Soil moisture detection using soil thermal response

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New approach of detecting soil moisture level using soil thermal response was introduced This approach analyzes soil thermal response on daily bases and relates soil temperature fluctuation to that of ambient temperature. The best depth was found to be 5-cm. Two measures were introduced for evaluating soil moisture, one based on full day monitoring which may suit digital control systems, and the other a simplified measure that may suit normal farmers situation. Reasonable accuracy was possible with 0.95 of confidence in moisture detection. This approach expected to simplify soil moisture detection for practical use with limited sensors in addition to obtaining soil temperature, which is needed in many agricultural activities.

تقدم هذه الدراسة طريقة لتقدير رطوبة التربة باستخدام الاستجابة الحرارية للتربة. يتم تحليل استجابة التربة الحرارية يوميا مع تحديد علاقة التذبذب في درجة حرارة التربة مع ما يقابلها من درجة حرارة الهواء المحيط. وجد إن افضل عمق عند ٥ سم لتطبيق هذه الطريقة و لجميع تركيبات التربة. تم تقديم محددين يمكن الاعتماد عليها لتقدير رطوبة التربة. الأول يعتمد على تحليل بيانات اليوم الكامل و يناسب نظم التحكم و المراقبة الرقمية أما الأخر فهو محدد مبسط و الذي يمكن الاستفادة منه في حال الاستخدام اليدوي و المزارعين العاديين. يتوقع أن تفيد هذه الطريقة في تسهيل تقدير رطوبة التربة للأغراض التطبيقية في الحقول و البيوت المحمية بتجهيزات محدودة و نحو إدارة افضل للمصادر المائية.

Keywords: Soil moisture detection, Soil temperature, Water management, Arid climate

1. Introduction

In sustainable agriculture, managing water resources is one of the great challenges facing farmers everywhere. Automatic control systems have been around for many years and their application spread to many aspects of our life. The spread of control systems in water management practices in fields or greenhouses has been inhabited mostly by the deficiency of reliable moisture detectors. Of course, the sensors available for moisture measurement vary from manual sensors like tensometers up to the most advance Time Domain Refractometer (TDR). In spite of availability of such sensors, most of them either are not for normal agricultural application with long period of installation or too much sophisticated for farmers' use.

Nowadays, soil temperature measurement is recommended for most agricultural activities especially during the beginning of crops life cycle. In fact, many sensors that measure soil moisture include soil temperature measurement as an integral part. Soil temperature within the top 25 cm of soil surface layer has a lot of interference with soil physical and thermal properties [1]. In pervious study on constant soil moisture lysimeter [2], it was noticeable the damping effect of constant soil moisture on soil top layer temperatures. In fact, soil temperature showed very small daily fluctuation during long period of monitoring. This case encouraged the current study in which the visibility of detecting soil moisture is being considered.

Since it is desirable to measure soil temperature within the top layer of the soil, it is possible to look for some type of relation to soil moisture. Soil temperature sensors are mostly rugged, cheap and simple to use. These sensors are available everywhere and interchangeable. To detect some variable quantity, it is basic to find some consistent relationship between the measured and measuring quantities. It is preferred to have linear relationship with some physical meaning. Furthermore, this relation should be as simple as possible for typical agricultural application.

2. Experimental arrangement

Experimental work was executed using three boxes with surface cross section 100 cm by 50 cm and 50 cm depth. Boxes sides were insulated with 10 cm impermeable Styrofoam. At bottom, boxes were allowed to exchange water with the bottom layer of soil. Each box was placed inside field cavity to give equal surface level with the field surface. Each box contains one type of soil, which included extreme cases of soil texture (sandy soil, clay soil and organic soil). Each soil was mixed thoroughly to insure homogeneity and left at the field for 10 days before starting the activities.

Measurement was implemented using type-T thermocouples at soil depths; zero cm, 5 cm, 10 cm and 20 cm in addition to the ambient temperature. PC-Computer with analog to digital converter was used for data collection with sampling interval of 60 sec. More meteorological data was available from nearby weather station including soil temperatures at various depths under natural conditions.

