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Soil heat flux under irrigated, partially irrigated wheat and bare vertisol in relation to varying soil moisture and leaf area index at Pune

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सार – सिंचित और आँशिक रूप से सिंचित गेहूँ और अनावृत काली वर्टिसॉल दोनों के शुष्क होने के चक्रों में नमी के अंश की क्रिया के रूप में मृदा उष्मा फलक्स का अध्ययन पर्ण क्षेत्र सूचकांक (एल.ए.आई.) मृदा जल अंश और मौसम वैज्ञानिक प्राचलों में परिवर्तन के लिए मृदा ऊष्मा फलक्सों में स्थानिक परिवर्तन से संबद्ध करने के लिए किया गया है। आँशिक रूप से सिंचित भूखंड में जब सिंचाई नहीं होती है उस समय धरातल की सतह पर आर्द्रता के अंश का भार 1–5 प्रतिशत और उपधरातल सतहों पर इसका भार 5–10 प्रतिशत तक नीचे गिर जाता है। इस अर्द्धशुष्क क्षेत्र में फसल संवर्द्धन मौसम के दौरान चरम साप्ताहिक माध्य भूमंडल नेट और परावर्तित विकिरण वर्ष 1996–97 में क्रमशः 655, 361 और 179 डब्ल्यू.एम.$^{-2}$ और वर्ष 1997–98 में क्रमशः 700, 366 और 137 डब्ल्यू.एम.$^{-2}$ तक पहुँच जाता है। सिंचित अवस्थाओं में 1430 बजे धरातल सतह (5.0 सें.मी.) पर मृदा का तापमान 27 से 40° से. के बीच होता है। शुष्कता चक्र के दौरान आँशिक रूप से सिंचित गेहूँ में धरातल और उपधरातल सतहों में यह क्रमशः 7 से 10° से. और 2 से 3° से. अधिक होता है। सिंचित अवस्था में ऊपरिमुखी मृदा उष्मा फलक्स 0730 बजे भा.मा.स. पर –3.3 से –29.7 डब्ल्यू.एम.$^{-2}$ के बीच होता है। जबकि अधोमुखी उष्मा फ्लक्स 1430 बजे 8.4 से 33.9 डब्ल्यू.एम.$^{-2}$ के बीच होता है। आँशिक रूप से सिंचित अवस्था में यह 0730 बजे यह –0.7 से –9.2 डब्ल्यू.एम.$^{-2}$ और 1430 बजे यह 10.4 से 20.9 डब्ल्यू.एम$^{-2}$ हो जाता है। जबकि अनावृत मृदा में यह 0730 बजे –4.2 से –17.6 डब्ल्यू.एम.$^{-2}$ तक और 1430 बजे भा.मा.स. के अनुसार 6.7 से 24.7 डब्ल्यू. एम.$^{-2}$ तक हो जाता है। सिंचित, आँशिक रूप से सिंचित और अनावृत्त मृदा की 5–20 सें.मी. मृदा की गहराई में अधिकतम माध्य उष्मा फलक्स वर्ष 1996–97 और 1997–98 में क्रमशः 10.2, 5.0 और 6.5 डब्ल्यू.एम.$^{-2}$ तथा 9.2, 7.1 और 6.7 डब्ल्यू.एम.$^{-2}$ थे। सिंचित गेहूँ और अनावृत वर्टिसॉल दोनों के लिए 1430 बजे मृदा का तापमान और आँशिक रूप से सिंचित गेहूँ में 0730 बजे मृदा के तापमान वाले भूमंडलीय विकिरण मृदा उष्मा फ्लक्स के लिए सबसे अच्छे पूर्वसूचक साबित हुए हैं। एल.ए.आई. और अन्य मौसम विज्ञान संबंधी प्राचलों सहित गहराई के विभिन्न अंतरालों पर मृदा उष्मा फ्लक्स और मृदा के जल के अंश के बीच के संबंधों का उपयोग सिंचित और आँशिक रूप में सिंचित गेहूँ तथा अनावृत वर्टिसॉल दानों के मृदा उष्मा फ्लक्स के आकलन हेतु किया जा सकता है।

ABSTRACT. Soil heat flux as a function of moisture content in the drying cycles both under irrigated and partially irrigated wheat and in bare black vertisol was studied to relate temporal changes in soil heat fluxes to changes in leaf area index (LAI), soil water content and meteorological parameters. Moisture content dropped as low as 1 to 5 percent by weight at surface layer and 5 to 10 percent by weight at subsurface layers when irrigation was shut off under partially irrigated plot. The peak weekly mean global, net and reflected radiation during the crop growing season in this semi-arid region goes as high as 655, 361 and 179 Wm^{-2} respectively in the year 1996-97 and 700, 366 and 137 Wm^{-2} respectively during the year 1997-98. Soil temperature at 1430 hours IST ranged from 27 to 40°C at the surface (5.0 cm) layer under irrigated condition. It was 7 to 10° C and 2 to 3° C higher in the surface and subsurface layers respectively under partially irrigated wheat during the drying cycle. The upward soil heat flux ranged from -3.3 to -29.7 Wm^{-2} at 0730 hours IST, whereas downward heat flux at 1430 hours IST ranged between 8.4 to 33.9 Wm^{-2} under irrigated condition. Under partially irrigated condition it varied from -0.7 to -9.2 Wm^{-2} at 0730 hours IST and from 10.4 to 20.9 Wm^{-2} at 1430 hours IST; whereas it varied from -4.2 to -17.6 Wm^{-2} at 0730 hours IST and 6.7 to 24.7 Wm^{-2} at 1430 hours IST, under bare soil. The maximum mean heat fluxes into 5-20 cm soil depth under irrigated, partially irrigated and the bare soil were 10.2, 5.0 and 6.5 Wm^{-2} and 9.2, 7.1, and 6.7 Wm^{-2} respectively in the years 1996-97 and 1997-98. Soil temperature at 1430 hours IST both for irrigated wheat and bare vertisol and global radiation with soil temperature at 0730 hours IST under partially irrigated wheat were found to be the best predictors of soil heat flux. The relationships between soil heat flux and soil water content at different depth intervals along with LAI and other meteorological parameters could be used for estimation of soil heat flux, both for irrigated and partially irrigated wheat and bare soil.

Key words – Soil heat flux, Soil moisture, Wheat, Vertisol.

1. Introduction

Wheat though grown mostly under irrigated condition, yet it is also grown in many parts of the world with one or two irrigations under limited water resources. During the developmental stages, it provides varying density of vegetative surface, influencing the radiation and energy budget of the land. Evapotranspiration (ET) being the main process of dissipating radiant energy causes considerable variation in the energy balance components from well-irrigated to partially irrigated wheat where ET is much less. The rates are significantly lower under grass lands, barren lands and even from forest areas (Kelliher, *et al.* 1993) compared to that of irrigated wheat. In spite of the important role of wheat canopy with respect to energy balance components in the vertisol situated in the semi-arid tropics of India, relatively few continuous records of the surface energy balance for this soil at Pune are currently available.

Soil heat flux is one of the most important energy balance components. Under a given soil-water-plant continuum the soil profile temperatures and heat flux may influence the pattern of soil moisture (Rosenberg, 1974). The soil heat flux at surface and sub-surface layers can give a good indication of the evaporation (Gardner and Hanks, 1966). Thus studies on soil heat flux under varying soil moisture regimes in wheat and bare soil will be useful in understanding energy balance components in semi-arid tropics where soil temperature below the canopy and in bare soil vary considerably during the growing season.

