An Array for Measuring Detailed Soil Temperature Profiles

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Soil temperature dynamics can provide insights into soil variables which are much more difficult or impossible to measure. We designed an array to measure temperature at precise depth increments that is also tough enough to be driven into the soil with a mallet. Data were collected to determine if the construction materials influence surface and near-surface temperature estimates during peak insolation. In dry sand, arrays disagreed with a bare reference thermistor at the soil surface by -6 to +5°C, averaging +0.42°C. At depths of 1 to 4 cm, the arrays averaged from 3 to 1°C warmer than measurements taken with bare thermistors during a sunny day, indicating that construction material was conducting heat from the surface at a greater rate than the sand. The average difference between arrays and a reference thermistor at the 13-cm depth in sand was -0.30°C (standard deviation = 0.42°C). Under field conditions in a dry silt loam, the arrays did not show the near-surface daytime bias, and agreed within 1°C of independent measurements at the 2- and 5-cm depths. The array facilitates multiple measurements of detailed temperature profiles. These measurements are capable of detecting the effect of soil conditions such as tillage, layering, or water content on the flow of heat at a resolution of centimeters.

In semiarid climates, the soil surface is sometimes tilled with the sole intent of reducing evaporation during the dry summer period. While models exist which predict how water and heat move through soils, these models usually require knowledge of unsaturated hydraulic conductivity, thermal diffusivity, and soil bulk density. Tillage causes appreciable variability in soil porosity, average size of voids, surface roughness, and other conditions that influence heat and water movement. One measurement that can be made directly and accurately under these conditions is temperature. Currently efforts are underway to estimate the more difficult-to-measure hydraulic properties from the spatial distribution of temperature waves produced daily by the sun (Heitman et al., 2008a; Heitman et al., 2008b). The ease with which we can produce high resolution temperature profiles under field conditions will, to a large extent, determine how quickly these efforts are developed and utilized.

Thermocouples or thermistors are commonly used as temperature sensors, because they are reliable, stable, and can be recorded with automated equipment. The most common configuration is an individual thermocouple or thermistor installed at the end of a cable. These can be inserted at any desired depth, but unless the connecting cables are extremely thin, they should be run horizontally at the same depth for several centimeters to make sure heat from other depths is not conduct-

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ed through the wire, especially at installations near the surface. To accomplish this, the sensors are often installed by digging a trench and inserting the sensors into the side of the trench.

When installing individual sensors, it is difficult to ensure that the vertical spacing remains precise and constant throughout the experiment. It is also difficult to install sensors at close intervals without causing soil disturbance within the zone of measurement. Sensors can be placed farther apart horizontally to facilitate smaller vertical spacing, but spatial differences in the soil surface may produce different temperature profiles at different locations.

To make it practical to produce numerous detailed temperature profiles under both tilled and untilled surface conditions, we developed a method of building solid arrays of thermistors. The goal was to be able to drive the array directly into the soil with a mallet, and then record temperatures at 1-cm intervals down to a 20-cm depth or below, and 5-cm intervals down to a maximum of a 45-cm depth.

The basic electronic design of such an array has been described before (McInnes, 2002). Thermistors are used for the temperature sensor, and a datalogger is used to read the voltage drop and current across each thermistor, from which the resistance is calculated. Resistance of a thermistor is directly and predictably related to its temperature. What has not been described before is a practical method to build an array of temperature sensors at close intervals that is sturdy enough to withstand being driven into the soil with a mallet. We are also not aware of any tests to determine how accurately such a device estimates surface and near-surface temperatures, given that the device might transmit heat more readily than soil.

MATERIALS AND METHODS

Construction and Operation

The thermistors (10 K ohm, NTC, ± 10%, 135–103F AG-J01, Honeywell, Morristown, NJ.) were mounted along the edge of a circuit board and wired in series so that they shared a common current (Fig. 1). A cable was attached to the circuit board to supply power from the datalogger and measure the resistance of each thermistor. After installing the electrical components and connecting cable, the entire circuit board was wrapped in layers of fiberglass and epoxy resin, with the addition of two strips of carbon fiber to increase stiffness over the length of the array. The resultant device was very tough, stiff, and waterproof. Many plastics conduct heat at about the same rate as soil (McInnes, 2002). Carbon fiber has an even lower heat conductivity and heat capacity, and would be a good reinforcement material for embedding the circuit board except that it is electrically conductive and this makes it difficult to prevent short circuits. We chose to use mostly glass fiber reinforcement with two carefully insulated strips of straight carbon fiber positioned on each side for stiffness. The encapsulated array was about 9-mm thick where the thermistors were located.

