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Relation between soil temperature and biophysical parameters in Indian mustard seeds

T. Adak[1]* *and N.V.K. Chakravarty*[2]

[1]Divison of Crop Production, CISH, Rehmankhera, Lucknow, Uttar Pradesh, India
[2]Division of Agricultural Physics, Indian Agricultural Research Institute, New Delhi, India

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A b s t r a c t. Temporal changes in surface soil temperature were studied in winter crop. Significant changes in bare and cropped soil temperature were revealed. Air temperature showed a statistically positive and strong relationship (R^2 = 0.79** to 0.92**) with the soil temperature both at morning and afternoon hours. Linear regression analysis indicated that each unit increase in ambient temperature would lead to increase in minimum and maximum soil temperatures by 1.04 and 1.02 degree, respectively. Statistically positive correlation was revealed among biophysical variables with the cumulative surface soil temperature. Linear and non-linear regression analysis indicated 62-69, 72-86 and 72-80% variation in Leaf area index, dry matter production and heat use efficiency in Indian mustard crop as a function of soil degree days. Below 60% variation in yield in Indian mustard was revealed as a function of soil temperature. In contrast, non-significant relationship between oil content and soil temperature was found, which suggests that oil accumulation in oilseed crops was not affected significantly by the soil temperature as an independent variable.

K e y w o r d s: soil temperature, Indian mustard seed, biophysical variables, cumulative soil thermal accumulation

INTRODUCTION

Soil is a key natural resource and soil temperature is one of the potential physical parameters that determines crop productivity and sustainability (Adak *et al*., 2012b; Gliński and Walczak, 1998). Soil temperature controls biological and biochemical processes in the soil which, in turn, affect soil organic matter formation, fertilizer efficiency, seed germination, plant development, plant winter survival, nutrient uptake and decomposition, and disease and insect occurrence (Jacobs *et al*., 2007; Karhu *et al*., 2010; Leifeld and Fuhrer, 2005; Vanhala *et al*., 2007; Verma *et al.*, 2011). In addition, soil temperature behaviour plays an especially important role in crop variety selection and farm management practices (Azadegan and Massah, 2011; Hartley *et al*., 2007). In arid and semi-arid zones of tropical and subtropical regions with low organic matter content and sandy in nature, soil moisture retention and soil thermal regulation is an important aspect of crop establishment as high soil heat stress may damage seedling emergence and root growth, and thereby crop growth and development (Adak *et al*., 2012a; Meena *et al*., 2012). Under normal conditions, farmers try to regulate soil heat balance by applying irrigation, mulching, improving drainage condition and adding organic fertilizers in order to prevent reflection of heat from soil, to preserve heat and soil moisture and to provide appropriate temperature for seed germination (Nabi and Mullins, 2008; Shekhawat *et al*., 2012; Zhang *et al*., 2007). Inadequate soil temperature delays germination, which results in retarded maturity and reduces the quality and quantity of the product.

Surface soil temperature undergoes spatiotemporal changes during crop growing season across land use management systems (Adak *et al*., 2011; Muçaj, 2005; Oliveira *et al*., 2001; Wada *et al*., 2006). Those changes are possible and their quantification is necessary to avoid any adverse effect of soil temperature to crop growth and development. Even a small rainfall event may change the hydrothermal regime in a way that may be suitable for crop growth and development. In the literature, however, soil temperature study is generally more employed in energy budgeting across different land use systems under various agroecology (Heusinkveld *et al*., 2004; Holmes *et al*., 2012; Hu and Feng, 2003; Sándor and Fodor, 2012) and soil related applications, for example, effect of soil temperature on pesticide degradation (Paraíba *et al*., 2003), soil microclimate under various tree stands (Johnson-Maynard *et al*., 2004), energy and water

*Corresponding author e-mail: tarunadak@gmail.com

budgeting of a river basin (Li *et al*., 2009) and determining soil thermal properties from soil moisture content (Usowicz and Kossowki, 1999). However, there are a limited number of soil temperature studies, particularly concerning its accumulation over crop growing season and the functional relationship of soil temperature with plants biophysical parameters under semiarid agroecosystem. For both biological and agricultural reasons, it was interesting to analyze the soil temperature data to find typical characteristics of a particular soil thermal environment that exits under a given agroclimatic zone within the boundary layer of soil-plant-atmosphere.