The latent (λE) and sensible (H) heat fluxes are greatly modified due to variation of leaf area index (LAI) and is also influenced by soil moisture and soil as well as leaf surface conditions (Kelliher, *et al.* 1993; Schulze, *et al.* 1994). Under a deficit soil moisture condition such fluxes are also affected due to variation of partitioning of available energy under varying LAI. Though the changes of these dynamics is expected with increasing variation of LAI and soil moisture, yet hardly a few data describing the effects of lower LAI and soil moisture on energy fluxes under drying cycles are available. Thus an attempt has been made in this study to investigate the relationships between canopy development of fully irrigated and partially irrigated wheat and the soil heat flux in relation to soil moisture, LAI and meteorological parameters.

2. Methodology

Weekly soil temperature and soil moisture data recorded under irrigated, partially irrigated wheat and bare soil have been used for computing the soil heat flux. The wheat crop (Raj 1555 and NI 1947) were sown in vertisol at Pune on 2 December 1996 and 19 November 1997 respectively in the years 1996-97 and 1997-98 and harvested on 28 March 1997 and 9 March 1998 respectively.

The soil is medium deep vertisol of about 100 cm depth with 54.4, 15.5, 30.1 percent clay, silt and sand respectively. Bulk density of the soil is 1 .04 g cm^{-3}. The average maximum available water holding capacity of the soil is 150 mm with field capacity and wilting point moisture content of 33.0 and 16.5 percent by weight respectively. The soil is fertile having nitrogen, phosphorus and potash content as 173, 13.5 and 263 kg/ha. The soil is slightly alkaline in nature (pH = 7.8) with organic matter 1.1%.

The crop was grown in the field of College of Agriculture, Pune, adjacent to Central Agromet Observatory, IMD, Pune. The soil temperature data for 5 cm and 20 cm depths recorded daily twice at 0730 hrs IST and 1430 hrs have been used for computation of soil heat flux (G) using the equation:

$$G = -K\,(dT/dZ)$$

$$= -K\,(T_2-T_1)/(Z_2-Z_1)$$

$$= K\,(T_1-T_2)/(Z_2-Z_1)$$

Where K is thermal conductivity and T_1 and T_2 are the soil temperatures at 05 cm (Z_1) and 20 cm (Z_2) depths. The thermal conductivity (K) for irrigated (wet) and bare (dry) soil have been considered 58.6 & 10.5 Wm^{-2} respectively. In this study gradual increase in conductivity with increase in soil moisture content in dry soil was considered for different ranges of soil moisture following Nakshabandi and Kohnke, 1965. Soil moisture data has been used for calculating soil water content in the soil profile at 0-10, 0-20, 0-42.5 and 0-80 cm depths. Continuous record of net, global and reflected radiation were made using Net Pyrradiometers and Pyranometers respectively installed in irrigated, partially irrigated wheat and bare plot keeping sensors at 1.2 m above the canopy and ground respectively. Weekly leaf area index (LAI) was calculated by measuring area of sample leaves by leaf area meter from 1 m × 1 m plots. Irrigation was shut-off just before the commencement of flowering of the partially irrigated wheat crop from 8 week after sowing (WAS).

TABLE 1

Mean meteorological parameters and their departure from normal along with particulars of sowing, harvesting and yield of wheat

S. No.	Parameters	1996-97				1997-98			
		Nov	Dec	Jan	Feb	Nov	Dec	Jan	Feb
1.	Rainfall (mm)	3.6	0	2.4	0	166.4	68.9	0	0
	Departure (%) from normal	12	-	120	-	574	1378	-	-
2.	Rainy days	1	0	0	0	8	4	-	-
	Departure from normal	-	-	-	-	6	3.6	-	-
3.	Mean maximum temperature (°C)	29.9	28.4	28.2	31.2	30.9	28.8	29.5	30.6
	Departure from normal	-0.9	-1.7	-2.5	-1.7	0.1	-1.3	-1.2	-2.3
4.	Mean minimum temperature (°C)	12.8	11.2	10.1	9.6	18.6	15.1	12.4	12.3
	Departure from normal	-2.2	-0.8	-1.9	-3.7	3.6	3.1	0.4	-1
5.	Relative humidity (%)								
	Hour-I	82	85	87	76	87	94	94	79
	Departure from normal	9	10	13	12	14	19	20	15
	Hour-II	43	39	35	25	61	55	42	31
	Departure from normal	3	4	5	2	21	20	12	8
6.	No. of days of fog	Nil	Nil	2	Nil	10	19	27	1
7.	BSS(total)	278.7	254.8	270.8	286.8	229.9	252.7	278.8	275.1
8.	Date of sowing	2 December 1996				19 November 1997			
9.	Date of harvest	28 March 1997				9 March 1998			
10.	Mean yield (kg/ha)								
	Irrigated plot	3750				2976			
	Partially irrigated plot	2659				2485			

