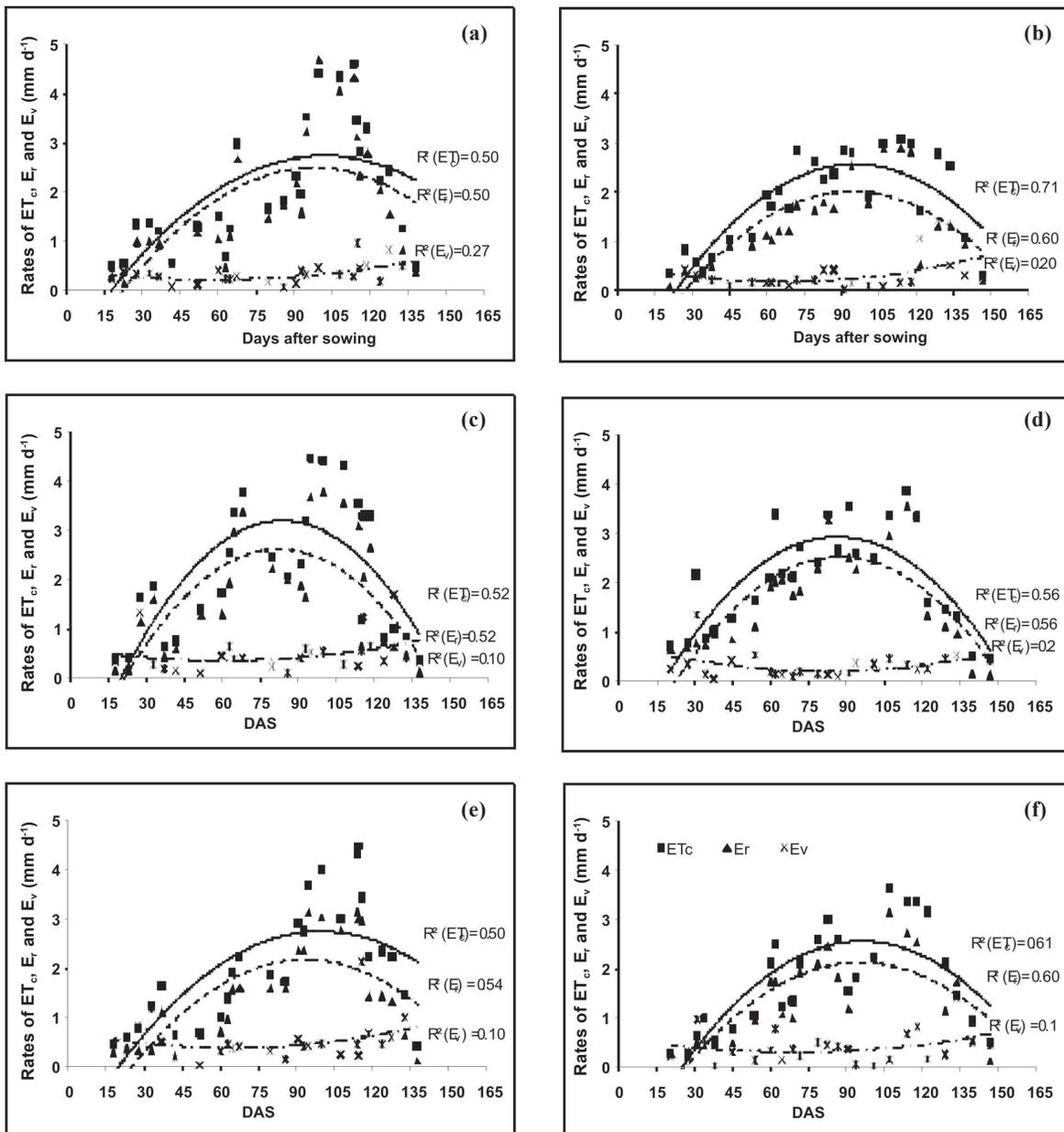


Fig. 3. Rates of crop evapotranspiration (ET_c), root water extraction (E_r) and soil evaporation (E_v) in the years 2009-10 and 2010-11 in DBW-17 (a-b), HD-2987 (c-d) and PBW-502 (e-f) under adequate irrigation regime

values to 0.1 mm d^{-1} or less. Beyond 115 DAS, ET_c and E_r decreased, while E_v increased to 1 mm d^{-1} , at par with E_r .

(b) *Under limited irrigation regime*

Initially (<60 DAS), average ET_a was lower than adequate irrigation by 21 (1st year) and 28% (2nd year) in DBW-17, 43 (1st year) and 15% (2nd year) in HD-2987 and no appreciable difference

was observed in PBW-502 (Fig. 4). Similarly, E_r was less by 6 and 35% (DBW-17), 32 and 11% (HD-2987) and no difference (PBW-502) in the 1st and 2nd year, respectively; E_v were $0.4\text{-}0.5 \text{ mm d}^{-1}$ (neglecting some of extremes). The peak values of ET_a and E_r (75-115 DAS) was $2\text{-}3.5 \text{ mm d}^{-1}$ with their means at 2 and 1.6 mm d^{-1} , respectively. E_v decreased continually to reach to $0.1\text{-}0.2 \text{ mm d}^{-1}$ and a sharp decline beyond 115 DAS was observed for ET_a and E_r , when E_r and E_v became nearly similar.