MATERIALS AND METHODS

Field experiments were conducted during two consecutive winter seasons, 2005-2007, at the experimental research farm of the Indian Agricultural Research Institute, New Delhi (28°35' N, 77°12' E). The soil was a Typic Ustocrepts soil under Gangetic Alluvium with sandy clay loam texture, having 0.47% organic carbon, 0.45 dS m^{-1} EC, 1.54 Mg m^{-3} bulk density and 0.9 cm h^{-1} saturated hydraulic conductivity. The experiment was laid out in a randomized block design with three replications and twelve treatments (two sowing dates: 15th and 30th October, three debranching/ defoliation treatments applied in two cultivars of Indian mustard (*Brassica juncea*) viz Pusa Jaikisan and BIO169-96) in a 5 × 5 m plot with row-to-row spacing of 45 cm and plant-to-plant distance of 15 cm. Sowing dates were chosen keeping in view the farmers practice that prevailed in the north and north-western parts of the country; advanced/ delayed by a 15 days or so due to delay in harvesting of previous crop. The defoliation treatment was applied at the flowering (D1) and pod filling (D2) stages, including one control plot (D0) without removing branches. Ammonium sulphate 40 kg N ha^{-1} was applied as basal dose, and urea 40 kg N ha^{-1} was applied as top dressing after first irrigation. Single super phosphate 40 kg P_2O_5 ha^{-1} and muriate of potash 40 kg K_2O ha^{-1} were also applied as basal dose as per recommendation, during disking at the time of seed-bed preparation. Sowings were done with hand drill, maintaining a row-to-row spacing of 45 cm and seed rate of 6 kg ha^{-1} was maintained. Thinning was done manually between 20 to 25 days after sowing to maintain plant-to-plant distance of 15 cm. Weeding was done manually in each plot as and when needed.

Surface soil temperature was measured at 5 cm soil depth using platinum resistance thermometers. Digital logger was used to record the temperature. The instrument was continuously recording soil temperature. However, to prevent over-parameterization and lag time of soil temperature with depths, weekly average soil temperature was reported at 7:30 and 14:30. This weekly average soil temperature was then cumulated over weeks to determine soil heat accumulation:

$$\text{Soil heat accumulation} = \sum_{i=n}^{i=1} \left\{ \frac{ST_{\max} + ST_{\min}}{2} - ST_{\ base} \right\}$$

where: n – number of days in the season, $ST_{\max}$, $ST_{\min}$ are the weekly maximum and minimum surface soil temperatures, and *ST* base is the base temperature of 5°C. These surface soil temperatures were correlated with the biophysical parameters (LAI, dry biomass production and partitioning along with heat use efficiency) cumulated up to maximum/ peak values to establish the functional relationship with cumulative soil temperature. Three randomly selected plant samples (aboveground) were taken and the leaf area was measured using leaf area meter (model LICOR-3100, Lincoln, NE, USA). The LAI was calculated using the formula: LAI = measured leaf area per plant (cm^2)/ground area covered by the plant (cm^2). The samples collected for estimating leaf area index were utilized for assessing the biomass production. The average seed yield (10^2 kg ha^{-1}) was calculated. Oil content (per cent) of the seeds was measured using low resolution pulsed H1 NMR (model No. PC20 Bruker, frequency – 20 MHz) in the Nuclear Research Laboratory, IARI, New Delhi. Heat use efficiency was calculated (dry matter production/growing degree days) to evaluate the functional relationship between soil degree days with heat utilisation capacity of the crops.

Statistical analysis viz, computation of correlation coefficients, linear and non-linear regression analysis, ANOVA, multiple correlation coefficients were carried out using Excel and SPSS packages (Version 12.0). Regression equations were fitted through the origin. This procedure gives the best estimates of the average biophysical parameters over the treatments. The required graphs were drawn using MS Excel/Power Point software packages.

RESULTS AND DISCUSSION

The weather analysis during crop growing season indicated that monthly mean ambient temperature varied from 12.8 to 25.6°C and mean relative humidity was around 65%. Total rainfall received was more in second season, highest pan evaporation of 7.4 mm and maximum bright sunshine hours of 8 h were observed. Mean monthly incoming shortwave radiation was found to be ranged between 10.2 and 22.4 MJ m^{-2} day^{-1}.