3. Random signal analysis

Soil temperature is widely modeled as a periodic sinusoidal signal [3-5]. Such modeling would be sufficient during numerical computation of soil environment; however, this cannot be the case when real time soil temperature is needed for water management systems in fields and greenhouses. Soil temperature is affected by several factors and mostly by soil moisture distribution at specific location and time. Consequently, real time signal of soil temperature cannot be predicted in precise manner before happening leading to the use of random signal analysis, which is mostly appropriate to use in this case. The period of completed daily cycle of soil temperature near surface is 24 hours. In addition, most decisions on water management practice are mostly taken on daily bases.

For any signal that cannot be modeled in some deterministic mathematical model, it can be regarded as random signal. Describing such signals can be possible using random signal analysis dealing with variation and rapidity of the signal, [6]. To define the characteristics of a random signal, some measures can be evaluated.

First characteristic of the signal is the average value $\overline{q(t)}$ for a random signal q (t):

$$\overline{q(t)} = \lim_{T\to\infty} \frac{1}{T}\int_0^T q(t)dt . \qquad (1)$$

Where t represents time interval and T is full period of daily measurement.

In spit of knowing that $\overline{q(t)}$ has no meaning of how large or small the fluctuations are, it is normally subtracted from each point of measured signal ensample producing an average of zero.

The most widely used measure of the magnitude of a random fluctuation is the mean squared value $\overline{q^2(t)}$ defined by:

$$\overline{q^2(t)} = \lim_{T\to\infty} \frac{1}{T}\int_0^T q^2(t)dt . \qquad (2)$$

In numerical processing, eqs. (1,2) can be rewritten as follows, respectively:

$$\bar{q} = \lim_{N\to\infty} \frac{1}{N}\sum_{k=0}^{N-1} q_s(k\Delta t) , \qquad (3)$$

$$\overline{q^2} = \lim_{N\to\infty} \frac{1}{N-1}\sum_{k=0}^{N-1} \left[q_s(k\Delta t) - \bar{q}\right]^2 , \qquad (4)$$

where Δt can be changed according to sampling rate. In many cases, it is desirable to have some measure with physical dimension as q and this encourages the use of Root-Mean-Squire (RMS) value.

$$q_{RMS} = \sqrt{\overline{q^2}} . \qquad (5)$$

In addition to these measures, it is possible to define the probability density

function $W_i(q_i)$ for inspecting temperatures distribution as follows:
Define the probability of $[q_{i1} < q_i < (q_{i1}+\Delta q_i)]$ as;

$$P[q_{i1},(q_{i1}+\Delta q_i)] = \lim_{T\to\infty} \frac{\sum \Delta t_i}{T} . \quad (6)$$

Then amplitude-distribution function becomes:

$$W_i(q_i) = \lim_{\Delta q_{i1}\to 0} \frac{P[q_{i1},(q_{i1}+\Delta q_i)]}{\Delta q_i} , \quad (7)$$

where $W_i(q_i)dq_i$ is the probability that q_i lies in dq_i. These analyses were applied for daily collected data samples.

4. Results and descussion

Measurement recording was continuous before, during, and after water application. Fig. 1 shows the results at four depths of soil; 0 cm, 5 cm, 10 cm and 20 cm in addition to ambient temperature for hours after water application. At start, soils were completely dry. The next day water was applied to saturation. It is apparent the damping effect of moisture level on soil thermal response. Indeed all depths of soil experienced large reduction of soil temperature especially the upper depths.
To investigate the visibility of using soil thermal response as moisture indicator, different analysis equations, as introduced early, were tested at various depths. Since soil temperature is subjected to daily and seasonal changes and our goal to filter the seasonal change and inspect daily changes, reference temperature was needed. It documented that daily average temperature is correlated to daily average of soil temperatures also daily ambient range is correlated to soil temperatures at the top of soil layer [7]. Consequently, it was found that using the ratio between soil temperatures and ambient temperature will be sufficient to detect soil moisture. This can be defined as Soil to Ambient Thermal Ratio (SATR) and in notation form is:

$$\mathrm{SATR} = \frac{Ts_{RMS}}{Ta_{RMS}} . \quad (8)$$

Where Ts_{RMS} and Ta_{RMS} donate root mean square of soil temperature at specific depth and root mean square of ambient respectively. This ratio relates the daily average range of soil temperature to that of ambient. If the ambient range is high because of seasonal change, soil temperature range will be high and visa versa. The only interruption for that will be water application. SATR was evaluated for all depths under consideration starting at surface to 20 cm depth. All depths showed some indication of moisture change but the best depth was at 5 cm for all type of soils. SATR gave unity for dry soils and increase with the increase of soil moisture content. Fig 2 shows SATR as a function of days after irrigation for three soils, organic, clay and sandy soil. When soils lost most of their field capacity moisture, the indicator gave values near or equal to unity. When moisture level became high, SATR approached three with some deference depending on soil texture. Clay soil showed lowest decline with time, which is normal situation with clay soil that tended to hold water. Fig. 3. shows the correlation between soil moisture and SATR, reasonable correlation was possible for all soil texture with linear relationship. Highest correlation coefficient was 0.978 for organic soil then sandy soil showed 0.961 correlation coefficient and finally clay soil gave 0.936 correlation coefficient.

During the experiment, SATR ranged between one and three. Here the most important characteristic of moisture indicator is the lower limit, which indicates when to apply water, which in the current case is one. From fig. 3 this corresponds to about 50% of field capacity for sandy soil. Static sensitivity can be defined by the following equation:

$$\frac{\phi_5}{\mathrm{SATR}} = K . \quad (9)$$

Where ϕ_5 donates soil moisture content based on dry weight at 5 cm depth of. K was 3.652 for organic soil, 6.228 for clay soil and 4.74 for sandy soil.

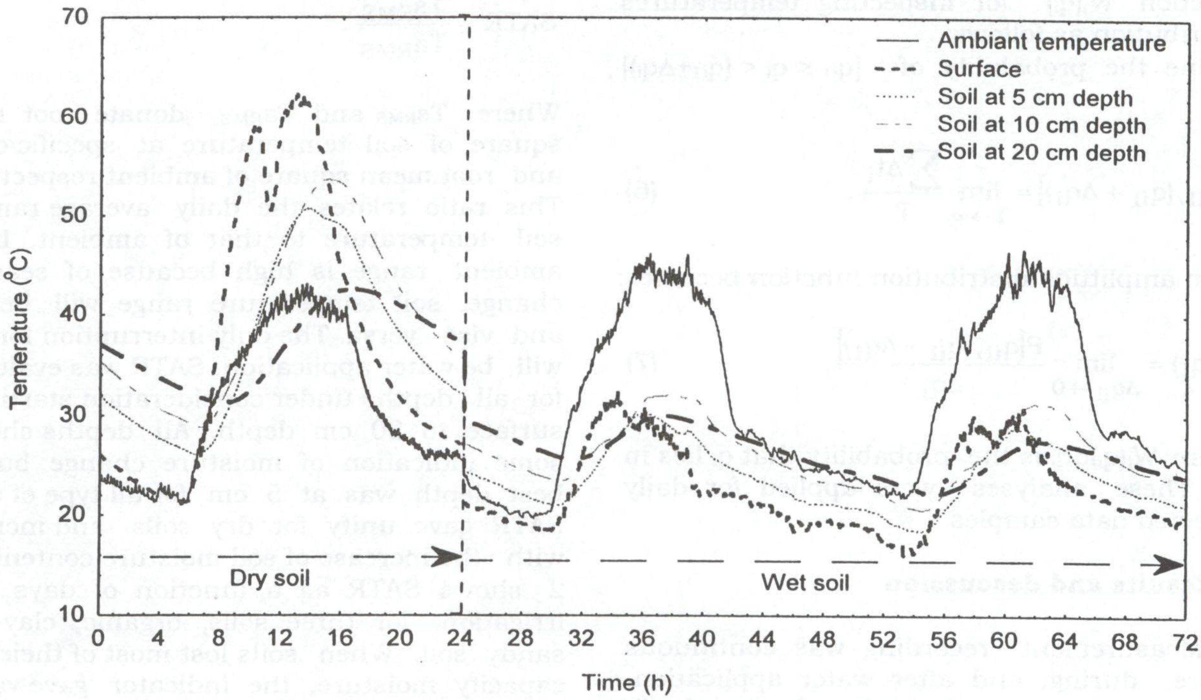

Fig.1. Soil temperature response as a result of water application.

To inspect the effect of seasonal change on SATR data were analyzed for full year from nearby weather station under natural condition of arid climate. Fig. 4 shows monthly average of SATR as a function of month of year 1997. It is noticeable the stability of the indicator during the year. On the same graph, ranges of soil moisture levels are superimposed. When implementing control system, the lower limit that should initiate the start of water application system is close to one. The system should apply specific quantity of water depending on field capacity or experience and this should be applied as a function of time. After water application completion, recording of soil temperature at 5 cm depth and ambient temperature should be recorded on hourly bases. Whenever the SATR reach one the system will go on.