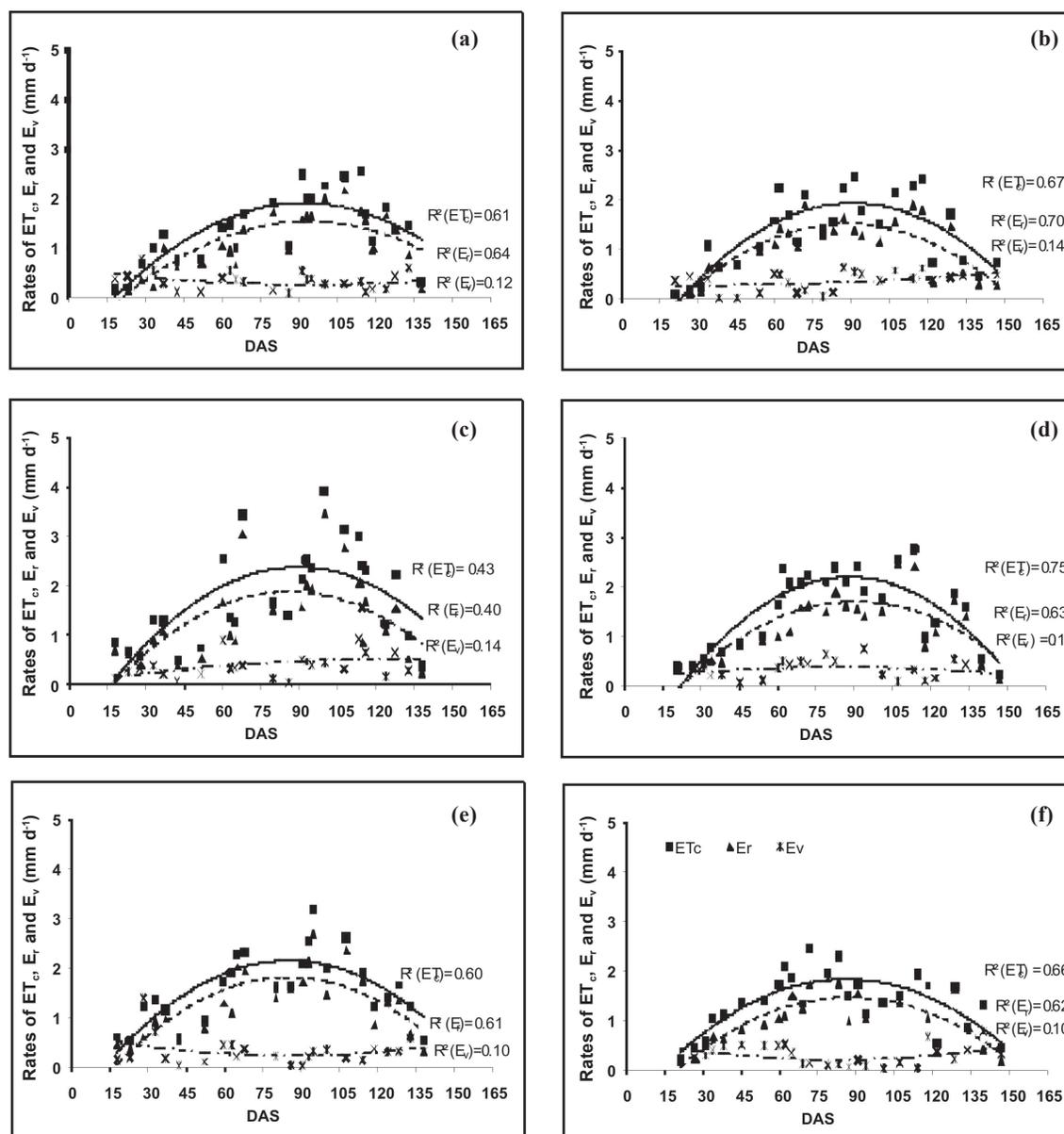


Fig. 4. Rates of actual evapotranspiration (ET_a), root water extraction (E_r) and soil evaporation (E_v) in the years 2009-10 and 2010-11 in DBW-17 (a-b), HD-2987 (c-d) and PBW-502 (e-f) under limited irrigation regime

Growth Stage-Specific Evapotranspiration Values

(a) Crown root initiation (CRI) stage

At this stage (up to 23 and 27 DAS in 1st and 2nd year, respectively), ET_c were higher than ET_a except in PBW-502. The ET_c values were 8.2 (1st year) and 5.6 (2nd year) mm in DBW-17, 16.0 (1st year) and 11.4 (2nd year) mm in HD-2987, and, 5.3 (1st year) and 3.5 (2nd year) mm in PBW-502. The ET_a were recorded as 3.2 and 2.2, 6.2 and 6.3, 7.6 and 5.3 mm in DBW-17, HD-2987 and PBW-502, respectively in the two years. Data revealed higher ET_c and ET_a in HD-2987 during 1st year while PBW-502 reported higher ET_a during 2nd year. Treatment differences were greatest (ET_c 61% higher than ET_a) in DBW-17 than the other two varieties.

(b) Tillering stage

The tillering stage, next to CRI in wheat extended till 42 (1st year) and 45 DAS (2nd year). With the advancement in plant growth the difference in ET_c and ET_a values minimized at this stage, though PBW-502 continued to show higher ET_a than ET_c . In the 1st year, ET_c were 24.4, 34.4 and 18.8 mm while ET_a were 23.8, 19.3 and 31.9 mm. The ET values were reported as 24.4 and 23.8 mm in DBW-17, 34.4 and 19.3 mm in DBW-17, HD-2987 and PBW-502, respectively. In 2nd year, both the ET_c and ET_a were low, although the treatment differences were maintained as the values were computed as 16.6 and 11.4 (DBW-17), 22.7 and 13.4 (HD-2987), 18.7 and 19.2 (PBW-502) mm. ET_c of HD-2987 was the highest, while ET_a was greater in PBW-502 in both the years.

(c) Jointing stage

The third major phenological stage was the jointing, which appeared after tillering and continued till 63 (1st year) and 65 (2nd year) DAS. The differences between adequate and limited irrigation reduced further at this stage, and recorded higher by 0.6, 14.8 and 9.0 mm under adequate irrigation during 1st year in DBW-17, HD-2987 and PBW-502, respectively. But during

2nd year, ET_c were higher by 2.9 and 11.8 mm in DBW-17 and HD-2987, respectively but was lower by 2.1 mm in PBW-502. ET_c were 31.2 mm (PBW-502) and 41.4 mm (HD-2987) under adequate irrigation during 1st and 2nd year, respectively; but ET_a were higher in PBW-502 under limited irrigation during 1st year (26.0 mm) and 2nd year (31.9 mm).

(d) Flowering stage

The flowering in the crop started after the jointing stage and continued till 86 DAS (1st year) and 91 DAS (2nd year). This was the most active growth and development period. At flowering, not only the absolute evapotranspiration but also the differences between treatments were broadened. The ET_c were 41.9 (1st year) and 63.8 (2nd year) mm in DBW-17, 59.7 (1st year) and 68.5 (2nd year) mm in HD-2987, 47.7 (1st year) and 58.4 (2nd year) mm in PBW-502 while ET_a were 35.9 and 44.8, 34.9 and 58.5, 35.2 and 44.7 mm in DBW-17, HD-2987 and PBW-502, respectively in respective years. The treatment differences were higher in HD-2987 (24.8 mm more under adequate irrigation) and DBW-17 (18.9 mm) during 1st and 2nd year, respectively. In PBW-502, ET_c showed relatively higher values from this stage onwards (12.5 and 13.7 mm higher during 1st and 2nd year, respectively). During 2nd year, the highest ET_c in DBW-17 occurred at flowering stage while at this same stage, ET_a in all the varieties achieved their maximum values.