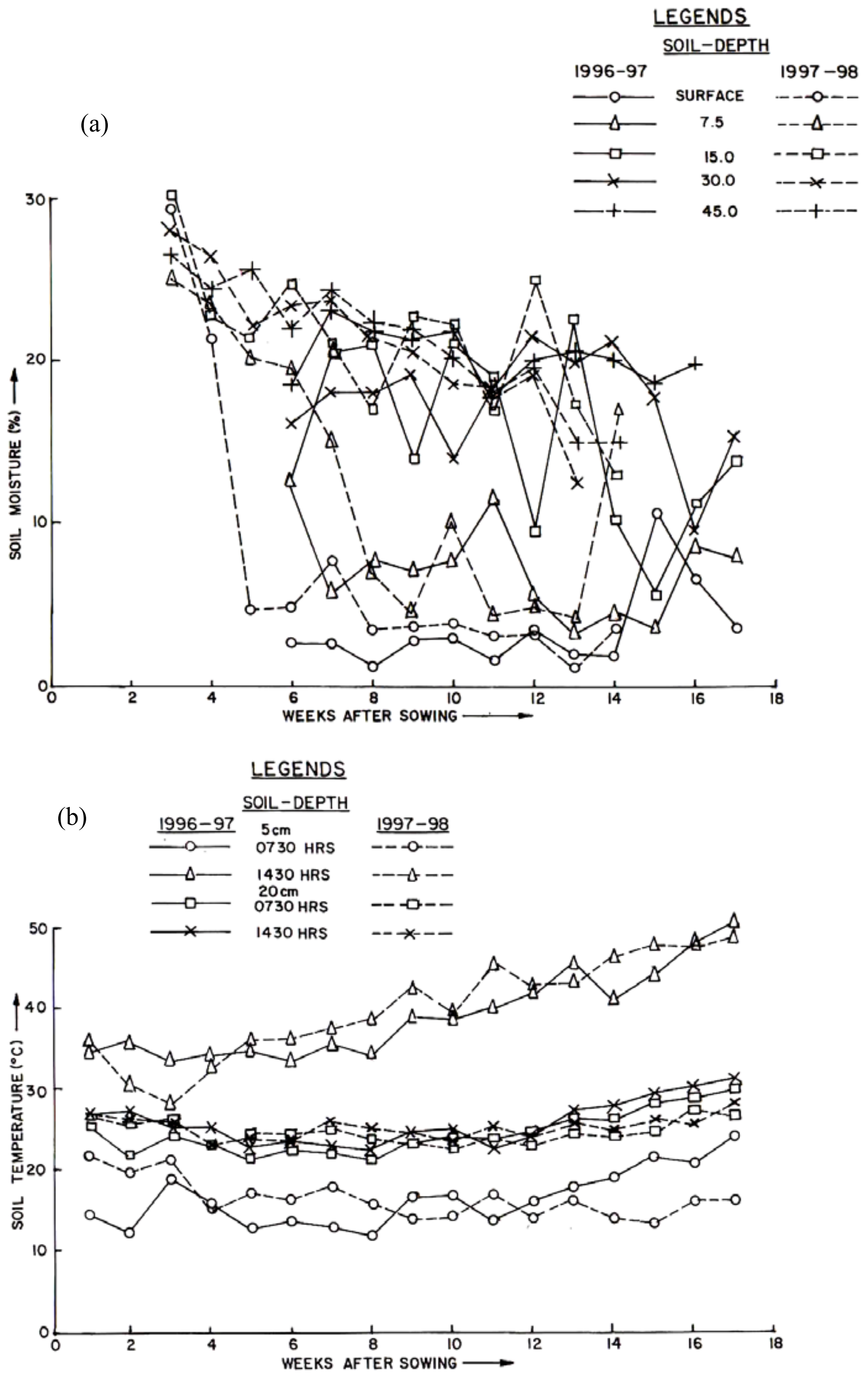
3. Results and discussion

The soil heat flux components vary differently depending on the season, condition of the sky, soil and the vegetations. The measurements were carried out during November to March 1996-97 and 1997-98. The bare soil was kept free from any vegetation by weeding out the same on regular intervals. The recordings from wheat field were started only after 4 and 3 week after sowing the seeds in 1996-97 and 1997-98 respectively.

3.1. *Meteorological condition and soil water content*

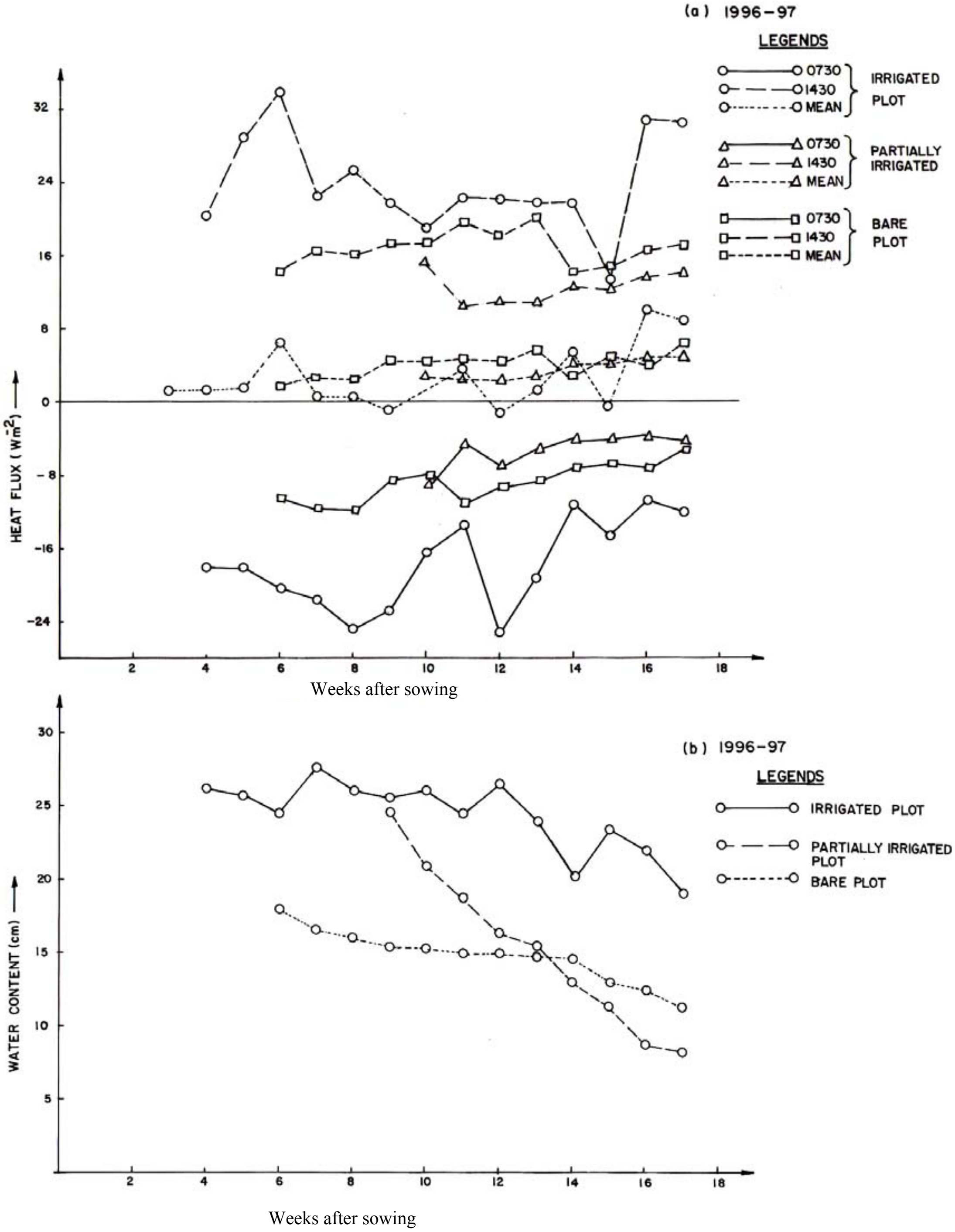
During the crop growing season of 1996-97 and 1997-98 mean maximum and minimum temperature were below normal by 1 to 2.5° C except in 1997-98 when mean minimum temperature was above normal (Table 1). Morning as well as afternoon mean relative humidity was above normal during November, December, January and February. Soil temperature as high as 44.0 and 48.9° C were observed at 5 cm depth under irrigated and partially irrigated wheat at dough to maturity stage at 1430 hours IST respectively in the year 1996-97. The rainfall was much above normal (574% and 1378% during November and December 1997 respectively) and these rains had badly affected the early sown crops causing reduction in growth and LAI and high water content in the soil (0-82.5 cm) profile.

The soil moisture at different growth stages during 1996-97 and 1997-98 under irrigated wheat varied from 25 to 4% and 12 to 6% by weight respectively at surface



