

Estimation of soil water content using plant and meteorological parameters under irrigated, partially irrigated wheat and bare dry soil at Pune

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सार – इस शोध-पत्र में पुणे क्षेत्र में गेहूँ की सिंचित एवं अर्धसिंचित खेती के दौरान मिट्टी में नमी की मात्रा का आकलन करने का प्रयास कैनोपि तापमान और कैनोपि वायु तापमान की भिन्नता, फसल के पत्तों से प्राप्त संकेतों और अन्य मौसम विज्ञान प्राचलों की सहायता से किया गया है। बिना फसल वाले खेत की मिट्टी में नमी की मात्रा का आकलन करने के लिए केवल मौसम विज्ञान के प्राचलों का ही उपयोग किया गया है। प्राप्त हुए परिणामों से न केवल जमीन की गहराई की भिन्नता के अनुरूप नमी की मात्रा में स्पष्ट भिन्नता का पता चला है बल्कि यह भी पता चला है कि पूर्व प्राचलों के अनुरूप की तीनों स्थितियों में अर्थात् सिंचित एवं अर्धसिंचित फसल वाले खेत की मिट्टी तथा बिना फसल वाले खेत की मिट्टी में 0–10, 0–20, 0–42.5 और 0–80 से.मी. की गहराई में गहराई की भिन्नता के अनुरूप ही नमी में भी स्पष्ट रूप से भिन्नता पाई गई है। बिना फसल वाले खेत की मिट्टी की नमी का आकलन करने के लिए दोपहर से पहले और दोपहर के बाद के समय के सीधे और परावर्तित विकिरणों के साथ मिट्टी के औसत तापमानों का सामंजस्य बेहतर पूर्वसूचक हैं। इसके विपरीत, सिंचित गेहूँ की फसल में मिट्टी की नमी की मात्रा का आकलन करने के लिए ऊपर बताई गई विभिन्न चारों गहराईयों के फसल के पत्तों से प्राप्त हुए संकेत सर्वाधिक प्रबल प्राचल पाए गए हैं। 1430 बजे लिए गए कैनोपि-वायु तापमान और मिट्टी के औसत में पाई गई भिन्नता से सिंचित गेहूँ की फसल में 0–42.5 से.मी. की गहराई पर अधिकतम प्रतिशत (67.64 प्रतिशत) की भिन्नता का पता चला है। धरातलीय मिट्टी की नमी की मात्रा के लिए सापेक्षिक आर्द्रता के साथ कैनोपि तापमान अथवा सीधा विकिरण बेहतर पूर्वसूचक पाए गए हैं जबकि अर्धसिंचित मिट्टी में 86.73 प्रतिशत और 87.74 प्रतिशत की भिन्नता का पता चला है। प्राप्त हुए परिणामों से यह पता चला है कि कैनोपि तापमान और वनस्पति एवं पर्यावरणीय प्राचलों विशेषकर ऊर्जा संतुलन और वायुगतिकी प्राचलों के सामंजस्य से मिट्टी में नमी की मात्रा की इस स्थिति में आगे और सुधार लाया जा सकता है।

ABSTRACT. Canopy temperature and canopy-air temperature difference, leaf area index and other meteorological parameters were used to estimate the soil water content in irrigated as well as partially irrigated wheat. In case of bare-dry soil, the meteorological parameters only were used to estimate soil water content. The results showed clear shifts not only in accounting for variations in the water content at different depths but also in the predominant parameters for each of the three cases viz., irrigated, partially irrigated and bare-dry soil and also at different depths viz., 0-10, 0-20, 0-42.5 and 0-80 cm. A combination of net and reflected radiations with morning and afternoon mean soil temperatures were found the best predictors to estimate soil moisture under bare-dry soil. On the contrary, leaf area index was found the most predominant parameter for each of the four depths for estimation of soil water content under irrigated wheat. Canopy-air temperature difference and mean soil temperature at 1430 hours explained the maximum percent variation (67.64%) at 0-42.5 cm depth under irrigated wheat. Relative humidity along with either canopy temperature or net radiation were found the best predictors for the surface soil water content and accounted for 86.73% and 87.74% variation under partially irrigated soil. The results suggest that further improvement in the simulation of soil water content may result from the combination of canopy temperature, plant and environmental parameters particularly the energy balance and aerodynamic parameters.

Key words – Soil water content, Meteorological parameters, Canopy temperature, Canopy-air temperature difference.