(e) Milking stage

The crop milking stage continued till 108 DAS (1st year) and 114 DAS (2nd year), and the maximum ET_c and ET_a for the entire growth stages were observed at this stage. The ET_c were recorded as 82.9 (DBW-17), 88.4 (HD-2987), 71.4 (PBW-502) mm while ET_a values were 51.0 (DBW-17), 55.4 (HD-2987), 47.1 (PBW-502) mm during 1st year. The corresponding maximum values in ET_c were 72.3 and 70.5 mm in HD-2987 and PBW-502, while it reduced to 61.2 mm in DBW-17 during 2nd year. In this year, the ET_a values started decreasing and were 44.5, 52.3 and 35.8 mm in DBW-17, HD-2987 and PBW-502, respectively. The differential irrigation effects

were clearly discernible at this stage in all the varieties except in PBW-502 (1st year) and DBW-17 (2nd year). The ET_c values were higher by 31.9 and 16.7 (DBW-17), 33.0 and 20.0 (HD-2987), 24.3 and 34.7 (PBW-502) mm under adequate irrigation during 1st and 2nd year, respectively. These peak values were mostly attained in HD-2987 under both the irrigation treatments irrespective of years.

(f) Dough stage

The next dough stage extended up to 124 DAS (1st year) and 129 DAS (2nd year) in which evapotranspiration decreased irrespective of treatments, varieties or years. The ET_c were recorded as 57.5 (DBW-17), 43.6 (HD-2987), 63.5 (PBW-502) mm in 1st year and 37.9 (DBW-17), 29.9 (HD-2987), 34.5 (PBW-502) mm in 2nd year; the ET_a were 36.1 (DBW-17), 22.6 (HD-2987), 34.4 (PBW-502) mm during 1st year and 24.4 (DBW-17), 19.6 (HD-2987), 20.2 (PBW-502) mm during 2nd year. Data showed that ET_a was lower in HD-2987 at this stage. Although the treatment differences in ET_c reduced except PBW-502, it was higher in adequate irrigation by 21.5, 21.0 and 29.1 mm during 1st year and 13.5, 10.4 and 14.3 mm during 2nd year in DBW-17, HD-2987 and PBW-502, respectively. Results indicated lesser differences between ET_c and ET_a in HD-2987 during both the years during this period.

(g) Maturity stage

From the dough stage onwards till harvest of the crop was the crop maturity stage. As the plant advanced towards maturity, evapotranspiration in all the varieties irrespective of irrigation treatments declined to very low values as 21.8 and 14.4 (DBW-17), 20.1 and 14.5 (HD-2987), 29.0 and 15.8 (PBW-502) mm during 1st year and 20.6 and 11.8 (DBW-17), 9.2 and 12.5 (HD-2987), 26.8 and 17.5 (PBW-502) during 2nd year of ET_c and ET_a , respectively. The ET_c were higher in PBW-502 while ET_a was lower in DBW-17 during both the years. The ET_c were always higher than ET_a (except in HD-2987 during 2nd year, which was 3.3 mm less under adequate

irrigation). The differences were ranging between 5.6 and 13.3 mm. Differences were higher in PBW-502 in both the years (13.2 and 9.3 mm during 1st and 2nd year, respectively). Overall, the stage-specific evapotranspiration values during 1st year were higher than 2nd year in all but jointing and flowering stages.

Normalized Difference Vegetation Index

In DBW-17, there were initial subtle differences in NDVI between the irrigation treatments (Fig. 5). The values increased up to 90-105 DAS and the peak values were recorded as 0.94 and 0.92 in 1st year; and 0.87 and 0.83 in 2nd year under adequate and limited irrigation, respectively. The treatment difference, however, was most distinct on 120 DAS (0.80 and 0.42 during 1st year and 0.74 and 0.58 during 2nd year under adequate and limited irrigation regimes, respectively). Values decreased thereafter till maturity with the treatment differences continuing.

In HD-2987, irrigation effect could be better differentiated in 1st year, where peak NDVI appeared early (on 61 DAS) compared to 2nd year (79 DAS). Treatment differences were on 120 DAS (0.75 and 0.61 during 1st year and 0.75 and 0.67 during 2nd year under respective irrigations). At maturity (on 129 DAS) values reduced with reduction in treatment differences and were recorded as 0.33 and 0.23 (1st year) and 0.29 and 0.24 (2nd year) under adequate and limited irrigations, respectively.

Temporal NDVI profile was similar in PBW-502, where the peak values were attained on 87 DAS in 1st year (0.87 under both the irrigations) and 71 DAS in 2nd year (0.87-0.92 under adequate and 0.83-0.85 under limited irrigation regime). Treatment difference maximized on 120 DAS and was 0.75 and 0.61 during 1st year, and 0.73 and 0.67 during 2nd year under adequate and limited irrigation regimes, respectively.

Canopy Thermal Regime

Difference in crop thermal signatures was most evident during the peak active growth (90