This case is visible when digital control and processing is possible; nevertheless, in extreme cases when the farmer has very limited instrumentation, it is possible to measure the maximum and minimum soil temperature at 5 cm and ambient maximum and minimum then Appling the following formula to get some estimate of SATR:

$$E(\text{SATR}) = \frac{Ts_{max} - Ts_{min}}{Ta_{max} - Ta_{min}}, \qquad (10)$$

Where E indicates estimation. Ts_{max} and Ts_{min} indicate soil daily maximum and minimum temperatures respectively. Ta_{max} and Ta_{min} represent daily maximum and minimum of ambient temperature respectively. Using eq. (10) will simplify water moisture indication procedure with very limited equipment, which may suit most farmers.

To inspect the distribution of soil hourly data of temperatures, eq. (6) was utilized for soils at 5 cm depth under different condition of moisture content. Fig. 5 shows four graphs of probability Density Functions (PDF). Graph (a) represents PDF of ambient temperature, graphs (b), (c), and (d) show the PDFs for soil temperature at 5 cm depth under dry, saturated and 50% moisture content of field capacity. It is evident the change in saturated distribution compared with that of dry soil which closely resemble ambient temperature distribution.

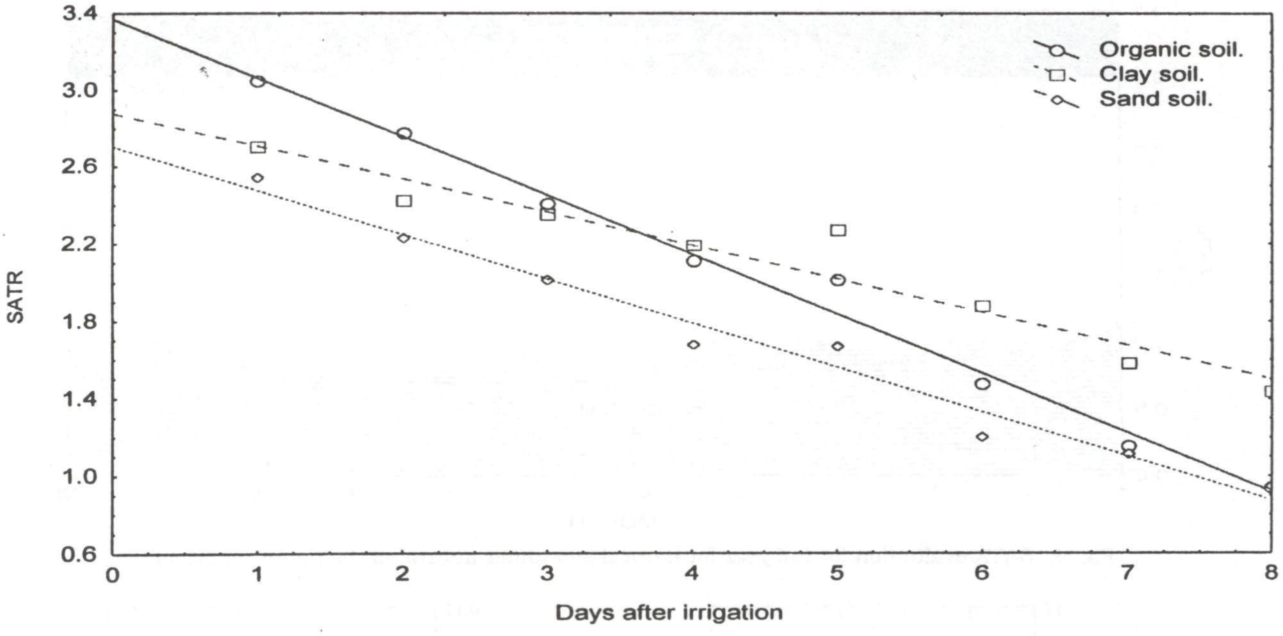

Fig. 2. SATR as a function of days after water application for three types of soil.