Temporal variations in soil and air temperatures. Mean minimum and maximum soil temperatures along with their statistical analysis are presented in Table 1. The soil temperature dynamics within the two cultivars and sowing dates in two seasons indicated that there were indeed variations in minimum as well as maximum soil temperatures. However, pooled data showed that the magnitude of the variations varied from 0.01 to 0.5°C among the treatments. Analysis of these pooled data was required to reduce the seasonal effects. Mean maximum soil temperature was higher by about 4.79 to 8.44, 5.29 to 8.93 and 5.49 to 8.58°C in D0, D1 and D2 treatments as compared to mean minimum temperatures.

Table 1. Statistical analysis of spatiotemporal variation in minimum (morning) and maximum (afternoon) soil temperature

Days after sowing	Mean	Standard deviations	Variance	CV%	SEm	Kurtosis	Skewness
			Morning				
			D0				
33	12.88	2.42	5.85	18.78	0.73	-1.76	-0.46
40	12.10	1.90	3.60	15.67	0.45	-2.20	0.02
47	10.38	2.24	5.03	21.60	0.63	-0.46	-0.61
54	10.51	1.56	2.42	14.82	0.30	-0.73	-0.64
61	9.71	1.40	1.95	14.37	0.24	-0.38	-0.93
68	8.92	1.45	2.10	16.26	0.26	-1.34	-0.22
75	8.92	1.40	1.97	15.73	0.25	-1.82	-0.70
82	9.42	1.48	2.20	15.75	0.28	-1.19	-0.42
89	9.37	1.62	2.63	17.30	0.33	-0.79	0.26
96	11.48	1.94	3.78	16.94	0.47	-0.08	0.25
103	12.29	3.11	9.68	25.32	1.21	-0.26	0.46
110	15.17	2.81	7.88	18.50	0.98	-0.74	0.43
117	16.45	2.43	5.92	14.79	0.74	-1.10	-0.48
124	18.27	1.48	2.19	8.10	0.27	-0.87	0.02
			D1				
33	12.59	2.39	5.70	18.96	0.71	-2.19	-0.11
40	11.74	1.96	3.86	16.74	0.48	-1.47	0.44
47	10.01	2.38	5.66	23.78	0.71	-0.63	0.17
54	10.28	1.38	1.90	13.42	0.24	0.10	0.49
61	9.45	1.56	2.42	16.48	0.30	0.17	-0.32
68	9.00	1.58	2.50	17.57	0.31	-0.61	-0.59
75	8.82	1.46	2.12	16.51	0.26	-1.49	-0.58
82	9.38	1.44	2.09	15.39	0.26	-1.10	-0.57
89	9.17	1.78	3.17	19.43	0.40	-1.40	0.15
96	11.46	1.74	3.03	15.20	0.38	-0.22	0.27
103	12.31	3.04	9.23	24.69	1.15	-0.41	0.39
110	14.86	2.63	6.92	17.71	0.87	-0.99	0.44
117	16.58	2.36	5.56	14.23	0.70	-1.18	-0.66
124	18.31	1.46	2.12	7.96	0.27	-0.54	-0.31
			D2				
33	12.83	2.35	5.50	18.29	0.69	-1.36	-0.61
40	12.02	2.08	4.31	17.26	0.54	-2.12	0.22
47	10.40	2.45	5.98	23.52	0.75	-0.75	-0.12
54	10.13	1.23	1.52	12.18	0.19	-0.21	0.83
61	9.21	1.60	2.57	17.42	0.32	-0.50	-0.69
68	8.87	1.85	3.42	20.84	0.43	-0.62	-0.57
75	8.67	1.80	3.23	20.72	0.40	-0.87	-0.52
82	8.99	1.52	2.31	16.91	0.29	-0.90	-0.64