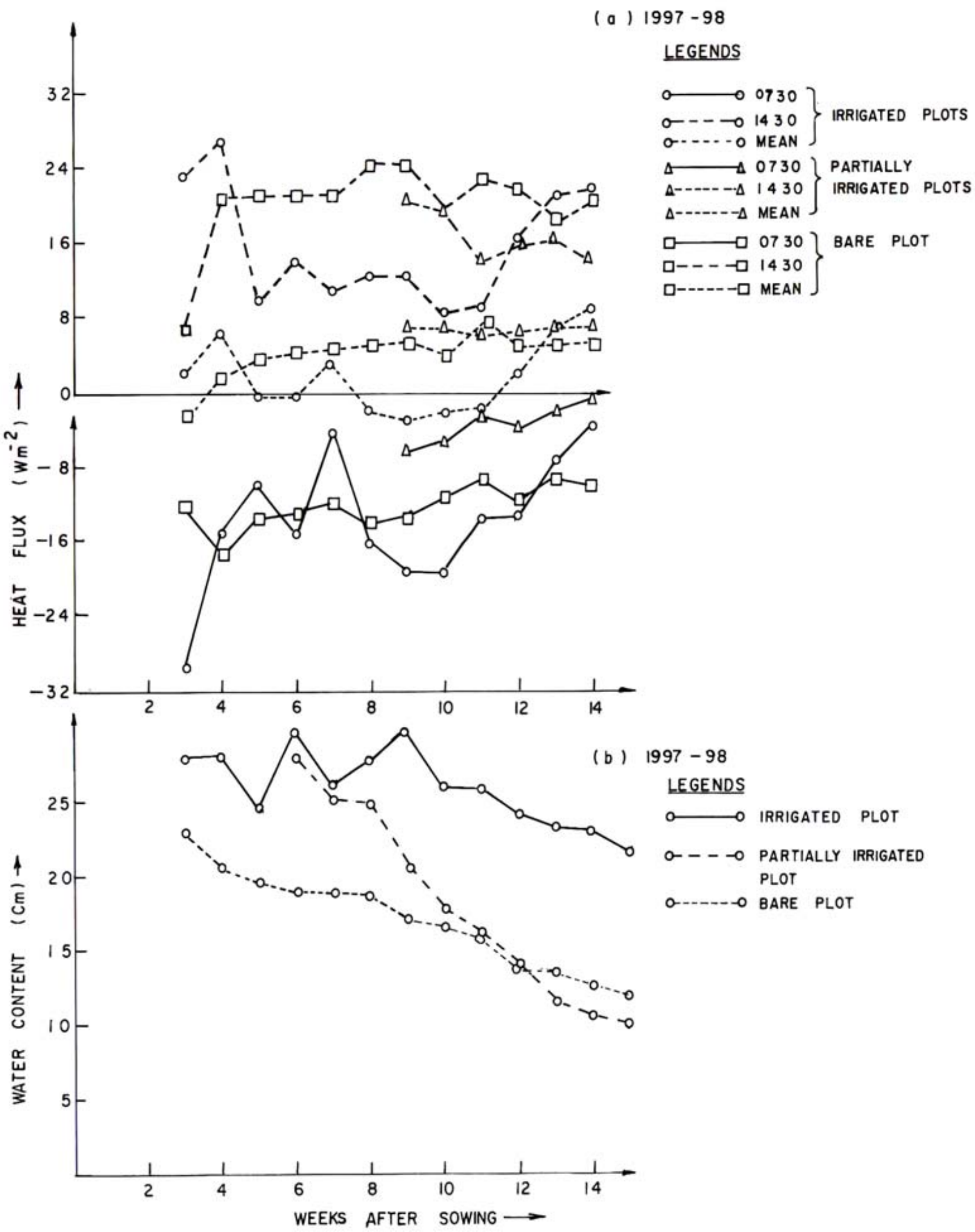
Figs. 1(a&b). (a) Weekly variation of soil moisture (%) and (b) Weekly variation of soil temperature (°C) at different depth under bare soil

layer, it varied from 5 to 1 and 12 to 6% by weight respectively in the years 1996-97 and 1997-98 under partially irrigated plot when irrigation was shut-off, whereas in bare soil it was 13 to 2 % and 29 to 1% by weight respectively in the years 1996-97 and 1997-98 when no irrigation was applied. The higher percent of moisture contents in 1997-98 were due to more rain at early stages of growth (Fig. 1).



Figs. 2(a&b). (a) Variation of soil heat flux under irrigated, partially irrigated wheat and bare black cotton soil and (b) variation of water content at 0-825 cm layer

During early growth stages of the crop soil moisture varied from 34 to 16 % and 38 to 19% by weight respectively in 1996-97 and 1997-98 at 7.5 to 30 cm soil depth under irrigated wheat and 31 to 16 % and 34 to 8% by weight respectively in the years 1996-97 and 1997-98 under partially irrigated wheat and in bare soil it was 23 to



Figs. 3(a&b). (a) Variation of soil heat flux under irrigated, partially irrigated wheat and bare black cotton soil and (b) variation of water content at 0-825 cm layer

6 % and 30 to 12% by weight respectively in the years 1996-97 and 1997-98. Soil moisture below 30 cm depth was quite high and ranged from 32 to 22 %, and 32 to 11% by weight respectively under irrigated and partially irrigated plots in 1996-97 and 1997-98. With the advancement of growth stages, soil moisture dropped progressively in the drying cycles at all the depths and it ranged from 30 to 25% by weight at deeper layers, whereas it was 20 to 6% by weight at subsurface layers under irrigated plot in the year 1996-97. Drastic fall in moisture content was noticed in partially irrigated wheat when irrigation was shut-off before flowering stage from 8 WAS. Moisture content dropped as low as 1 to 5% by weight at surface layer and 5 to 10% by weight at subsurface layers in the year 1996-97. Such drop in moisture content in partially irrigated wheat caused

considerable variation in LAI due to water stresses condition in the cropped field. LAI dropped drastically from 2.9 to 1.1 and 1.89 to 0.3 respectively in 1996-97 and 1997-98 at milk to dough stage of the crop in partially irrigated wheat.

3.2. *Seasonal variation of soil heat flux*

Soil temperature in the years 1996-97 and 1997-98 under irrigated wheat ranged from 10 to 20.0° C and 14 to 23.0° C respectively at 5 cm depth and 20.0 to 26.0° C and 21.0 to 25.0° C respectively at 20 cm depth at 0730 hours IST whereas at 1430 hours IST it varied from 27.0 to 40.0° C and 24.0 to 35.0° C respectively at 5 cm depth. The temperature at 5 cm depth were higher by 2 to 8° C under partially irrigated wheat at 1430 hrs IST. On the contrary, in the years 1996-97 and 1997-98 bare soil temperature at 5 cm depth ranged respectively from 12 to 25° C and 13 to 22° C respectively at 0730 hrs IST and 34 to 51° C and 28 to 50° C respectively at 1430 hrs IST higher by about 7 to 11° C from the irrigated wheat whereas at 20 cm depth it was marginally higher by 1 to 4° C from that of irrigated wheat. This marginal increase in soil temperature at deeper depth (20 cm) clearly indicates that heat flow from surface to deeper depth was restricted due to less soil moisture and more air pore space of the soil.

Average weekly soil heat flux (G) ranged from -1.26 to 10.05, 2.09 to 5.02 and 1.26 to 6.5 Wm^{-2} respectively under irrigated, partially irrigated and bare soil in the year 1996-97 (Fig. 2). It ranged from -3.35 to 9.21, 5.86 to 7.12 and -1.67 to 6.70 Wm^{-2} respectively under irrigated, partially irrigated wheat and bare soil in the year 1997-98 (Fig. 3). Extreme negative values of G were recorded during rainy days or on days when irrigations were applied. Relatively lower G under partially irrigated wheat in the year 1996-97 compared to that in 1997-98 was due to relatively higher LAI which intercepted the incoming radiation more compared to that in 1997-98 when LAI was low due to poor crop stand. Weekly average G values ranged from -13.4 to -29.7 Wm^{-2} at 0730 hrs IST in the weeks when irrigation were applied in the year 1997-98. Contrary to this average G were in the range of -3.3 to -10.1 Wm^{-2} at the same hour during the period when soil was relatively dry. Under partially irrigated wheat when irrigation was shut-off from 8 WAS, the G values from between -0.7 to -6.7 Wm^{-2} at 0730 hrs IST. Under bare soil G ranged from -9.2 to -14.2 Wm^{-2} at 0730 hours IST when surface soil experienced gradual drying in the absence of rainfall / irrigation (Fig. 3). G values showed U shaped variation with extreme values at early vegetative and late dough to maturity stages under irrigated wheat at 1430 hours IST. The maximum G were in the range of 23.5 to 27.2 Wm^{-2} at vegetative stage when LAI was 1.25 to 1.82 and it was in the range of 16.7 to 21.8 Wm^{-2} at dough to maturity stages when LAI was in the range of 0.3 to 0.45 in the year 1997-98 (Fig. 3). The soil heat flux from 7 to 11 WAS was small in both the years when the soil was fully covered with crop canopy (LAI ranged between l.82 and 4.34).