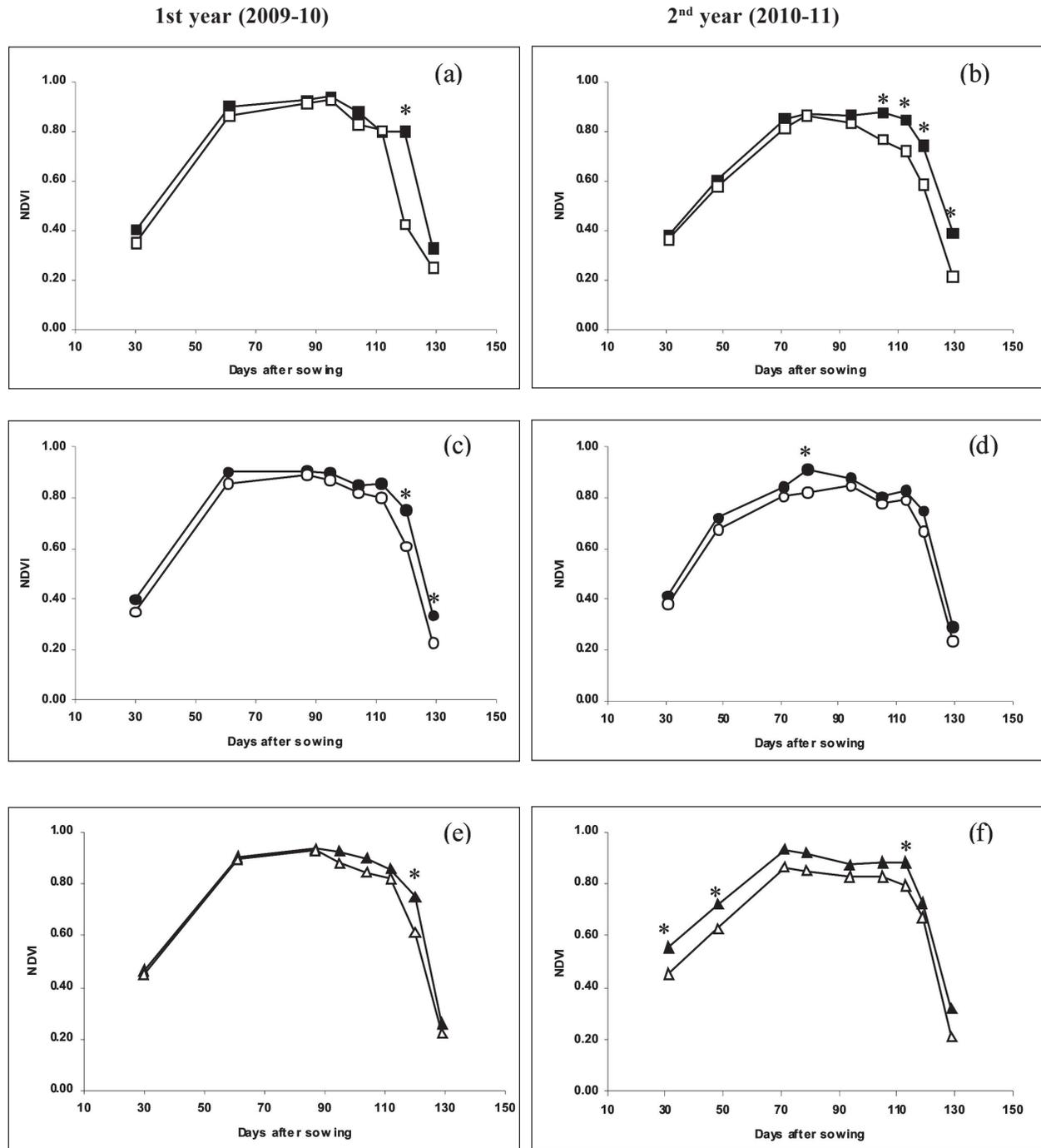


Fig. 5. Hyperspectral NDVI in DBW-17 (a, b); HD-2987 (c, d); PBW-502 (e,f) under adequate (bold lines) and limited (light lines) water regimes (*denoted significant difference at P<0.01)

to 130 DAS) (Fig. 6). Canopy temperatures (T_c) were lower by 5-6 and 6-10% under adequate irrigation during 1st year (90 DAS) and 2nd year (93 DAS), respectively. Beyond 110 DAS, treatment differences got progressively increased

where peak values under adequate irrigation were lower by 9, 14 and 10% during 1st year and 10, 11 and 15% during 2nd year in DBW-17, HD-2987 and PBW-502 varieties. The greatest differences were noticed on 120 (1st year) and

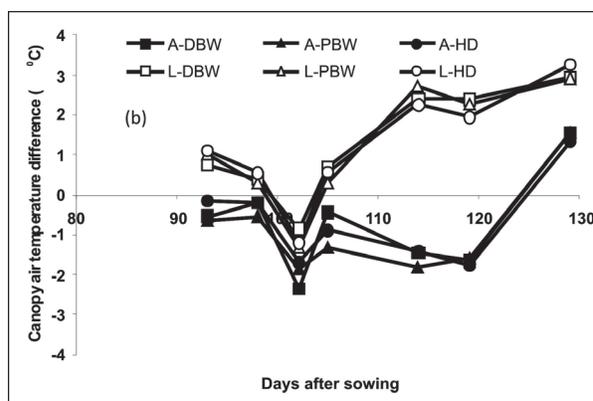
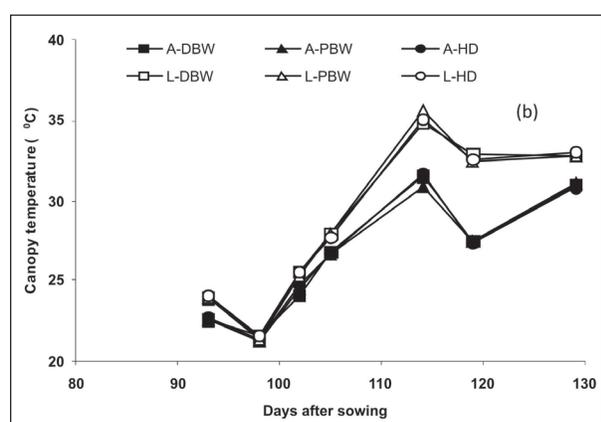
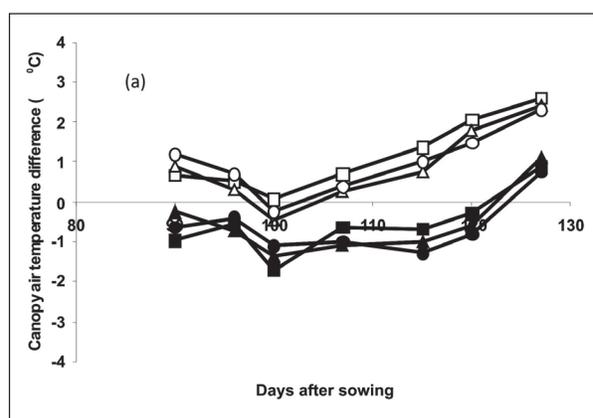
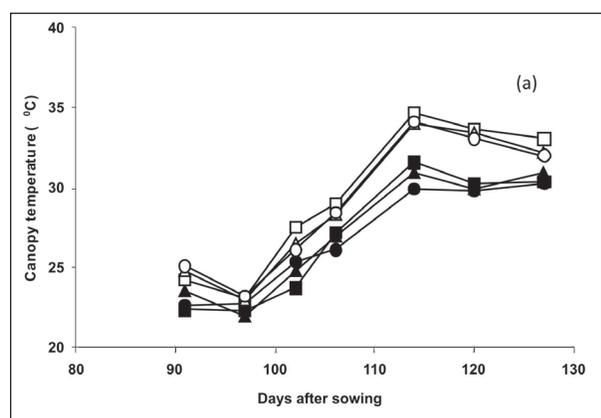


Fig. 6. Canopy temperature ($^{\circ}\text{C}$) variations in wheat varieties DBW-17, PBW-502 and HD-2987 adequate (A) and limited (L) irrigation regimes during (a) 1st (2009-10) and (b) 2nd (2010-11) year

Fig. 7. Canopy air temperature difference ($^{\circ}\text{C}$) variation under adequate (A) and limited (L) irrigation regimes during (a) 2009-10 and (b) 2010-11

119 (2nd year) DAS, where the values under adequate irrigation were lower by 11 and 20% in all the varieties during 1st and 2nd year, respectively. During this period, T_c was the lowest in HD-2987 (29.8 and 27.3 $^{\circ}\text{C}$) under adequate irrigation, while the highest values under limited condition was recorded in DBW-17 (33.6 and 33.0 $^{\circ}\text{C}$) during respective years. Thereafter, differences reduced. Overall, the effect of irrigation was visible on 100 and 105 DAS but the maximum difference noted around 120 DAS.