T a b l e 1. Continuation

Days after sowing	Mean	Standard deviations	Variance	CV%	SEm	Kurtosis	Skewness
89	8.99	1.99	3.94	22.10	0.49	-1.19	0.40
96	11.36	1.58	2.51	13.94	0.31	-0.97	-0.41
103	12.10	3.06	9.39	25.33	1.17	-0.72	0.19
110	14.87	2.70	7.30	18.17	0.91	-1.31	0.53
117	16.48	2.36	5.55	14.30	0.69	-0.69	-0.71
124	18.59	1.83	3.35	9.84	0.42	-0.89	0.27
Afternoon							
D0							
33	20.23	1.61	2.58	7.95	0.32	-0.31	-1.18
40	20.54	1.22	1.49	5.94	0.19	1.32	1.28
47	18.45	1.98	3.93	10.75	0.49	-0.69	-0.46
54	17.19	2.08	4.32	12.10	0.54	-1.66	-0.30
61	16.42	1.23	1.52	7.50	0.19	-0.18	0.76
68	14.28	1.53	2.35	10.74	0.29	-1.73	0.54
75	14.88	1.78	3.18	11.98	0.40	-0.26	-0.52
82	14.95	2.90	8.40	19.38	1.05	-1.19	0.64
89	15.31	1.72	2.97	11.26	0.37	0.76	-1.27
96	17.23	2.26	5.12	13.13	0.64	1.78	-0.59
103	17.77	3.24	10.51	18.24	1.31	-0.41	0.60
110	19.95	2.06	4.24	10.32	0.53	1.66	1.07
117	22.23	2.43	5.89	10.92	0.74	1.21	0.03
124	24.01	1.97	3.89	8.22	0.56	3.30	-1.25
D1							
33	20.19	1.94	3.76	9.61	0.47	-1.12	-0.63
40	20.67	1.72	2.97	8.34	0.37	-1.08	0.60
47	18.61	1.60	2.55	8.59	0.32	-0.30	0.42
54	17.54	1.92	3.70	10.97	0.46	-1.94	-0.17
61	16.63	1.42	2.03	8.57	0.25	-1.01	-0.22
68	14.53	1.36	1.86	9.40	0.23	-1.42	0.29
75	15.15	1.62	2.62	10.68	0.33	-1.56	0.16
82	15.21	2.85	8.12	18.73	1.01	-1.32	0.69
89	15.50	1.70	2.88	10.95	0.36	3.89	-1.65
96	17.24	2.51	6.32	14.58	0.79	0.92	-0.72
103	17.83	3.44	11.82	19.28	1.48	-1.05	0.35
110	20.15	2.12	4.52	10.55	0.56	1.95	1.24
117	22.30	2.45	5.99	10.97	0.75	0.75	0.06
124	24.31	2.10	4.41	8.64	0.63	3.32	-1.38

T a b l e 1. Continuation

Days after sowing	Mean	Standard deviations	Variance	CV%	SEm	Kurtosis	Skewness
				D2			
33	19.76	1.85	3.01	9.38	0.38	-0.53	-1.08
40	20.60	1.35	1.59	6.54	0.20	-1.18	0.42
47	18.49	2.14	4.01	11.58	0.50	-0.07	0.37
54	17.41	2.36	4.86	13.54	0.61	-1.32	-0.58
61	16.66	1.35	1.60	8.12	0.20	-0.97	-0.46
68	15.12	1.23	1.32	8.11	0.16	-1.09	0.22
75	15.86	2.10	3.88	13.27	0.48	-0.85	-0.19
82	15.74	2.94	7.57	18.68	0.95	-1.43	0.62
89	15.90	1.61	2.26	10.10	0.28	-0.52	-0.99
96	17.45	2.02	3.57	11.58	0.45	0.58	-0.70
103	18.33	2.73	6.51	14.89	0.81	-0.78	0.46
110	20.48	2.04	3.65	9.97	0.46	1.63	1.13
117	22.47	2.30	4.65	10.26	0.58	1.38	0.33
124	24.09	1.99	3.38	8.25	0.48	2.42	-1.27

D0, D1, D2 – stand for: control plot, defoliation treatment at the flowering and pod filling stages respectively; SEm – standard error of mean.