1. Introduction

Soil water content (SW) in the root zone depth is an important parameter for evapotranspiration measurement,

irrigation scheduling, crop water stress monitoring, water management studies and also as an input data in various crop simulation models. This parameter is measured by various conventional methods viz., tensiometric, neutron

probes, gravimetric soil sampling, lysimetric method and soil electrical resistance. But gives point measurement rather than large scale measurements and also time consuming.

Recently attempts have been made to use remote sensing techniques for measuring soil water content. Various theoretical models have also been constructed to explain the process of soil water movement and heat exchange. McCumber and Peilke (1981) observed that soil water content is an important soil and surface parameter governing the heat fluxes from the soil. The water content in the soil also alters the soil reflection thereby modifying the albedo (α). Attempts have also been made to use several meteorological and plant parameters for soil water content estimation. Geiser *et al.*, (1982) developed an empirical irrigation scheduling method for Minnesota that used net radiation, humidity and surface-air temperature difference ($T_c - T_a$) to estimate soil water content for corn. Werner and Slack (1983) also observed that higher ($T_c - T_a$) were correlated with lower soil water contents.

Several other researchers (Ehrler *et al.*, 1978; Idso *et al.*, 1981 and Howell *et al.*, 1984) have reported good relationship between soil water content and daily plant-surface temperature differences. They have used infrared thermometry for measuring plant surface temperatures. Studies on soil moisture variations in the surface layer and the movement of moisture through the soil have been made by Ramdas and Malik (1942), Ramdas (1951), Baier (1969). Biswas and Dasgupta (1979) estimated soil moisture at deeper depths from soil moisture at or near the surface layer by fitting regression equations.

In order to explore the possibilities of estimating soil water content from well-watered (irrigated) and partially irrigated wheat crop grown in the black cotton soil at Pune situated in the semi-arid tract of India an attempts has been made to (i) formulate the soil water content as a function of canopy temperatures and other meteorological parameters, (ii) compare the soil water content estimations using canopy temperature and other predominant meteorological/plant parameter, (iii) compare the soil water content estimations using meteorological and plant parameters excluding canopy temperature and (iv) compare the soil water content estimations at different depths of the soil profile.

2. Material and methods

Weekly soil temperature and soil moisture data were recorded under irrigated, partially irrigated wheat and

bare-dry soil. The crop was grown in the field of College of Agriculture, Pune, adjacent to Central Agromet Observatory (CAgMO), IMD. Weekly soil moisture observations were recorded from 5, 15, 30, 45 and 60 cm depths both from irrigated and partially irrigated wheat and bare-dry soil plots by gravimetric method. To observe the sensitivity of soil profile to temperature and other environmental conditions, soil water contents were computed for different depths *viz.*, 0-10, 0-20, 0-42.5 and 0-80 cm by multiplying soil moisture content with depth intervals and bulk density which are designated as SW1, SW2, SW3 and SW4 respectively. The differences between canopy and ambient air temperatures were measured using portable infrared thermometer. Canopy temperature for irrigated and partially irrigated plots were measured at a height of 1.2 m with a 45° angle of incidence. The ambient air temperature was also recorded at 1.2 m height. Continuous record of net and reflected radiation were made using Net pyrradiometers and inverted pyranometer respectively. These instruments were installed above the crop canopy of irrigated, partially irrigated wheat and on bare-dry soil plots. Global radiation was recorded using pyranometer installed at CAgMO adjacent to wheat plots. Relative humidity, wind speed, soil temperatures from two soil depths *viz.*, 5 and 20 cm depths at 0730 and 1430 hours IST were measured from irrigated, partially irrigated wheat and bare-dry soil plots and averaged over each sampling period at weekly intervals. Plant height, number of tillers, leaf area index and number of panicles measured from irrigated and partially irrigated plots were also averaged over each sampling period at weekly interval.

3. Model description and statistical analysis

As the soil water content in the profile alters the albedo and various energy balance components and affect local convection systems, attempts have already been made by scientists to express the energy balance equation for a soil surface (Mahrer and Pielke, 1977 and McCumber and Pielke, 1981). The energy balance components at the soil surface under bare soil condition as well as under crop with irrigation and with partial irrigation in the drying cycle are influenced not only by the meteorological parameters *viz.*, net solar radiation, wind speed, relative humidity and temperature both soil, canopy and air but also by the crop characteristics particularly the leaf area index. Some of these parameters are mutually correlated (Shih, 1984). Under such condition, it becomes difficult to use same mathematical form to estimate soil water content for bare-dry soil, irrigated and partially irrigated plots. Thus an attempts has been made in this paper to develop relationship between soil water content and other environmental as