Variation of soil water content at 0-10, 0-20, 0-42.5 and 0-80 cm depth intervals under irrigated, partially irrigated and bare vertisol are presented in Tables 2 & 3. Drastic drop in water content was observed at all depth intervals both under partially irrigated and bare soil during the growing season. It was more prominent at the end of the growing season. Soil water content at 0-10 cm depth decreased as low as 0.31 and 0.13 cm from that of 1.4 under bare soil and it decreased as low as 0.32 and 0.63 cm from that of 1.67 and 2.28 cm under partially irrigated wheat respectively in the years 1996-97 and 1997-98. Similar drop in water content was also noticed at 0-20, 0-42.5 and 0-80 cm depth intervals in the drying cycle.

At later stages of the crop growth when water extraction was more from the deeper depths especially under partially irrigated wheat, the soil water content dropped as low as 8.2 and 10.4 cm from that of 24.84 and 28.39 cm observed at 9th and 6th WAS respectively in the years 1996-97 and 1997-98. Under bare soil, it dropped to 11.41 and 11.95 cm from that of 18.06 and 20.65 cm respectively in the years 1996-97 and 1997-98. However, under irrigated wheat plots where irrigation was applied at regular interval to replenish the depleted water from the soil profile, there was zig zag variation of soil water content at all depths in the drying cycle. It varied between 3.14 to 1.19 cm and 3.18 to 1.82 cm at 0-10 cm depth in the years 1996-97 and 1997-98 respectively. Soil water content at 0-80 cm soil profile was also quiet high and ranged from 27.46 to 19.2 and 28.37 to 23.11 cm respectively in the years 1996-97 and 1997-98. Thus water depletion to the extent of 7.8 and 11.2 cm more in bare soil from that of irrigated wheat was observed in the drying cycle respectively in the years 1996-97 and 1997-98. Root water extraction from 0-80 cm soil profile under partially irrigated wheat was more by 11.0 and 12.7 cm than that under irrigated wheat in the years 1996-97 and 1997-98 respectively.

Under partially irrigated wheat when irrigation was shut-off from 8 WAS, the G ranged from 10.89 to 15.49 and 14.2 to 20.9 Wm^{-2} at 1430 hours IST respectively in

TABLE 2

Variation of global (Gr), Net (Rn), Reflected, (Rr) radiation, albedo (α), soil heat flux (G), Leaf area index (LAI) and soil water content (cm) at different growth stages of irrigated (I), partially irrigated (PI) wheat and bare soil

Growth stage	1996-97																								
														Water content (cm) at 0-10, 0-20, 0–42.5 and 0-80 cm depths											
	WAS	Gr. (Wm^{-2})	Rn (Wm^{-2})			Rr (Wm^{-2})			LAI		G (Wm^{-2})			Bare soil				Irrigated wheat				Partially irrigated wheat			
			I	PI	Bare soil	I	PI	Bare soil	I	PI	I	PI	Bare soil	0-10	0-20	0-42.5	0-80	0-10	0-20	0-42.5	0-80	0-10	0-20	0-42.5	0-80
Tillering	4	456.2	192.5	210.6	144.5	61.9 (14)	66.1 (15)	89.7 (20)	0.35	0.35	1.26	-	1.26												
Vegetative	5	467.6	210	205.9	161.8	75.6 (16)	83.1 (18)	80.0 (17)	0.61	0.61	1.67	-	1.26												
	6	439.5	219.2	235.3	156.4	94.7 (21)	81.2 (19)	74.2 (17)	0.87	0.87	6.7	-	1.85	1.4	3.95	10.43	18.06	1.76	4.67	11.95	24.49				
	7	448.4	248.1	227	150.3	114.5 (26)	111.1 (25)	72.5 (16)	1.49	1.49	0.42	-	2.7	0.44	2.71	7.21	16.78	2.05	5.54	13.68	27.46				
Flowering	8	544.3	288.7	308.9	198.7	140.6 (26)	138.9 (25)	88.3 (16)	1.89	1.89	0.42	-	2.3	0.5	2.83	7.34	16.29	1.91	4.89	12.71	26.03				
	9	557.1	302.6	306.5	176.7	150.6 (27)	143.6 (26)	91.4 (16)	2.6	2.39	-0.84	-	4.65	0.61	2.13	6.78	15.48	1.85	4.75	12.57	25.56	1.67	4.56	12.18	24.84
	10	587.9	290.3	319.5	193.7	171.7 (29)	156.7 (27)	94.7 (16)	4.34	2.9	1.26	2.93	4.2	0.57	2.9	6.31	15.14	3.14	6.7	13.98	26.11	1.28	3.66	9.48	21.05
Milk to dough	11	627.7	286.4	350.1	195	178.9 (29)	153.3 (24)	102.8 (16)	3.89	2.18	3.77	2.93	4.4	5.3	2.4	6.13	15.47	1.75	4.04	9.71	18.12	1.08	3.51	7.35	14.98
	12	642.1	352.8	361.2	211.4	178.1 (28)	135.0 (21)	108.1 (17)	1.77	1.38	-12.6	2.09	4.4	0.49	2.18	5.79	15.04	3.11	6.61	14.48	26.61	0.76	2.2	5.39	11.69
	13	633.1	319.8	356.7	206.4	165.6 (26)	125.9 (20)	103.9 (16)	1.43	1.11	1.26	2.93	5.8	0.52	1.69	5.6	15.01	3.14	6.7	13.98	26.11	0.58	1.78	5.15	11.58
Dough to maturity	14	576.5	351.6	334.2	175.3	137.5 (24)	113.1 (19)	105.3 (18)	1.23	0.93	5.44	4.18	3.3	0.43	1.5	5.92	14.99	1.5	4.03	9.8	20.15	0.44	1.5	4.47	10.2
	15	568.4	305.6	320.6	175	121.1 (21)	108.9 (19)	106.9 (19)	0.94	0.71	-0.42	4.18	4.2	0.41	1.4	5.78	13.21	2.58	5.4	11.83	23.53	0.24	1.12	3.89	9.39
	16	609.8	299.5	330.5	188.9	116.4 (19)	119.7 (20)	117.2 (19)	dry	dry	10.05	5.02	4.6	0.38	1.26	5.41	12.5	1.75	4.46	10.7	22.21	0.42	1.08	3.8	8.87
	17	655.4	282.3	311.7	196.4	140.3 (21)	125.1 (19)	123.6 (19)	dry	dry	9.21	5.02	6.5	0.31	1.15	4.46	11.41	1.19	3.48	8.93	19.2	0.32	0.9	3.5	8.2

α - Values are presented in the parenthesis

the years 1996-97 and 1997-98. Under bare soil G in 5-20 cm soil layer was in the range of 13.8 to 20.1 and 16.7 to 24.7 Wm^{-2} at 1430 hours IST respectively in the years 1996-97 and 1997-98 (Figs. 2 & 3). The higher G values in the year 1997-98 may be due to higher soil moisture in the profile due to 574 and l378 % above normal rainfall in the months of November and December, 1997.

3.3. *Leaf area index (LAI) in the growing period*

The LAI increased with the advancement of growth stages and was maximum (4.34) at flowering stage at 10 WAS, thereafter it decreased to 1.23 at maturity stage under irrigated plot, whereas under partially irrigated wheat maximum LAI (2.90) was comparatively less at 10 WAS at flowering stage in 1996-97. The lower LAI in partially irrigated wheat was due to water stress as induced by shutting off irrigation from 8 WAS. In 1997-98 the lower maxima LAI of 2.36 and 1.89 both under irrigated and partially irrigated wheat respectively were due to poor crop stand caused by abnormal high rainfall at early stages of the crop growth.

3.4. *Seasonal variation of global, net and reflected radiation and albedo over wheat and bare soil*

Average weekly global radiation (short-wave) during the crop growth seasons 1996-97 and 1997-98 ranged between 430 Wm^{-2} during tillering stage (6 WAS) and 700 Wm^{-2} at maturity stage (17 WAS). Net radiation under irrigated and partially irrigated wheat was, in general, more compared to that in bare plots in 1996-97 and 1997-98. It ranged from 193 to 356, 190 to 365 and 193 to 240 Wm^{-2} respectively under irrigated, partially irrigated wheat and bare plot during crop growing seasons (Tables 2 & 3).