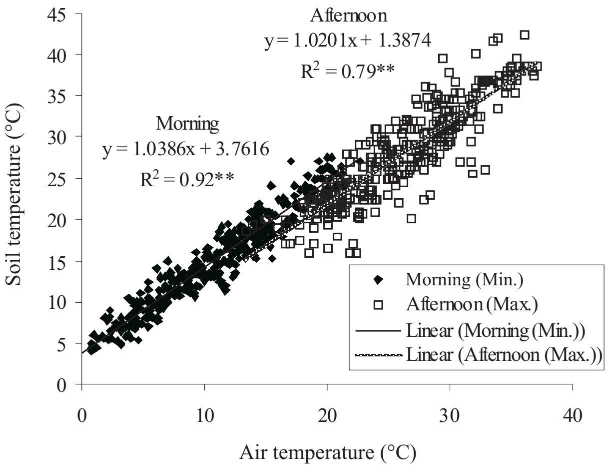

Fig. 1. Functional relationship between air and bare soil temperature (n = 846) at morning and afternoon hours during crop growing season (2005-2007).

It is of interest to relate the significant changes in soil temperature to ambient temperature. In fact soil temperatures are normally impacted by surface characteristics and turbulent and radiative energy balance in which incoming solar radiation, temperature and other variables are relevant. Here we relate the soil temperature to the ambient one (Fig. 1) and it was revealed that there was indeed a positive and significant correlation between the two factors. The linear trend (n = 846) results in soil temperature = 1.0386 × air temperature + 3.7616 with a coefficient of determination of R^2 = 0.92**, which means that each unit increase in ambient temperature would lead to increase in minimum soil temperature by 1.0386 unit while maximum soil temperature by 1.02 (soil temperature = 1.0201 × air temperature + 1.3874, R^2 = 0.79**). This means that the heat capacity of soil is indeed dependent on the ambient temperature, apart from soil intrinsic factors, and normally was in equilibrium under given atmospheric condition; any change in air temperature would certainly cause increase in soil heat accumulation over periods and thereby soil thermal regimes. The time variable soil heat accumulation was thus calculated to assess its range over the crop growing season and an increasing trend was found as growth stages advanced, starting from the seedling emergence. The cumulative value initially started from 10°C day and finally attained its maximum value at around 200°C day. The progressive heat accumulations were pooled (Fig. 2a), correlated with time variables and could be predicted by linear regression equations of the following type.

Soil thermal accumulation /soil degree days = 1.0889 ×air temperature (R^2 = 0.89**).

During the experimental period, the sum of around 1600 degree-days was observed, and when the soil thermal accumulation was plotted against ambient heat accumulation, a significant linear trend was observed (Fig. 2b).

Correlation among biophysical variables with soil degree days. The functional relationship of soil thermal accumulation with the biophysical variables like leaf area index (LAI) and dry biomass (DM), up to its maximum peak value,

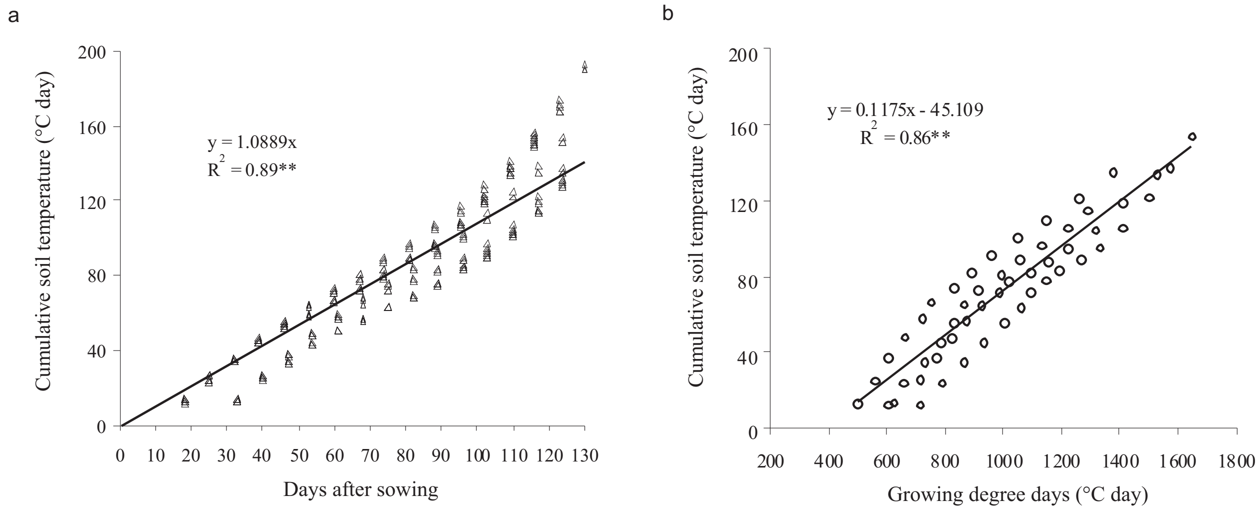

Fig. 2. Time variable soil heat accumulation (a) and its relation with ambient heat accumulation over growing season (b).