Canopy air temperature difference (CATD, in $^{\circ}\text{C}$) during the same period (90-130 DAS) exhibited a general decline following irrigation but increased till the next irrigation indicating progressively warmer plant canopy (Fig. 7). On

90 (1st year) and 93 (2nd year) DAS, adequate irrigation showed all negative CATDs, while these were all positive under limited condition; the differences were 1.60, 1.84 and 1.18 $^{\circ}\text{C}$ during 1st year and 1.30, 1.25 and 1.67 $^{\circ}\text{C}$ during 2nd year in DBW-17, HD-2987 and PBW-502, respectively. The minimum values were recorded as -1.71 and 0.06 (DBW-17), -1.10 and -0.27 (HD-2987), -1.35 and -0.48 (PBW-502) $^{\circ}\text{C}$ on 100 DAS in the 1st year; and -2.35 and -0.85 (DBW-17), -1.70 and -1.20 (HD-2987), -1.90 and -1.30 (PBW-502) $^{\circ}\text{C}$ on 102 DAS in 2nd year under adequate and limited irrigations, respectively. Thereafter the CATD increased steadily till maturity under limited water treatment as no irrigation water applied during this period. But under adequate condition, CATD values increased initially after 102 DAS but showed little changes up to 115-

120 DAS and thereafter increased till maturity. In the 1st year, treatment difference was maximum on 120 DAS and recorded as -0.30 and 2.07°C (DBW-17), -0.82 and 1.48°C (HD-2987), -0.58 and 1.79°C (PBW-502) under adequate and limited irrigation, respectively. During 2nd year, differences maximized on 119 DAS for DBW-17 (-1.65 and 2.40°C) and HD-2987 (-1.75 and 1.95°C), while in PBW-502, the difference was the largest on 114 DAS (-1.40 and 2.70°C).

Leaf Area Index (LAI)

In the 1st year, effect of irrigation on LAI started appearing from 62 DAS onwards in DBW-17 and HD-2987, and 70 DAS in PBW-502 (Fig. 8). Treatment differences were significantly higher on 79 DAS in all the varieties, and were recorded as 3.77 and 2.00 (DBW-17), 4.45 and 2.53 (HD-2987), 3.20 and 2.20 (PBW-502) under adequate and limited water regimes, respectively.

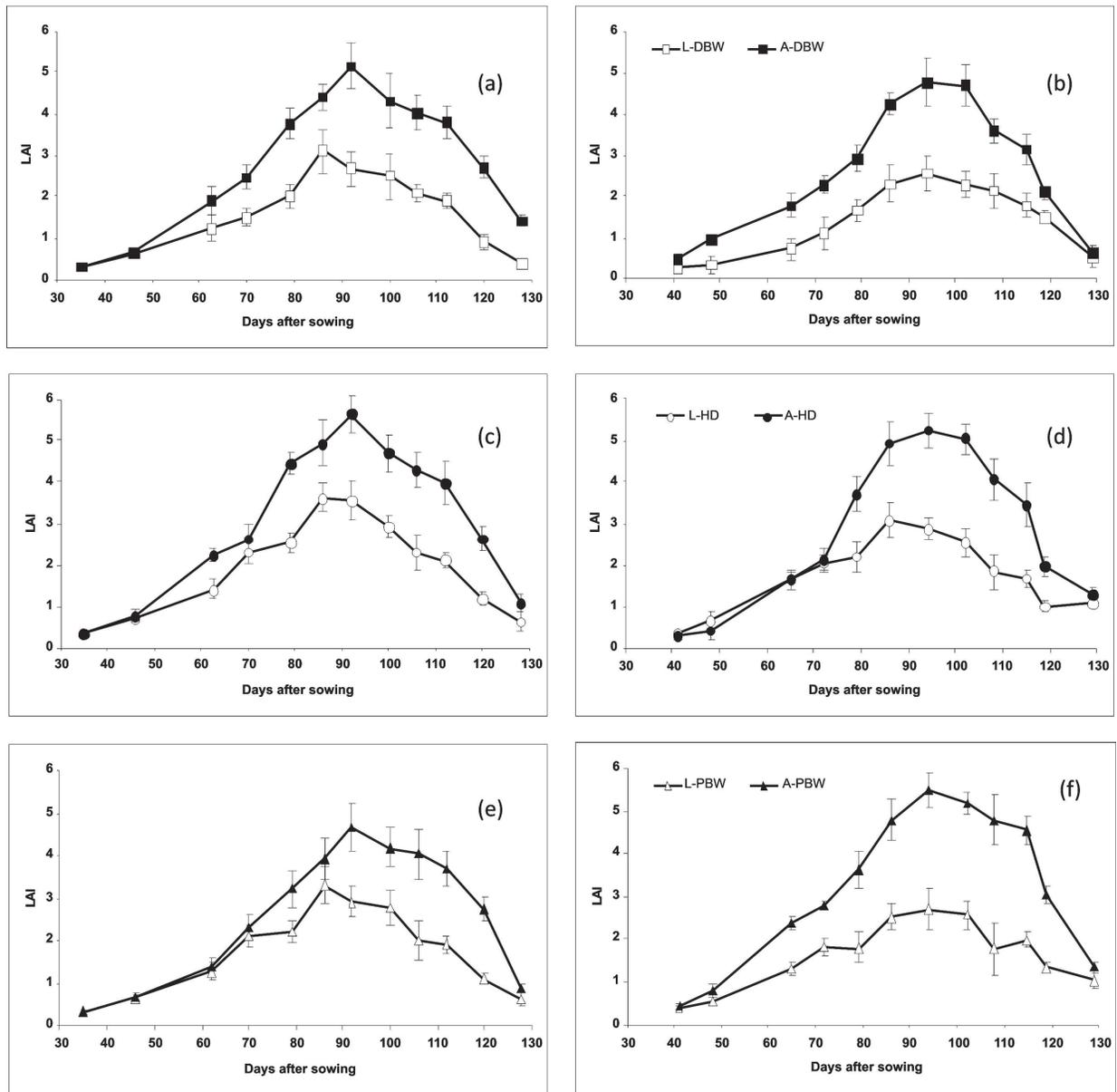


Fig. 8. Leaf area index (LAI) in wheat during the growing season in 2009-10 and 2010-11 for DBW-17 (a, b), HD-2987 (c, d) and PBW-502 (e, f) varieties under adequate (A) and limited (L) irrigation regimes

The peak value was the highest for HD-2987 (5.63) on 86 DAS under limited irrigation, while it shifted to 92 DAS (5.14) like other varieties. Although the LAI reduced thereafter, differential irrigation effect was most pronounced on 120 DAS (66, 54 and 60% higher in DBW-17, HD-2987 and PBW-502, respectively under adequate irrigation).