TABLE 3

Variation of global (Gr), Net (Rn), Reflected (Rr) radiation, albedo (α), soil heat flux (G), Leaf area index (LAI) and soil water content (cm) at different growth stages of irrigated (I), partially irrigated (PI) wheat and bare soil

Growth stage	1997-98																								
														Water content (cm) at 0-10, 0-20, 0–42.5 and 0-80 cm depths											
	WAS	Gr. (Wm^{-2})	Rn (Wm^{-2})			Rr (Wm^{-2})			LAI		G (Wm^{-2})			Bare soil				Irrigated wheat				Partially irrigated wheat			
			I	PI	Bare soil	I	PI	Bare soil	I	PI	I	PI	Bare soil	0-10	0-20	0-42.5	0-80	0-10	0-20	0-42.5	0-80	0-10	0-20	0-42.5	0-80
Tillering	4	486.5	245.6	248.4	237.8	52.5 (11)	54.2 (11)	70.9 (15)	0.89	0.89	6.28	-	1.67	1.4	3.92	10.5	20.65	3.18	7.11	14.96	28.37				
Vegetative	5	457.9	223.7	235.7	214.5	71.9 (16)	74.7 (16)	83.1 (18)	1.25	1.25	-0.42	-	3.76	1.35	3.71	9.13	19.65	2.39	5.29	12.14	24.51				
	6	420.8	227.3	237.3	239.8	87.2 (21)	83.9 (20)	87.2 (21)	1.59	1.59	-0.42	-	4.17	1.33	4.05	9.89	19.01	2.7	6.49	15.3	29.9	2.28	5.99	14.36	28.39
	7	451.7	236.1	249.5	231.9	110.6 (24)	105.6 (23)	79.2 (17)	1.82	1.82	3.35		4.61	1.25	3.57	9.29	18.9	2.3	5.24	12.94	26.31	1.91	4.98	12.28	25.07
Flowering	8	476.7	231.7	212.5	225	120.3 (25)	105.6 (23)	80.3 (17)	1.96	1.89	-2.09		5.23	0.56	2.45	7.74	16.69	2.84	6.46	13.93	27.79	2.69	5.27	12.09	24.92
	9	471.8	204.5	190.5	206.4	119.5 (25)	125 (26)	76.4 (16)	2.36	0.99	-3.35	7.12	5.65	0.45	2.94	8.06	17.01	3.94	7.8	16.36	29.57	1.49	3.62	8.99	19.34
	10	495.7	247.7	208.7	209.8	134.7 (27)	127.8 (26)	85.3 (17)	1.69	0.78	-2.51	7.12	3.98	0.43	2.55	7.75	16.0	2.87	6.07	13.82	26.36	1.2	2.95	7.9	17.8
Milk to dough	11	519.5	285.3	228.1	215.3	136.7 (26)	135.6 (26)	94.2 (18)	1.02	0.3	-2.09	5.86	6.7	0.41	2.26	6.67	14.14	2.38	5.7	13.22	25.8	0.79	1.85	5.36	11.13
	12	516.5	276.7	256.2	193.4	125.6 (24)	123.1 (24)	88.1 (17)	0.86	0.15	1.67	6.28	5.03	0.46	2.23	5.38	13.66	2.37	5.61	12.14	23.61	0.77	1.72	5.19	10.96
	13	566.2	356.4	363.4	214.7	126.1 (22)	118.1 (21)	93.9 (17)	0.64	0.1	7.12	7.12	4.82	0.27	2.17	5.3	12.49	1.98	5.1	12.1	24.15	0.7	1.6	5.1	10.87
Dough to maturity	14	583.9	326.7	348.4	224.8	127.8 (22)	119.2 (20)	96.9 (17)	0.45	dry	9.21	7.12	5.44	0.13	2.58	5.1	11.95	1.82	4.85	11.56	23.11	0.63	1.51	4.85	10.42
	15	651.8	350.6	365.6	240.6	134.2 (21)	126.9 (19)	105.0 (16)	0.3	dry	-	-	4.81	-	-	-	-	-	-	-	-	-	-	-	-
	16	627.1	-	-	-	-	-	-	0.1	dry	-	-		-	-	-	-	-	-	-	-	-	-	-	-
	17	699.9	-	-	-	-	-	-	dry	dry	-	-		-	-	-	-	-	-	-	-	-	-	-	-

α - Values are presented in the parenthesis

The highest albedo (α) values 29 and 27 % were found under irrigated and partially irrigated plots respectively when maximum LAI was attained during flowering stage by the crop at 10 WAS in the year 1996-97, whereas in 1997-98 maximum α under irrigated and partially irrigated wheat were 27 and 26.5% during flowering stage at 9 and 8 WAS respectively (Table 3). The radiation balance of crop canopies is determined by the reflectivity (albedo) for short wave radiation which depends on the angle of elevation of sun, nature of soil and leaves and the leaf-angle distribution (Goudrian, 1977, Monteith and Unsworth, 1990). At early stages, α values ranged from 14 to 15% in 1996-97, whereas in 1997-98 it was about 11%. On the contrary α over bare plot ranged from 17 to 20% and 15 to 18% in 1996-97 and 1997-98 respectively. During early stages of growth the reflection from the irrigated soil is lower than that of bare but dry soil. The values of α over irrigated wheat overshoots those over partially irrigated wheat and bare soil once the crop starts growing into different stages. Except initial few weeks during emergence, crown root initiation and tillering stages the α values were considerably higher under irrigated and partially irrigated wheat compared to that of bare soil in both the years from 9 WAS onward. α values were higher by about 5 to 11 % under irrigated wheat compared to that of partially irrigated wheat. This is due to higher LAI and soil moisture content in the irrigated wheat. The low values of albedo at early stages were strongly influenced by the low reflectivity of soil (wet soil) (Kalma and Badham, 1972; Goudrian, 1977).

3.5. *Variation of soil heat flux in relation to albedo and LAI*

Maximum α values under irrigated and partially irrigated wheat were associated with maximum LAI

TABLE 4

Multiple regression equations, percentage of variation explained (R^2), level of significance and F values for the estimation of soil heat flux (G) under irrigated wheat

Case-I		Eq. No.	Regression equation	R^2	Level of significance (%)	F value
Irrigated	Water content at (0-10 cm) SW_1	1	$G = -34.22 + 0.61LAI + 1.36ST_2$	83.11	1	49.22
		2	$G = -30.08 + 1.24ST_2$	81.63	1	93.33
		3	$G = -30.14 + 1.24ST_2 + 0.001\alpha$	81.63	1	44.44
		4	$G = -27.95 + 1.19ST_2 - 0.34\ SW_1$	81.81	1	44.98
Irrigated	Water content at (0-20 cm) SW_2	5	$G = -30.64 + 0.002Gr + 1.22ST_2$	81.71	1	44.70
		6	$G = -30.92 + 0.1LAI + 1.2ST_1$	81.94	1	45.38
		7	$G = -28.81 + 1.21ST_2 - 0.11SW_2$	81.68	1	44.59
Irrigated	Water content at (0-42.5 cm) SW_3	8	$G = -30.64 + 0.002Gr + 1.22ST_2$	81.71	1	44.70
		9	$G = -30.92 + 0.10ST_1 + 1.2ST_2$	81.94	1	45.38
		10	$G = -26.60 + 1.18ST_2 - 0.14SW_3$	81.88	1	45.19
Irrigated	Water content at (0-80 cm) SW_4	11	$G = -25.28 + 1.17ST_2 - 0.11SW_4$	82.12	1	45.93