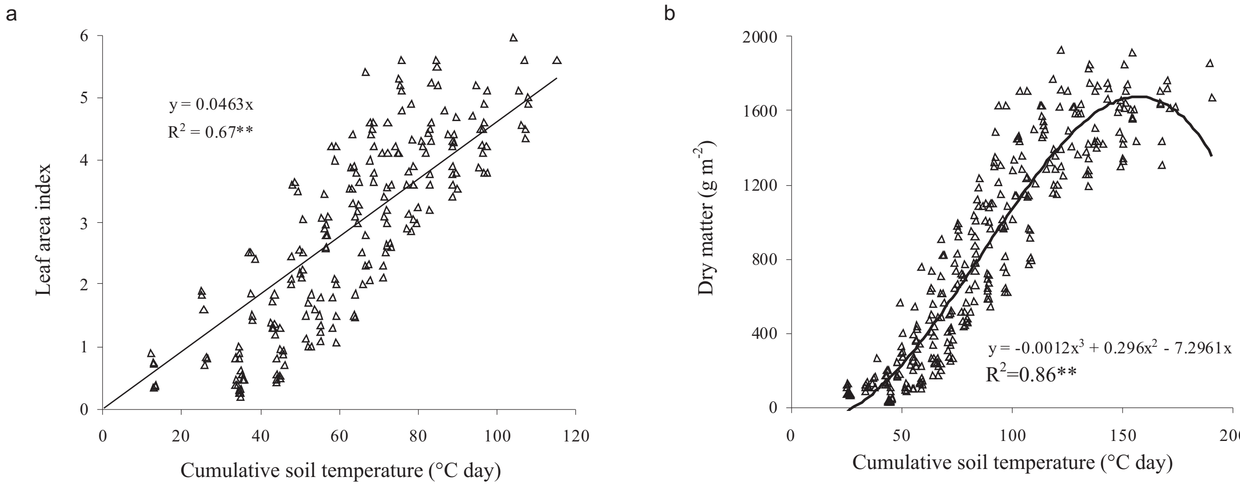

Fig. 3. Prediction of leaf area index (a) and dry matter production (b) with soil heat accumulation.

was established through linear regression analysis. Since differences in varietal response were observed even under similar hydrothermal regimes, owing to variation in crop geometry, pooled data of LAI and DM were used in this correlation. We observed statistically significant and positive correlation among the variables. It was inferred that the cumulative soil temperature could explain 67% of the variations in LAI (Fig. 3a). Thus, on average, around 67% of the variation in LAI could be explained through differential rate of soil temperature accumulation during the crop growing season. Statistically significant and positive regression models indicated the possibility of predicting small scale changes in LAI as a function of soil degree days. Regression equations were fitted through the origin. This procedure gives the best estimates of the average LAI over the treatments. Therefore, cutting across the treatments, the prediction model developed to predict the LAI was as follows:

$$\text{LAI} = 0.0463 \times \text{soil degree days} \ (n = 220,\ R^2 = 0.67^{**}).$$

In order to quantify the differential DM production in Indian mustard as a function of soil thermal accumulation, it was found that the heat accumulating in soil over crop growing season could explain around 86% of the variability in DM (Fig. 3b). Since dry matter production showed a sigmoid trend in crop cycles, best fit polynomial third order regression equations were developed. The regression equations were fitted through the origin as this procedure gives best estimates of the average DM over the years. Henceforth, cutting across the treatments, the third order prediction model developed to predict the DM was as follows:

$$\text{DM (g m}^2\text{)} = -0.0012x^3 + 0.296x^2 - 7.2961x \ (n=320,\ R^2=0.86^{**})$$

where x = soil degree days.