During 2nd year, effect of irrigation started visible on 65 (DBW-17 and PBW-502) and 79 (HD-2987) DAS. The maximum LAI was attained on 94 DAS for all the varieties (4.78, 5.24 and 5.47 under adequate and 2.55, 3.08 and 2.70 under limited in DBW-17, HD-2987 and PBW-502, respectively), except HD-2987, where it appeared on 86 DAS under limited irrigation. Though LAI decreased after 94 DAS till maturity, treatment difference was better on 108 DAS in HD-2987 (55% higher in adequate irrigation) and PBW-502 (63% higher in adequate) but on 102 DAS in DBW-17 (51% higher in adequate).

Grain Yield

Biomass at harvest was recorded as 1289.6 and 1084.8 (DBW-17), 1293.8 and 1106.2 (HD-2987), 1318.4 and 1110.4 (PBW-502) g m⁻² in the 1st year and 1065.6 and 915.2 (DBW-17), 1150.0 and 1025.0 (HD-2987), 1116.8 and 889.6 (PBW-502) g m⁻² in 2nd year under adequate and limited irrigations, respectively. Similar to biomass, the yields were also higher under adequate water regime and were noted as 517 and 470 (DBW-17), 500 and 483 (HD-2987), 489 and 450 (PBW-502) g m⁻² in the 1st year and 488 and 400 (DBW-17), 493 and 425 (HD-2987), 494 and 412 (PBW-502) g m⁻² in 2nd year under adequate and limited regimes, respectively, indicating 10, 4 and 8% higher grain yield during 2nd year and 22, 16 and 20% during 1st year under adequate water condition; least differences were obtained in HD-2987 and largest in DBW-17 during both the years. Harvest index (HI) is the only parameter which exhibited comparatively lower values under adequate (except in DBW-17 and HD-2987 during 2nd year), ranging from 0.37-0.40 (under adequate irrigation) and 0.41-0.44 (under limited irrigation) during 1st year and 0.43-0.46

(under adequate irrigation) and 0.41-0.45 (under limited irrigation) during 1st year. Data showed that the difference in values of HI was lower in DBW-17 during both the years; though PBW-502 and HD-2987 showed higher HI under adequate (0.46 and 0.43) than limited one (0.45 and 0.41) during 2nd year.

Evapotranspiration (ET)

Finally the evapotranspiration (both the ET_c and ET_a) values throughout the growing period were computed as 263.0 and 190.0 mm in DBW-17, 297.0 and 173.0 mm in HD-2987 and 270.9 and 198.0 mm in PBW-502 under adequate and limited irrigations, respectively during 1st year; the same during 2nd year were 237.0 and 167.6, 255.4 and 192.1, 243.2 and 175.5 mm in DBW-17, HD-2987 and PBW-502, respectively. Data revealed that evaporation from soil surface accounted for (average) 20 and 25% of evapotranspiration for the whole season. The percentage contribution of transpiration i.e. root water extraction to seasonal crop ET were higher in DBW-17 (86 and 80% under adequate and limited water regimes, respectively) and HD-2987 (84 and 80% under adequate and limited water regimes, respectively). Except in DBW-17 during 2nd year (negligible difference- 1% higher under limited irrigation), the transpiration in relation to ET were always higher under adequate irrigation than limited; though the differences were not significant.

Water Use Efficiency (WUE)

Irrespective of the varieties and years, the WUE_{yield} under limited regime were always higher (25-66% in 1st year and 14-16% in 2nd year) than under adequate regime. It was remarkably higher as 66% in HD-2987 during 1st year while the same during 2nd year was higher in DBW-17 (16%). The WUE_{yield} were recorded as 1.97 and 2.06 g m⁻²mm⁻¹ in DBW-17, 1.68 and 1.93 g m⁻²mm⁻¹ in HD-2987 and 1.81 and 2.03 g m⁻²mm⁻¹ in PBW-502 during 1st and 2nd year, respectively under adequate irrigation; the same under limited condition were 2.47 and 2.39, 2.79 and 2.21, 2.27 and 2.35 g m⁻²mm⁻¹ in DBW-17, HD-2987 and

PBW-502, respectively. Considering both the years, PBW-502 showed higher WUE_{yield} under adequate irrigation treatment; under limited water situation, this was achieved in both DBW-17 and HD-2987 varieties. In general $WUE_{biomass}$ were also higher (15 to 46 and 14 to 18% during 1st and 2nd year, respectively) under limited irrigation and were ranging from 4.36 to 4.90 (1st year) and 4.50 to 4.59 (2nd year) $g\ m^{-2}\ mm^{-1}$ under adequate irrigation; 5.61 to 6.39 (1st year) and 5.22 to 5.33 (2nd year) $g\ m^{-2}\ mm^{-1}$ under limited irrigation. $WUE_{biomass}$ under adequate condition was the highest in DBW-17 (4.9 $g\ m^{-2}\ mm^{-1}$) and PBW-502 (4.59 $g\ m^{-2}\ mm^{-1}$) during 1st and 2nd year, respectively; but under limited water regime the values were higher in HD-2987 (1st year: 6.39 and 2nd year: 5.33 $g\ m^{-2}\ mm^{-1}$) during both the years.

Relationships between LAI and NDVI

The best fitting curve between LAI and NDVI was obtained through logarithmic regression equations ($R^2= 0.62$). At high values of NDVI, slight increase in indices corresponded to a relatively larger increase in green leaf area. It is also understood that at higher values of LAI, NDVI gets saturated at LAI=3-3.5.