TABLE 1

Multiple regression equation for the estimation of soil water content at different depths under bare-dry soil

Soil water content (cm)	Eqn. No.	Regression Eqn.	R ²	F value
SW1 (0-10 cm)	1	SW1 = 1.21 – 0.0007Gr	1.26	0.26
	2	SW1 = –0.13 + 0.005Rn	6.51	1.46
	3	SW1 = 1.13 – 0.0032Rr	0.98	0.28
	4	SW1 = –0.11 + 0.054α	1.81	0.38
	5	SW1 = 0.88 – 0.0024ST1	1.90	0.0004
	6	SW1 = 1.48 – 0.02ST2	2.1	0.45
SW2 (0-20 cm)	7	SW2 = 5.83 – 0.0056Gr	21.83	5.86
	8	SW2 = 5.78 – 0.031Rr	24.82	6.93
	9	SW2 = 4.51 + 0.19α – 0.15ST2	28.38	3.96
	10	SW2 = 5.89 – 0.14ST1	19.63	5.13
	11	SW2 = 3.50 + 0.01Rn – 0.03Rr	35.58	5.52
	12	SW2 = 6.98 – 0.12ST2	23.24	6.36
SW3 (0-42.5cm)	13	SW3 = 19.99 – 0.008Gr – 0.25ST2	63.27 **	17.22
	14	SW3 = 15.41–0.086Rr	51.88 **	22.69
	15	SW3 = 19.85 + 0.29ST1 – 0.56ST2	63.31 **	17.25
	16	SW3 = 14.89 + 0.36 α	61.73 **	16.13
	17	SW3 = 16.89 + 0.016Rn + 0.35ST1 – 0.61ST2	68.44 **	13.73
	18	SW3 = 19.60 – 0.37ST2	56.56 **	27.35
SW4 (0-80 cm)	19	SW4 = 30.28+0.026Rn–0.068Rr+0.67ST1–0.83ST2	84.60 **	24.73
	20	SW4 = 31.10 + 0.40α + 0.46ST1 – 0.97ST2	77.17 **	22.09
	21	SW4 = 36.93 – 0.01Gr + 0.48ST1 – 0.78ST2	80.09 **	25.48

Where,

Rn = Net radiation, Wm⁻²; Gr = Global radiation, Wm⁻²; Rr = Reflected radiation, Wm⁻²; α = albedo (%); ST1 = Mean soil temperature (°C) at 5 & 20 cm depths at 7.30 hours; ST2 = Mean soil temperature (°C) at 5 & 20 cm depths at 14.30 hours; ** = 1% level of significance

well as plant parameters by using stepwise multiple regression analysis. The form can be expressed as :

$$SW_i = a_0 + a_1T_c + a_2(T_c - a) + a_3R_n + a_4\alpha + a_5RH + a_6W + a_7ST_1 + a_8ST_2 + a_9Gr + a_{10}R_r + a_{11}LAI \quad (1)$$

where,

SW_i = Soil water content in cm at different depths, viz., 0-10, 0-20, 0-42.5 and 0-80 cm respectively

T_c = Canopy temperature (°C)

T_c-T_a = Difference of canopy and air temperature (°C)

Gr = Global radiation (Wm⁻²)

Rn = Net radiation (Wm⁻²)

Rr = Reflected radiation (Wm⁻²)

α = albedo (%)

RH = Mean relative humidity (%)

W = Mean wind speed (km/hr)

ST1 = Mean soil temperature (°C) of 5 & 20 cm depths at 0730 hours

ST2 = Mean soil temperature (°C) of 5 & 20 cm depths at 1430 hours

LAI = Leaf area index

TABLE 2

Multiple regression equation for the estimation of soil water content at different depths under irrigated wheat

Soil water content (cm)	Eqn. No.	Regression Eqn.	R ²	F value
SW1 (0-10 cm)	1	SW1 = 1.66 - 0.0002Tc + 0.72LAI	47.07 *	5.78
	2	SW1 = 7.26 + 0.07(Tc-Ta) - 0.18ST2	52.47 *	7.17
	3	SW1 = 1.11 + 0.12W + 0.81LAI	51.83 *	6.99
SW2 (0-20 cm)	4	SW2 = 14.32 - 0.28Tc + 0.38(Tc-Ta)	41.9 *	4.69
	5	SW2 = 0.36 + 0.20W + 1.20LAI	44.29 *	5.17
SW3 (0-42.5 cm)	6	SW3 = 33.44 - 0.42Tc + 0.65(Tc-Ta) - 0.30ST2	67.64 **	8.36
	7	SW3 = 8.71 + 0.42W + 2.26LAI	52.10 *	7.07
SW4 (0-80 cm)	8	SW4 = 51.65 - 0.87Tc + 1.19(Tc-Ta)	56.14 *	8.32
	9	SW4 = 15.12 + 0.11RH + 0.53W + 2.19LAI	62.30 **	6.61