The linear and polynomial regression models thus developed for Indian mustard may also be used for other related oilseed Brassica for the prediction of biophysical

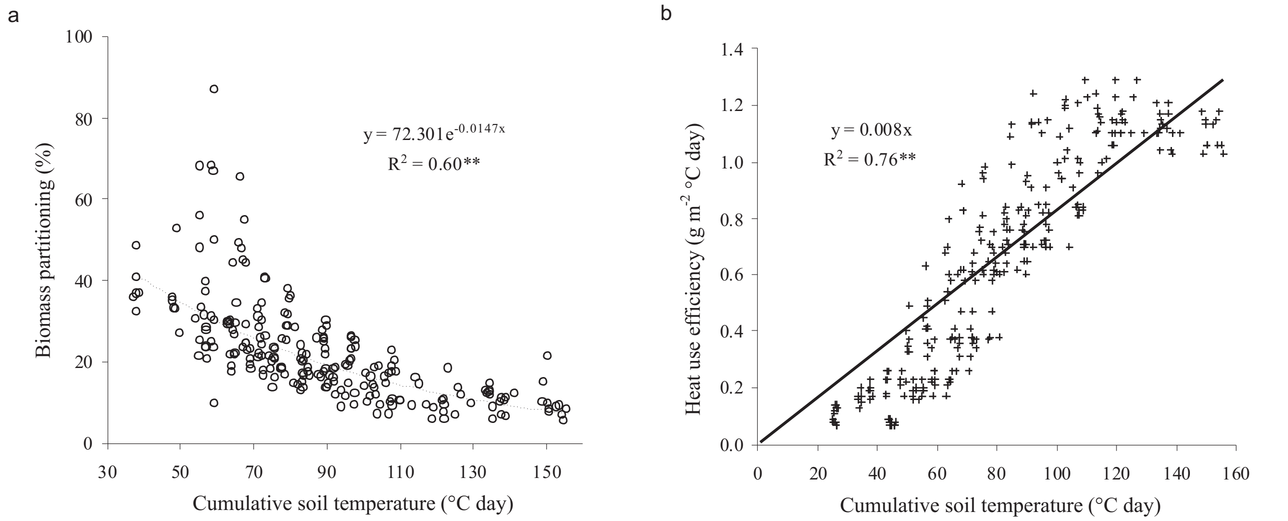

Fig. 4. Correlation of: a – biomass partitioning and b – heat use efficiency with soil heat accumulation.

T a b l e 2. Linear and non-linear regression models for predicting leaf area index, dry matter production and heat use efficiency in Indian mustard as a function of cumulative soil temperature

Models		R^2	R
	LAI		
Linear	$y = 0.0463x$	0.67	0.82
Polynomial	$y = 0.0002x^2 + 0.0329x$	0.69	0.83
Logarithmic	$y = 2.8214 \ln(x) - 8.6437$	0.62	0.79
Exponential	$y = 0.3727e^{0.0284x}$	0.63	0.79
Power	$y = 0.006x^{1.4561}$	0.62	0.79
	DM		
Linear	$y = 10.046x$	0.75	0.87
Polynomial	$y = -0.0012x^3 + 0.296x^2 - 7.2961x$	0.86	0.93
Logarithmic	$y = 1102.8 \ln(x) - 4006.4$	0.80	0.89
Exponential	$y = 73.323e^{0.0231x}$	0.72	0.85
Power	$y = 0.0915x^{1.9911}$	0.80	0.89
	HUE		
Linear	$y = 0.0083x$	0.76	0.87
Polynomial	$y = 0.0002x^2 + 0.0067x$	0.77	0.88
Logarithmic	$y = 0.7762 \ln(x) - 2.7033$	0.79	0.89
Exponential	$y = 0.088e^{0.0214x}$	0.72	0.85
Power	$y = 0.0004x^{1.6813}$	0.80	0.89

variables like LAI and DM across diverse agro ecological regions. Such information may be used as an input parameter in dynamic crop simulation models wherein soil thermal regimes should be considered for enhancing the efficacy of the model towards its accurate estimate of plant biophysical parameters. Moreover, biomass partitioning was found to be best fitted in an exponential curve and heat use efficiency followed a linear trend (Fig. 4).

Linear and non-linear statistical analysis also confirmed that indeed there was a positive and significant correlation between mustard crop biophysical variables with that of soil heat accumulation over its growing cycle (Table 2).