Discussion

The soil water content profile indicated a perpetual decrease from sowing to harvest; rate of decrease was higher under adequate irrigation during most of the crop growth phases, but higher in limited irrigation at maturity. The profile (1 m depth) water content under adequate irrigation was nearly 75-80% of field capacity moisture content (θ_{FC}) up to jointing stage (63-65 DAS), reduced thereafter to 50-60% of θ_{FC} till dough stage and remained <40% θ_{FC} at maturity and harvest. In contrast, profile water content in limited irrigation treatment was initially 55-75% of θ_{FC} , but for most of the periods remained 40-50% of θ_{FC} , and from 100 DAS onwards, close to wilting point moisture content (100 $mm\ m^{-1}$ depth of soil). The reduced soil moisture content were exhibited by the crop in terms of 32% less total

root water extraction and 30% less of seasonal crop evapotranspiration. The rate of depletion in water was higher in PBW-502 and HD-2987 varieties than DBW-17 under adequate irrigation regimes. Although profile water content under DBW-17 in adequate irrigation was marginally higher at certain periods, it was consistently and significantly higher in the limited water regime till 65-70 DAS in the 2nd year of experiment. The profile water depletion was also substantially higher (21-60 DAS, 2nd irrigation cycle) under this variety in the same year, suggesting a lesser soil water utilization, evidenced by a low canopy coverage and leaf area index of this variety during this period of growth. However, the varietal effect in profile moisture distribution was not very prominent, as this was between the irrigation treatments. In all the cases, extraction of soil water was the maximum from 0-35 cm soil depth, suggesting monitoring of this layer soil water for irrigation scheduling in sandy loam soils of subtropical regions.

The drainage component in the water balance is often ignored while computing the crop evapotranspiration (ET_c), assuming that there is no significance loss of water from the soil profile (Musick *et al.*, 1994; Wang *et al.*, 2001; Kang *et al.*, 2002). Our study indicates that there may be as high as 10 mm of drainage down the profile which accounts to ~4% of the ET_c . It is therefore, desirable to compute the ET_c through water balance, while monitoring of drainage must not be neglected. The seasonal evaporation from the soil surface varied between 19-23% of the total ET_c in wheat, close to that reported by Liu *et al.* (2002) in North China Plain. Although soil evaporation at the full growth stage were small in comparison to total ET_c , its absolute value was large, indicating the importance in control of evaporation at the stage to conserve soil moisture for better utilization by crop. The seasonal ET_c in our study varied between 237-297 mm with an average of 261 mm. This was in between the measured values of 250 mm in West Bengal, east India (Bandyopadhyay and Mallick, 2003) and 336 mm in Karnal, north India (Tyagi *et al.*, 2000). The peak ET_c (4-5 $mm\ d^{-1}$) and its time of

Table 1. Growth stage specific evapotranspiration (mm) in three wheat varieties under adequate and limited irrigation supply during 2009-10 and 2010-11

Growth stages	Irrigation treatments											
	Adequate irrigation						Limited irrigation					
	DBW-17		HD-2987		PBW-502		DBW-17		HD-2987		PBW-502	
	1 st year	2 nd year										
Crown root initiation	8.2	5.6	16.0	11.4	5.3	3.5	3.2	2.2	6.2	6.3	7.6	5.3
Tillering	24.4	16.6	34.4	22.7	18.8	18.7	23.8	11.4	19.3	13.4	31.9	19.2
Jointing	26.4	31.4	34.9	41.4	35.2	30.8	25.7	28.5	20.1	29.7	26.0	32.9
Flowering	41.9	63.8	59.7	68.5	47.7	58.4	35.9	44.8	34.9	58.5	35.2	44.7
Milking	82.9	61.2	88.4	72.3	71.4	70.5	51.0	44.5	55.4	52.3	47.1	35.8
Dough	57.5	37.9	43.6	29.9	63.5	34.5	36.1	24.4	22.6	19.6	34.4	20.2
Maturity	21.8	20.6	20.1	9.2	29.0	26.8	14.4	11.8	14.5	12.5	15.8	17.5

appearance in wheat (at milking stage) were in close agreement with Tyagi et al. (2000) in prevailing north Indian climate, as in the present study.

A persistently cooler micro-climate in 2010-11 during wheat growing period (seasonal average maximum and minimum air temperatures at 24.1 and 9.8 °C, respectively, compared to 26.2 and 10.5 °C in 2009-10) has led to a marginal decline (30.6 mm) in cumulative reference evapotranspiration (ET_0 , calculated by using FAO Penman-Monteith equation). In consequence, ET_c remained 20 (limited irrigation) and 32 (adequate irrigation) mm lower in the 2nd year. Over the season, this was reflected in rates of crop evapotranspiration, more so under adequate irrigation water regime and also at initial stages. The maximum rate of evapotranspiration reached during 75-115 DAS, irrespective of irrigation treatments, coinciding with the most active phase of crop growth. The second-order polynomial equations expressing the trends in ET_c and root water extraction (E_r) were similar indicating a gradual increase till the maximum values were obtained and then the rates were falling till harvest. The evaporation rates from soil in comparison, were irregular and did not follow any trend; however, their values decreased to the active stages of crop growth and increased as the crop progressed to maturity.

When averaged over a definite time period as per the distinguished phenological phases, the milking stage (86-91 to 108-114 DAS) emerges as the period when the wheat is evapotranspiring the most (Table 1). This distinction of milking stage, when the ET_c is the greatest, is more visible under adequate irrigation mostly in the 1st year. In the 2nd year, when the air temperature was cooler, ET_c under adequate irrigation was similar or with little difference between flowering and milking stages. Moreover under limited irrigation, ET_c was either the highest during flowering or there is no difference between flowering and milking stages. It is obvious that the seasonal air temperature profile varies from year to year. The rate of crop growth and its water use being synchronous and as the crop growth is fundamentally related to thermal time, the definition of the phenophases should be obtained through consideration of time/temperature relationship. Our results emphasize the need to explore the growing-degree-days to clearly distinguish the major growth stages and crop water use at respective stages.

It is important for the arid and semi-arid region to reduce soil evaporation and increase grain yield to improve the water use efficiency (WUE). Except in case of HD-2987 variety in the 1st year, yields under adequate irrigation treatment were significantly higher than under limited irrigation, though the differences widely varied

(39 to 88 g m⁻²). The WUE, on the other hand was significantly higher (except two cases), indicating substantial amount of water-saving under limited irrigation. Thus, the greater WUE were not achieved through an increase in yield, but through saving of a sizeable quantity of irrigation water, compensating the yield reduction to a great extent. This also indicates that it need to be further explored in reducing the amount of irrigation recommended to wheat (6 cm at critical growth stages in semi-arid regions like Delhi), and to utilize the limited water resources effectively in condition of less irrigation water availability. This was beyond the scope of the present study and thus, could not be investigated further. In winter wheat at North China Plains, 4-5 Mg ha⁻¹ of targeted yield could be achieved with significant improvement in crop WUE through supplemental irrigation (Zhang *et al.*, 2011). In the present study, yields under the limited irrigation were between 4.0-4.9 kg ha⁻¹ and thus, not far behind the yields obtained under the adequate irrigation (4.9-5.2 kg ha⁻¹). We have applied less amount of water in each irrigation and also escaped 4th irrigation to impose mild stress on the crop, which certainly had a bearing on the harvestable yields. This implies that we need to identify the growth stages at which withdrawal or reducing the amount of irrigation water might not be significantly affect the grain yield, but maximize the WUE. The harvest index was 0.37-0.46 under adequate and 0.41-0.45 under limited irrigation, indicating a scope of improving the index through moderation of water application. In the present study, soil water limitation was imposed through withdrawal of irrigation during grain filling (dough) stages, which might have led to better remobilization of carbohydrate reserves in stem and leaf sheathes (Palta *et al.*, 1994; Kang *et al.*, 2002). This is although due to regional variability in environment and agronomic practices, and need to be further explored.