Where,
Gr = Global radiation, Wm^{-2},
α = Albedo (%),
ST_1 = Mean soil temperature (°C) at 5 and 20 cm depths at 0730hr IST,
ST_2 = Mean soil temperature (°C) at 5 and 20 cm depths at 1430hr IST,
LAI = Leaf area index,
SW_1 = Soil water content (cm) at 0-10 cm depth,
SW_2 = Soil water content (cm) at 0-20 cm depth,
SW_3 = Soil water content (cm) at 0-42.5 cm depth,
SW_4 = Soil water content (cm) at 0-80 cm depth.

attained during flowering stage of the crops in both the years (Tables 2 & 3). The irrigated wheat attained maximum LAI of 4.34 and 2.36 in the year 1996-97 and 1997-98 respectively. During this time the canopy height was about 0.5 m. When the canopy was fully developed most of the incoming short wave radiation did not reach the soil surface and either reflected or absorbed thereby causing less heating of soil and minimum heat flux values *i.e.*, less gain of heat at the ground. Higher LAI and height of the crop intensified radiation trapping which reduces the reflection co-efficient (Monteith and Unsworth, 1990).

At the flowering stage when the crop attained maximum LAI, the values of heat flux found to be reduced in both the years. The mean heat flux (in 1996-97) under irrigated condition were -0.84, -1.26 and -0.42 Wm^{-2} (at 9, 12 and 15 WAS when crop was irrigated) and 10.05 Wm^{-2} (at 16 WAS when soil was dry) whereas under partially irrigated wheat it varied from 2.09 to 5.02 Wm^{-2} at flowering to maturity stages.

In 1997-98, the heat flux varied from -2.51 Wm^{-2} at flowering stage when crop attained maximum canopy to 9.21 Wm^{-2} at harvesting stage under irrigated wheat, whereas under partially irrigated wheat it varied from 5.86 Wm^{-2} at 11 WAS at milk to dough stage and 7.12 Wm^{-2} at harvesting stage.

The U shaped variation of G at 1430 hours IST in the years 1996-97 and 1997-98 were strongly influenced by the reverse U type of variation in LAI of irrigated wheat. However, there was gradual increase in the G values from extreme negative towards higher G in the partially irrigated wheat at 0730 hours IST. At 1430 hours IST no trend is observed under falling LAI with gradual drop in soil moisture in the soil profile.

3.6. *Heat flux and water content*

The mean heat flux into 5-20 cm soil layer ranged between -1.26 to 10.05 and 2.09 to 5.02 Wm^{-2} under

TABLE 5

Multiple regression equations, percentage of variation explained (R^2), level of significance and F values for the estimation of soil heat flux (G) under partially irrigated wheat

Case-II		Eq. No.	Regression equation	R^2	level of significance (%)	F value
Partially irrigated	Water content at (0-10 cm) SW_1	1	$G = 2.68 - 0.009\ Gr - 1.08\ LAI + 0.34\ ST_1 + 2.39\ SW_1$	97.03	1	73.76
		2	$G = 8.64 - 0.02\ Gr + 0.42\ ST_1$	88.85	1	43.84
		3	$G = -1.81 - 0.01\ Gr + 0.42\ ST_2 + 3.32\ SW_1$	91.71	1	36.88
Partially irrigated	Water content at (0-20 cm) SW_2	4	$G = 2.16 - 0.009\ Gr - 1.5\ LAI + 0.35\ ST_1 + 1.18\ SW_2$	97.31	1	81.57
		5	$G = 2.77 - 0.009\ Gr - 1.52\ LAI + 0.39\ ST_1 - 0.04\ ST_2 + 1.1\ SW_2$	97.33	1	58.35
		6	$G = 1.79 - 0.009\ Gr - 1.51\ LAI + 0.35\ ST_1 + 0.01\ \alpha + 1.15\ SW_2$	97.32	1	58.14
Partially irrigated	Water content at (0-42.5 cm) SW_3	7	$G = -3.06 - 2.19\ LAI + 0.25\ ST_1 + 0.84\ SW_3$	96.72	1	98.41
		8	$G = -3.14 - 2.19\ LAI + 0.25\ ST_1 + 0.004\ ST_2 + 0.84\ SW_3$	96.72	1	66.43
		9	$G = -3.55 - 2.17\ LAI + 0.25\ ST_1 + 0.03\ \alpha + 0.79\ SW_3$	96.74	1	66.92
Partially irrigated	Water content at (0-80 cm) SW_4	10	$G = -2.57 - 2.29\ LAI + 0.22\ ST_1 + 0.39\ SW_4$	95.66	1	73.52
		11	$G = -0.39 - 2.32\ LAI + 0.36\ ST_1 - 0.13\ ST_2 + 0.33\ SW_4$	96.01	1	54.27
		12	$G = -4.27 - 2.21\ Gr + 0.23\ ST_1 + 0.1\ \alpha + 0.32\ SW_4$	95.96	1	53.53

Where,
Gr = Global radiation, Wm^{-2},
α = Albedo (%),
ST_1 = Mean soil temperature (°C) at 5 and 20 cm depths at 0730hr IST,
ST_2 = Mean soil temperature (°C) at 5 and 20 cm depths at l430hr IST,
LAI = Leaf area index,
SW_1 = Soil water content (cm) at 0-10 cm depth,
SW_2 = Soil water content (cm) at 0-20 cm depth,
SW_3 = Soil water content (cm) at 0-42.5 cm depth,
SW_4 = Soil water content (cm) at 0-80 cm depth.

irrigated and partially irrigated wheat respectively and under bare soil it ranged from 1.26 to 6.50 Wm^{-2} in the year 1996-97 (Table 2). In 1997- 98, heat flux values were from -3.35 to 9.21, 5.86 to 7.12 and 1.67 to 6.70 Wm^{-2} under irrigated, partially irrigated and bare soil respectively (Table 3). The diurnal range of heat flux was considerably high in irrigated wheat than in partially irrigated wheat. The heat fluxes at 0730 hours IST are negative and higher negative values were observed under irrigated condition than partially irrigated and bare soil. Similarly the heat flux values at 1430 hours IST are positive. Higher positive values were observed in irrigated wheat. G was considerably higher compared to that under partially irrigated and bare soil, [Figs. 2 (a&b) and Figs. 3 (a&b)]. The higher ranges of heat flux under irrigated wheat was due to higher water content which increases thermal diffusivity (Sambasiva Rao *et al*., 1986). In general, the direction of heat flow was negative (heat loss) at 0730 hours IST. These negative heat flux values were observed higher when the soil water content was more. Similarly, at 1430 hours IST heat flow values were higher and positive (heat gain) when water content was comparatively more. In bare plot too, when there was rainfall causing increase in soil moisture content in the surface layer, the diurnal range of heat flux was found considerably higher. The weeks at which irrigation was applied or rainfall occurred, the negative heat flux values were observed under wheat plots and bare soil. It may be seen that at 9, 12 and 15 WAS in 1996-97 and 5, 6 and from 8-11 WAS in 1997-98 have negative heat flux values whereas values were positive when soil was relatively dry [Figs. 2(a&b) and Figs. 3(a&b)]. The frequent irrigation along with dense foliage coverage during flowering stage of the irrigated wheat crop cause heat flow either at equilibrium or negative.