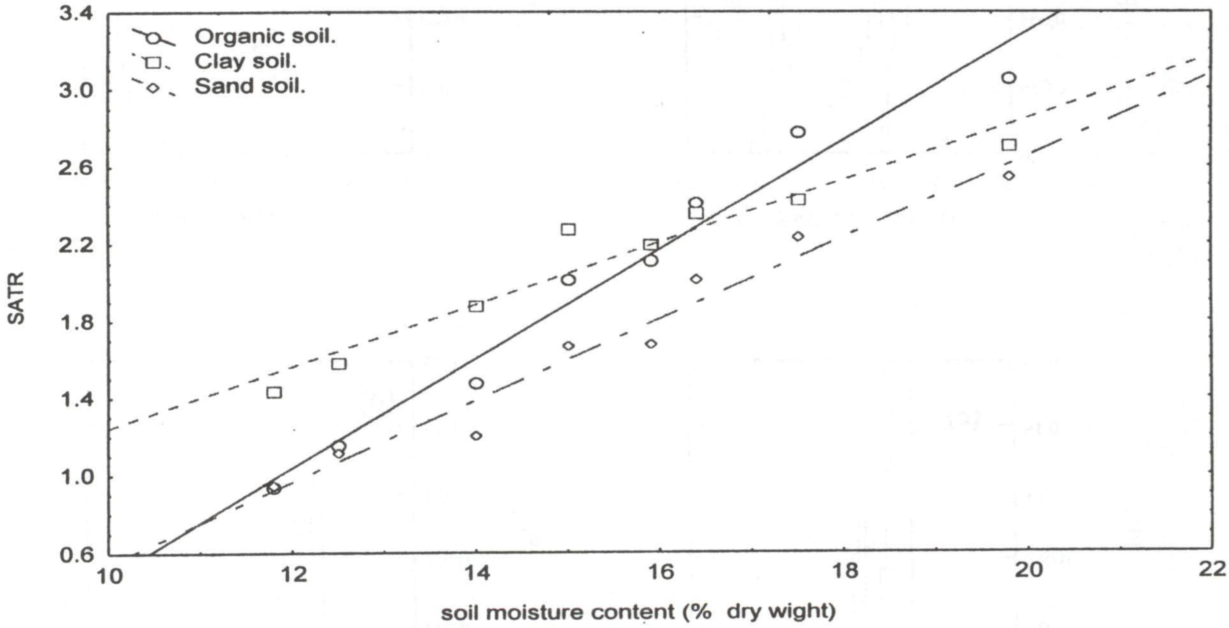

Fig. 3. SATR as a function of soil moisture content.

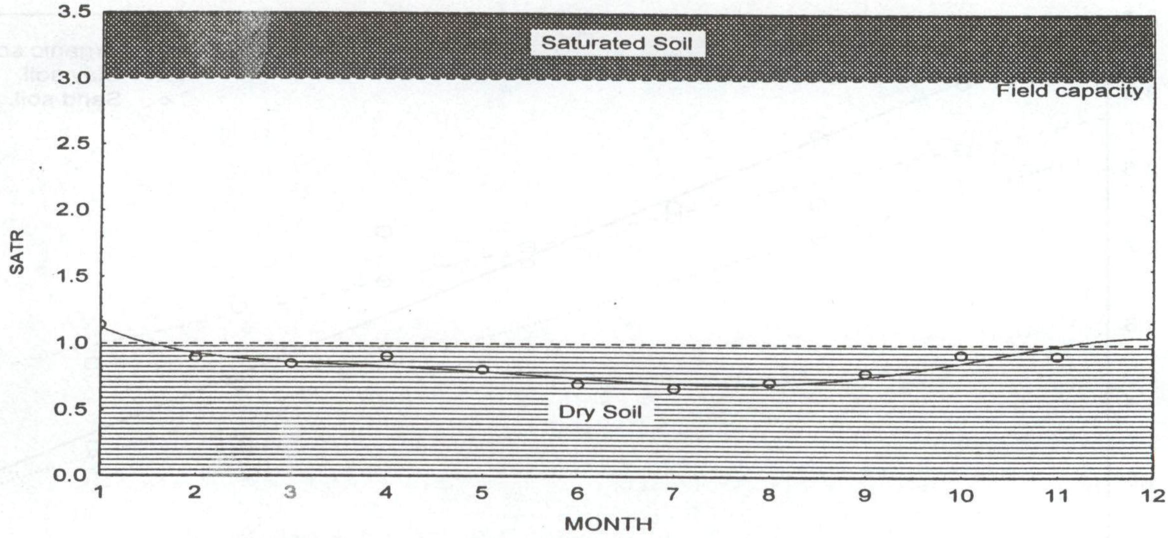

Fig. 4. SATR evaluation for full year for natural soil under natural arid climate condition.