A reduction in leaf area index in the limited treatment showed as early as 61 DAS, the effect on plant biomass started showing from 112 DAS. The canopy coverage followed nearly the similar

trend as in LAI. The LAI once reached to their peak values and started declining from 85-95 DAS. This is obvious that at the later stages of growth, the variation in LAI was mostly due to senescence of leaves, and not to leaf growth. The crop even at the advanced senescent stage was able to intercept much of radiation and the growth continued (biomass continued to increase even after 120 DAS).

The LAI shows an exponential response to NDVI, which in agreement to a previous study (Richardson *et al.*, 1992; Duchemin *et al.*, 2006). The NDVI saturated as LAI becomes >3.5, which does not make NDVI as a good predictor of LAI estimates in wheat, as LAI is often recorded >4.0 in well-developed canopies. It is reported that as LAI reaches a limit between 2 to 6 (depending on vegetation type), additional leaf growth (increasing in LAI) could not be depicted through NDVI (Baret and Gyrot, 1991; Hall *et al.*, 1995; Duchemin *et al.*, 2006).

Conclusions

Leaf area index and remotely sensed index NDVI relation had a good agreement, although the saturation at moderately high LAI might be a limitation. The canopy thermal environment, though suitably captured through remote sensing, a possible explanation by relating the plant water status need further attention. Application of limited irrigation has a potential to improve the water use efficiency, which requires extensive field evaluation. This is applicable to skipping irrigation at certain stages without putting any detrimental effect on crop growth and yield.

References

- Balasubramanian, P., and Palaniappan, S.P. 2001. Principles and practices of agronomy. Agrobios, Jodhpur, India.
- Bandyopadhyay, P.K., and Mallick, S. 2003. Actual evapotranspiration and crop coefficients of wheat (*Triticum aestivum*) under varying moisture levels of humid tropical canal command area. *Agric. Water Manage.* **59**: 33-47.

- Baret, F. and Guyot, G. 1991. Potentials and limits of vegetation indices for LAI and APAR assessment. *Remote Sens. Environ.* **35**: 161-173.
- Duchemin, B., Hadria, R., Er-Raki, S., Boulet, G., Maisongrande, P., Chehbouni, A., Escadafal, R., Ezzahar, J., Hoedjes, J.C.B., Kharrou, M.H., Khabba, S., Mougenot, B., Olioso, A., Rodriguez, J.-C., and Simonneaux, V. 2006. Monitoring wheat phenology and irrigation in Central Morocco: On the use of relationships between evapotranspiration, crops coefficients, leaf area index and remotely-sensed vegetation indices. *Agric. Water Manage.* **79**: 1-6.
- Gajri, P.R. 1980. Root development, water use and yield of wheat as affected by timing of small irrigation on loamy and sandy loam soil. Ph.D. Thesis submitted to Punjab Agricultural University, Ludhiana, Punjab, India.
- Hall, F.G., Townshend, J.R., and Engmann, E.T. 1995. Status of remote sensing algorithms for estimation of land surface parameters. *Remote Sens. Environ.* **51**: 138-156.
- Hanks R.J., Klute, A., and Bresler, E. 1969. Numerical method for estimating infiltration, redistribution, drainage and evaporation of water from soil. *Water Resour. Res.* **5**: 1064-1069.
- Hanks, R.J., and Ashcroft, G.L. 1980. Applied soil physics: soil water and temperature applications. In: Advanced Series in Agricultural Review 8, Springer Verlag, New York.
- Jackson, R.D. 1972. On the calculation of hydraulic conductivity. *Proc. Soil Sci. Soc. Amer.* **36**: 380-382.
- Kang, S., Zhang, L., Liang, Y., Hu, X., Cai, H., and Gu, B. 2002. Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China. *Agric. Water Manage.* **55**: 203-216.
- Klute, A. 1986. Water retention: laboratory methods. In: Klute, A. (Ed.), Methods of Soil Analysis Part-I, ASA, Monograph, Madison, Wisconsin, USA, pp. 635-662.
- Liu, C., Zhang, X., and Zhang, Y. 2002. Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. *Agric. For. Meteorol.* **111**: 109-120.
- Musick, J.T., Ordie, R.J., Bobby, A.S., and Donald, A.D. 1994. Water-yield relationships for irrigated and dryland wheat in the US Southern Plains. *Agron. J.* **86**: 980-986.
- Palta, J.A., Kobata, T., Turner, N.C., and Fillery, I.R. 1994. Remobilization of carbon and nitrogen in wheat as influenced by post anthesis water deficit. *Crop Sci.* **34**: 118-124.
- Richards, L.A. 1948. Methods of measuring soil moisture tension. *Soil Sci.* **68**: 95-112.
- Rowse, J.W., Haas R.H., Schell, J.A. and Deering, D.W. 1974. Monitoring vegetation systems in the Great Plains with ETRS. Third ETRS Symp. NASA, Sp-357, **1**: 309-317.
- Sondhi, S. K. 2001. Irrigation water saving technologies for the major agro ecologies of the Indo-Gangetic basin. In: www.waterandfood.org/gga/SK_Sondhi_WaterSaving.
- Stibbe, E. 1975. Soil moisture depletion in summer by a Eucalyptus grove in a desert area. *Agro-Ecosys.* **2**: 117-126.
- Tyagi, N.K., Sharma, D.K., and Luthra, S.K. 2000. Evapotranspiration and crop coefficients of wheat and sorghum. *J. Irrig. Drain. Engng.* **126**: 215-222.
- Wang, H.X., Zhang, L., Dawes, W.R., and Liu, C.M. 2001. Improving water use efficiency of irrigated crops in the North China Plain—measurements and modeling. *Agric. Water Manage.* **48**: 151-167.
- Zhang, X., Chen, S., Sun, H., Shao, L., and Wang Y. 2011. Changes in evapotranspiration over irrigated winter wheat and maize in North China Plain over three decades. *Agric. Water Manage.* **98**: 1097-1104.