Economic yield and oil content of oilseed crops are generic in nature. Response of same or different genotypes under similar hydrothermal regimes may differ. Influence of soil thermal regime in impacting economic sinks may not be

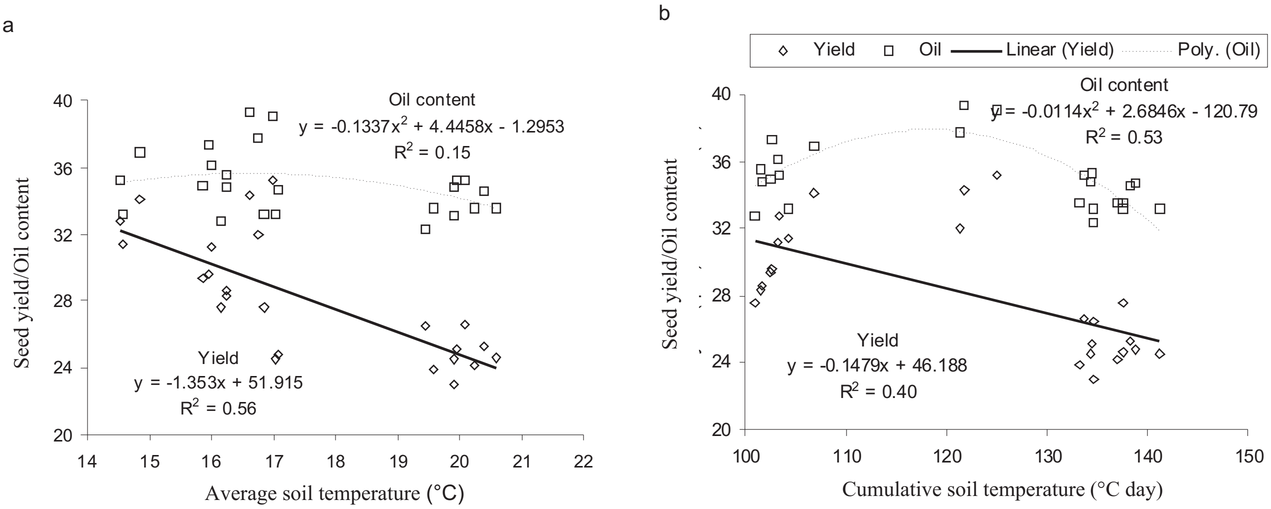

Fig. 5. Functional relationship among yield (10^2 kg ha^{-1}) and oil content (%) with: a – average and b – cumulative soil temperature.

of any statistical significance but the variability may be revealed. Henceforth, the concept of soil thermal accumulation was applied to evaluate the variability and it was observed that 40 and 53% of the variations in yield and oil content could be explained through cumulative soil temperature, respectively (Fig. 5), while average soil temperature showed 53% variations in yield and a lower non-significant oil content of 15% only. Thus, <60% variation in yield prediction in Indian mustard was revealed as a function of soil temperature. In contrast, non-significant relationship between oil content and soil temperature was found. The results suggest that oil accumulation in oilseed crops may not be affected significantly by the surface soil temperature as an independent variable.

CONCLUSIONS

1. Air temperature showed a statistically positive and strong relationship (R^2 = 0.79** to 0.92**) with the soil temperature both at morning and afternoon hours, indicating the fact that if air temperature is going to change over periods, it will have an impact on soil temperature also.

2. Linear regression analysis indicated that each unit increase in ambient temperature would lead to increase in minimum and maximum soil temperatures by 1.04 and 1.02 degree, respectively.

3. Soil thermal accumulation showed a significant and positive correlation against ambient heat accumulation with a correlation coefficient of R = 0.93**.

4. Cumulative surface soil temperature could indicate 67 and 8% variation in biophysical parameters, leaf area index and dry matter production, respectively.

5. Dry matter production showed a sigmoid trend, biomass partitioning was found to be best fitted in exponential curve, and heat use efficiency of oilseed Brassica under semiarid tropics condition followed a linear trend.

6. Linear and non-linear statistical analysis confirmed that indeed there was a positive and significant correlation between mustard crop biophysical variables with that of soil heat accumulation over its growing cycle.

7. Below 60% variation in yield in Indian mustard was revealed as a function of soil temperature. In contrast, non-significant relationship between oil content and soil temperature was found, which suggests that oil accumulation in oilseed crops was not affected significantly by the soil temperature as an independent variable.

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