Where,

Tc = Canopy temperature (°C); LAI = Leaf area index; W = Wind speed (km/hr); Tc-Ta = Canopy-air temperature difference; RH = Mean relative humidity (%); ST2 = Mean soil temperature (°C) at 14.30 hours

* = 5% level of significance, ** = 1% level of significance

4. Results and discussion

Using the model presented in equation (1), the relationships between soil water contents at different depths (*i.e.* SW1, SW2, SW3 and SW4) and remotely sensed canopy temperature, canopy-air temperature difference, other meteorological parameters and LAI were established by stepwise multiple regression technique (Tables 1, 2 and 3). Soil water content for each of the depth was analyzed for eleven cases forcing one parameter at a time in the model. We have presented the results in three major categories *viz.*, bare dry soil, irrigated and partially irrigated wheat and two sub-categories one with canopy temperature along with predominant meteorological or / and plant parameters and the second one with other meteorological and plant parameter. With the objective of using remotely sensed canopy temperature as one of the predictor in the equation, the forcing was done with canopy temperature for predicting each of the four water content for the four depths.

4.1. Estimation of soil water content under bare-dry soil

It is interesting to note that SW1 and SW2 under bare-dry soil condition were not significantly related to none of the meteorological parameters (Table 1). Meteorological parameter accounted for only 1% to 6.5% and 19.63% to 35.58% variation of soil moisture in the 0-10 and 0-20 depths respectively thereby indicating that these meteorological parameters alone or in combination are not in a position to predict the soil moisture content in the surface layers. This also indicates that inter-relationship between moisture content and energy balance

processes including heat and water transfer in the surface is disrupted when soil moisture content reaches near hygroscopic level. However, considerable improvement in predicting the soil moisture for the deeper depths was observed in cases of SW3 and SW4. In case of SW3 the relationships with meteorological parameters accounted for 51.88% to 68.44% variation in soil moisture content in the depth of 0-42.5 cm. ST1 and ST2 along with Rn were found to be the best predictors of soil moisture content accounting for 68.44% variation. ST1 and ST2 accounted for 63.31% variation. When forcing was done with net radiation, the model accounted for another 5.13% variation more along with ST1 and ST2. ST1 and ST2 were found the most predominant parameters in this case. In case of SW4 further improvement were observed in the relationships between soil moisture content and meteorological parameters. Rn along with Rr, ST1 and ST2 were the best predictors for soil water content which accounted for 84.60% variation (Eqn. 19, Table 1). The second group of best predictors were Gr along with ST1 and ST2 which accounted for 80.09% variation. Thus Rn and Rr in combination with ST1 and ST2 or Gr in combination with ST1 and ST2 could be used respectively to estimate the soil water content under bare-dry soil.

4.2. Estimation of soil water content under irrigated wheat

Under irrigated wheat Tc along with Tc-Ta and ST2 gave the best regression model for predicting water content at 0-42.5 cm depth. This model accounted for 67.64% variation in water content and was found significant at 1% level. Canopy-air temperature difference was found to be the most predominant parameter along with canopy temperature which

TABLE 3

Multiple regression equation for the estimation of soil water content at different depths under partially irrigated wheat

Soil water content (cm)	Eqn. No.	Regression Eqn.	R ²	F value
SW1	1	SW1 = - 0.24-0.03Tc + 0.045RH	86.73**	35.94
(0-10 cm)	2	SW1 = - 0.19-0.27Rn + 0.04RH	87.74**	39.38
SW2	3	SW2 = 2.89 - 0.059Tc + 1.9LAI	78.17**	19.69
(0-20 cm)	4	SW2 = 3.62 - 0.008Rn + 1.55LAI	82.88**	26.62
SW3	5	SW3 = 8.41 - 0.14Tc + 3.79LAI	73.07 **	14.92
(0-42.5 cm)	6	SW3 = 10.05 - 0.02Rn + 2.97LAI	78.95**	20.63
SW4	7	SW4 = 15.05 - 0.21Tc + 7.62LAI	73.88**	15.56
(0-80 cm)	8	SW4 = 22.02 - 0.04Rn + 5.57LAI	81.95 **	24.98