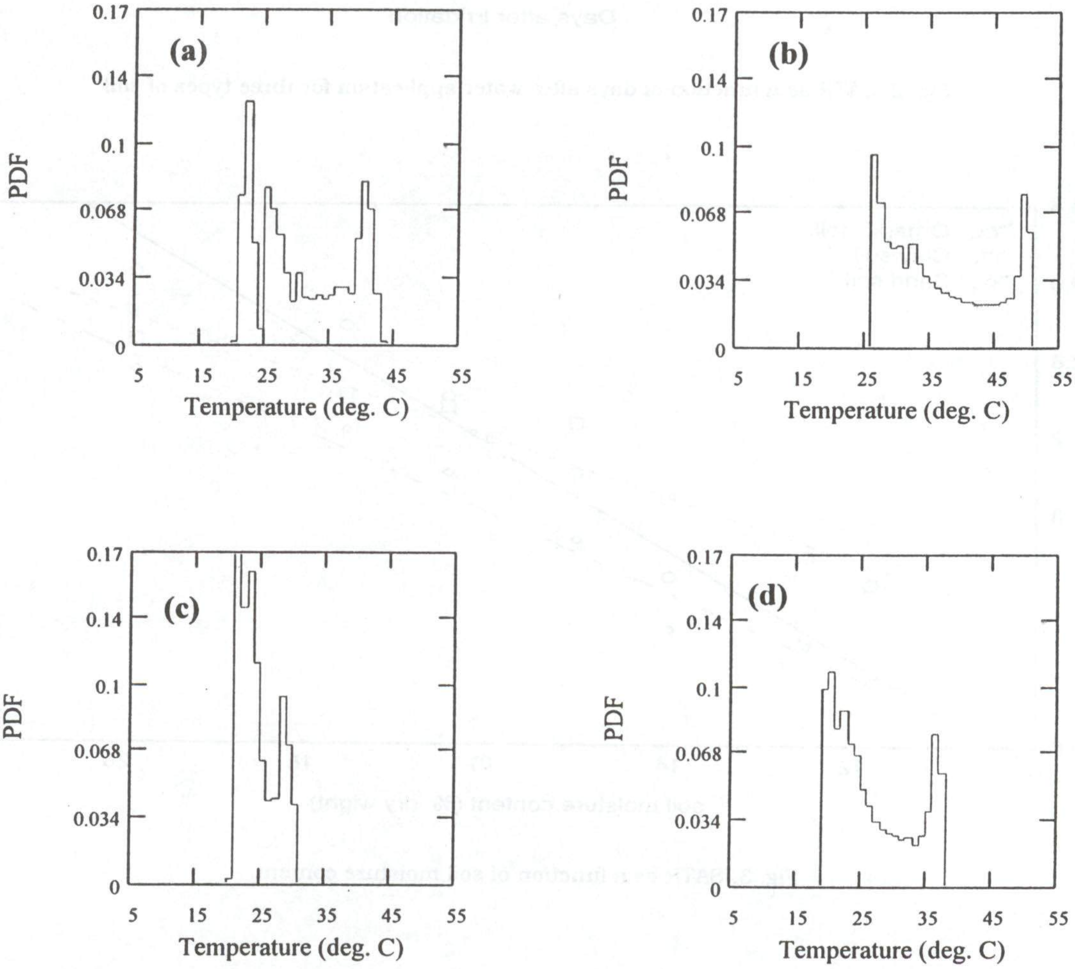

Fig. 5. Probability density function (PDF) for hourly temperature of (a) ambient, (b) dry soil at 5 cm depth, saturated soil at 5 cm depth and (d) simi-dry soil at 5 cm.

6. Conclusions

The visibility of detecting soil moisture using soil thermal response and relying only on temperature sensors was demonstrated. Detecting soil moisture applied using two measures one suitable for digital monitoring and control systems and the other for manual farmers use. Confidence of 0.95 was possible for all type of soil under consideration. The analysis was conducted under arid climate condition and other type of climate may need farther research beside the presence of large crops.

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Received June 17, 2001
Accepted December 5, 2001