3.7. *Relationships between soil heat flux and soil moisture, meteorological parameters and leaf area index*

The relationships between soil heat flux and soil moisture content for each of the four soil layers 0-10,

TABLE 6

Multiple regression equations, percentage of variation explained (R^2), level of significance and F values for the estimation of soil heat flux (G) under bare soil during winter to early summer months (During wheat growing period)

Case-I		Eq. No.	Regression equation	R^2	Level of significance (%)	F value
Bare soil	Water content at (0-10 cm) SW_1	1	$G = -12.78 - 0.32\ SW_1 + 0.01\ Gr + 0.02Rn - 0.13Rr + 0.55ST_2$	81.97	1	15.45
		2	$G = -13.03 + 0.01\ Gr + 0.02\ Rn - 0.\ 13\ Rr + 0.56\ ST_2$	80.88	1	19.04
		3	$G = -6.64 - 0.05\ Rr - 0.26\ ST_1 + 0.64\ ST_2$	72.15	1	16.41
		4	$G = -6.29 + 0.02\ Rn - 0.06\ Rr - 0.34\ \alpha + 0.54\ ST_2$	77.71	1	15.69
Bare soil	Water content at (0-20 cm) SW_2	5	$G = -7.18 + 0.08\ SW_2 - 0.05\ Rr - 0.26\ ST_1 + 0.65\ ST_2$	72.37	1	11.78
Bare soil	Water content at (0-42.5 cm) SW_3	6	$G = -9.76\ +0.20\ SW_3 - 0.35\ ST_1 + 0.60\ ST_2$	65.95	1	12.26
Bare soil	Water content at (0-80 cm) SW_4	7	$G = -14.31 + 0.\ 23\ SW_4 -0.42\ ST_1 + 0.71\ ST_2$	68.58	1	13.82

Where,
Gr = Global radiation., Wm^{-2},
Rn = Net radiation, Wm^{-2},
Rr = Reflected radiation, Wm^{-2},
α = AJ bedo (%),
ST_1 = Mean soil temperature (°C) at 5 and 20 cm depths at 0730hr IST,
ST_2 = Mean soil temperature (°C) at 5 and 20 cm depths at 1430hr IST,
LAI = Leaf area index,
SW_1 = Soil water content (cm) at 0-10 cm depth,
SW_2 = Soil water content (cm) at 0-20 cm depth,
SW_3 = Soil water content (cm) at 0-42.5 cm depth,
SW_4 = Soil water content (cm) at 0-80 cm depth,

0-20, 0-42.5, 0-80 cm, meteorological parameters and LAI under irrigated, partially irrigated wheat and bare soil were worked out by step-wise multiple regression technique and presented in Tables 4 to 6. Soil water content beyond 20 cm depth *i.e.*, 0-42.5 and 0-80 cm layers were also considered to find out the relationship as the capillary movement of water from deeper to upper layers be continuously change the soil water content there by modifying the soil heat flux. The soil heat flux has given a significant correlation coefficients with α, ST_1, ST_2, SW_1, SW_2, SW_3, SW_4 and LAI. The symbols are explained in Tables 4 and 6. It was not significant with Gr. The relationships with ST_2 alone and ST_2 with other meteorological parameters or LAI were found significant at 1% level and accounted for 81.63 to 83.11% variation in heat flux. ST_2 was found to be the most predominant parameter and it alone accounted for 81.63% variation in soil heat flux (Table 4). The correlation coefficient between G and ST_2 was highly significant (r = +0.90), significant at 1% level. G was positively and significantly correlated with ST_2 and ST_1 of irrigated, partially irrigated and bare soil. On the other hand G was negatively and significantly correlated with soil water content of irrigated wheat for all the four depth intervals (SW_1, SW_2, SW_3 and SW_4). It was also negatively and significantly correlated with the water content of deeper depth intervals *i.e.*, SW_3 (r = -0.54) and SW_4 (r = -0.58) but not significantly correlated with water content of upper depth intervals of bare soil and for all the depth intervals of partially irrigated wheat. r values were small for all the depth intervals of partially irrigated wheat and upper depth intervals of bare soil. This indicates that when water content decreases beyond a certain limit under partially irrigated wheat and bare soil, it does not contribute towards heat flux in the soil.

The relationships worked out with G and soil water content (SW_1, SW_2, SW_3 and SW_4) in combination with other meteorological parameters and LAI for the partially irrigated wheat show a clear shifts not only in accounting for percent variation in G but also in the predominant parameters (Table 5). Gr and ST_1 were found to be the most predominant meteorological parameters and accounted for 88.85 % variation in G under partially irrigated wheat. When other parameters *viz*., LAI, ST_2, α and SW were also included in the model separately, the regression models accounted for 95 to 97 percent variation in G. Thus Gr and ST_1, in combination with LAI, ST_2 and soil water content (SW, i = 1 to 4) could be used to estimate soil heat flux under partially irrigated and rain fed wheat (Table 5).

The relationships between G and Gr, α, Rn, Rr, ST_1, ST_2. SW_1, SW_2, SW_3 and SW_4 under bare soil were also established by stepwise multiple regression analysis. It is interesting to note that G was significantly and positively correlated with ST_1 (r = 0.43) and ST_2 (r = 0.73) and negatively and significantly correlated with SW_3 (r = -0.54) and SW_4 (r = -0.58). Other meteorological parameters were not significantly correlated. ST_2 was found to be the most predominant meteorological parameter with r = +0.73 significant at 1% level. A combination of ST_2 along with Gr, Rn, Rr and soil water content at 0-10 cm layer (SW_1) accounted for 81.97 percent variation in G. When SW_1 was excluded from the equation, it accounted for 80.88% variation in G indicating that SW_1 is not an important parameter and G can be estimated by Gr, Rn, Rr and ST_2 alone. When SW_1 was replaced either by SW_2 or SW_3 or SW_4, the regression equations (5), (6) and (7) accounted for 72.37, 65.95 and 68.58 percent variation respectively (Table 6). This clearly indicates that water content either from surface or deeper layers need not be included in estimation of G. A combination of soil temperature and radiation parameters has shown considerable improvement in the model formulation. This suggests that further improvement in the simulation of G may result from the combination of other climatic parameters. Further study is required to optimize the parameter formulation. The break in capillary movement of water in the upper layers of dry bare and partially irrigated soil due to loss of moisture caused by evaporation and evapotranspiration respectively may be the reason for such non-significant relationships. The availability of more moisture in the deeper layers of bare soil profile helps the capillary movement of water providing conducive soil physical condition for better thermal diffusivity and heat flux.

4. Conclusions

(*i*) The daily soil temperature at 5 cm depth under irrigated wheat was lower by 7 to 11° C than that observed under bare soil at 1430 hours IST. Soil temperature at 5 cm depth in bare soil ranged from 12 to 25° C and 34 to 51° C respectively at 0730 and 1430 hours.

(*ii*) The heat loss (upward heat flux) ranged from -13.9 to -29.7, -0.7 to -6.7 and -9.2 to -14.2 Wm^{-2} respectively at 0730 hours IST and maximum heat gain (downward heat flux) ranged between 23.5 to 27.2, 14.2 to 20.9 and 16.7 to 24.7 Wm^{-2} at 1430 hours IST under irrigated, partially irrigated and bare soil respectively.

(*iii*) When crop attained maximum LAI, the values of heat flux dropped as low as -1.26 and 2.09 Wm^{-2} in the irrigated and partially irrigated wheat respectively due to trapping of radiation in the crop canopy.

(*iv*) Mean heat flux at 0730 hours IST and 1430 hours IST showed negatively significant correlation with soil water content for all the depths under irrigated condition and for deeper depths under bare soil indicating that higher moisture content beyond a certain value caused reduction in heat flux.

(*v*) A combination of soil temperature with radiation and other meteorological parameters has shown considerable improvement in the model formulation. These parameters could be used to estimate soil heat flux under irrigated, partially irrigated and bare soil condition. However, it may be mentioned that further study is required to optimize the parameter formulation.

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