Where,

Tc = Canopy temperature (°C); LAI = Leaf area index; Rn = Net radiation (Wm⁻²);

RH = Mean relative humidity (%); ** = 1% level of significance

accounted for only 41.9% and 56.14% variation respectively for water contents of 0-20 and 0-80 cm depths. For surface layer (0-10 cm) LAI was found to be the most predominant predictor and the equation developed with this parameter along with canopy temperature accounted for 47.07% variation in water content (Table 2). When forcing was done with other meteorological parameters except canopy temperature, the LAI was found to play the most important role along with relative humidity. LAI was found to be the most predominant parameter for each of the four depths. When forcing was done with wind speed, the combination of LAI and wind speed were found to be the best predictors of soil water content for 0-10, 0-20 and 0-80 cm depths which accounted for about 5%, 2% and 6% more variation compared to that of the combination of Tc and LAI, Tc and (Tc-Ta) (Table 2). However, for 0-42.5 cm depth Tc, (Tc-Ta) and ST2 were found to be the best predictors and accounted for about 15% more variation of soil water content. This may be due to non limiting water supply with frequent irrigations under medium deep black cotton soil when root zone remain restricted in the upper layers.

4.3. Estimation of soil water content under partially irrigated wheat

Relationships worked out with soil water contents and meteorological and plant parameters for the partially irrigated wheat show a clear shift not only in accounting for percent variation in the soil water contents but also in the predominant meteorological parameters for different depths (Table 3). Canopy temperature along with RH as well as Rn along with RH accounted for the maximum variation (86.73% and 87.74% respectively) of soil water content at 0-10 cm depth (Table 3, Eqn. Nos. 1 and 2). This is in contrast to the irrigated wheat and bare-dry soil

plots where variation accounted for were in the range of 47.07% to 52.47% and 0.98% to 6.51% respectively. It is also interesting to note that mean RH and LAI were the most predominant parameters accounted for the maximum variation of soil water content for the surface and deeper depths respectively. Under partially irrigated wheat in the drying cycle when soil water content decreased gradually due to evaporation loss and water extraction by the root, Tc in combination with LAI accounted for 78.17%, 73.07% and 73.88% variation in soil water content for the depths of 0-20, 0-42.5 and 0-80 cm respectively. Amongst the other meteorological parameters, Rn was found to be the predominant parameter in explaining the variation of soil water content of SW2, SW3 and SW4. Rn in combination with LAI accounted for 82.8%, 78.9% and 81.95% variation of soil water content respectively for SW2, SW3 and SW4. The R² values are greater than 73% in all the four cases. This implies that soil water content for all the depths can be estimated using remote sensing technique as well as by the conventional method of measuring meteorological parameters along with LAI measurement.

The combination of temperature and radiation parameter has shown considerable improvement in the model formulation. This suggests that further improvement in the simulation of soil water content may result from the combination of other meteorological parameters. For deeper depths soil temperature may be considered for further improvement. Further study is required to optimize the parameter formulation.

5. Conclusion

(i) Mean soil temperature at 0730 and 1430 hours, leaf area index, mean relative humidity and wind speed were

found to be most predominant predictors of soil water content under bare-dry soil, irrigated and partially irrigated wheat.

(ii) The meteorological parameters alone or in combination could not predict the soil water content in the surface (0-10 cm) and (0-20cm) layers under bare-dry soil. However, soil water content for deeper depths *viz.*, 0-42.5 and 0-80 cm could be predicted with reasonable accuracy using mean soil temperature, net and reflected radiation.

(iii) Remotely sensed canopy temperature, canopy-air temperature difference and afternoon mean soil temperature were the best predictors which accounted for 67.64% variation of soil water content for 0-42.5 cm depth under irrigated wheat. The combination of leaf area index and wind speed or leaf area index, wind speed and mean relative humidity were found to be the best predictors of soil water content for 0-10, 0-20 and 0-80 cm depths and accounted for 51.83% to 62.30% variation of soil water content.

(iv) Canopy temperature alongwith mean relative humidity and net radiation alongwith mean relative humidity accounted for the maximum percentage of variation (86.73% and 87.74% respectively) of soil water content at 0-10 cm depth under partially irrigated wheat. A combination of radiation and leaf area index or net radiation and leaf area index can be used to predict the soil water content of deeper depths under partially irrigated wheat.

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