The circuit board includes a simple current-regulating circuit (LM 234Z, National Semiconductor; www.national.com) and two precision resistors to measure the current running through the thermistors. The current was about 0.008 mA, far less than what might cause the thermistors to self-heat. An inexpensive, uncalibrated thermistor was selected because it is possible to perform calibrations on the finished array to a much greater precision than is available from reasonably priced calibrated thermistors. A custom circuit board was designed using free software supplied by the circuit board manufacturer. This made precise spacing of each thermistor possible and simplified assembly.

The thermistors were positioned along one edge of the device so that they could be pushed into undisturbed soil that is on the opposite side of the array from the connecting cable. The array can be installed in the field facing south (in the northern hemisphere), so that the body of the array that sticks up slightly above the soil surface does not shade the soil directly touching the thermistors. The connecting cable exits the array about 5 cm below the soil surface so the cable can be buried horizontally in the soil for about 20 cm to prevent heat flow to and from the array (McInnes, 2002). Making a slot for the cable is the only soil excavation necessary during installation of the arrays in the field.

The datalogger setup required a multiplexer to switch between thermistors while making voltage measurements across the thermistors and the precision resistors. This allowed one datalogger to monitor multiple arrays, each with its own multiplexer connected to one of the datalogger's differential voltage ports. A 32-switch multiplexer can measure 30 thermistors and two precision resistors. We operated four multiplexers attached to four arrays on each datalogger, powered

Fig. 1. The circuit board and a finished array. The numbers on the circuit board mark depth in centimeters. There are two thermistors located at the soil surface position (0 cm).

by a 7 amp-hour battery. The battery lasts two or more months per charge.

The cost of materials to build the arrays is about $100 to $400 each depending on the source and quantity of materials purchased. One datalogger and multiplexer total about $2000. A detailed materials list, circuit board file, and datalogger and calibration program are available from the author.

Calibration and Testing

One reason for making the temperature arrays waterproof is ease of calibration. A well-stirred, well-insulated tank of water was used to assure that all thermistors were at the same temperature, and then the temperature of the water was determined using a calibrated, high accuracy temperature probe (THS-294–120, Thermoworks, Inc. Alpine, UT). The tank we used for a water bath was a vacuum insulated, 10 gallon stainless steel coffee urn. The neck of the urn was just large enough to fit the array cables, a thermostatically controlled circulating heater, and a refrigerated cold finger to balance the thermostat. We also placed an aquarium circulator in the bottom of the tank to ensure thorough and rapid mixing. The temperature of the water bath was adjusted from 1 to 50°C in steps of 5°C. When the temperature of the water bath was stable, the datalogger was used to record the resistance of each thermistor. The reciprocal of temperature (K^{-1}) was fit to a third-order equation of the natural log of resistance. The coefficients were then entered into the datalogger program for computation of °C from subsequent readings of resistance of each thermistor.

It is easy to test the array for accurate and consistent temperature output, but it is much more difficult to be certain that the temperature profiles measured in the field represent the actual temperature of the soil, especially under intense sunshine and windy conditions. For example, during development of the arrays it was found that if there is much material rising above the soil surface, this tends to cool the thermistor located at the soil surface during hot, sunny days. Furthermore, the array casing provides potential for heat transfer between the surface and subsurface that may differ from heat transfer occurring in surrounding soil.

To test the influence of the array casing on temperature measurements, we built one small array of five thermistors which were not encased in plastic for comparison. These thermistors were attached to a tightly stretched, thin thread to hold them at constant 1-cm intervals. The encased arrays and the bare array were installed into a bed of fine sand and measured for several hot, sunny days. The bare thermistor array had extremely small thermal mass, and all wiring was horizontal and at the same depth as each thermistor.

Temperature measurements from the encased arrays at the 13-cm depth in the sand were also compared to measurements made with the commercially calibrated temperature probe used for water bath calibrations (see above). The probe was inserted within 5-cm horizontal distance of each array, one at a time, and a reading was taken when the probe output stabilized to within a variation 0.01°C over a 3-s period. The 13-cm depth of insertion with full sand contact assured that the thin stainless steel probe would not conduct significant amounts of heat down to the measurement depth.

We next installed the arrays in a fallow field of Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll containing 32% fine to very fine sand, 60% silt, 8% clay, and about 7.3 g kg^{-1} organic C in the top 10 cm) under two tillage treatments (tilled and untilled) replicated in four complete blocks. We compared the array temperatures at the 2-cm depth to a fine-wire thermocouple (type K, 0.2 mm) and at the 5-cm depth to the calibrated temperature probe. The thermocouple was inserted into a small hole created by a metal rod. Both the thermocouple and probe were inserted into soil within 1- to 5-cm horizontal distance of the temperature arrays, and an attempt was made to find similar surface residue and soil conditions. It was assumed that 5 cm of soil contact was enough to prevent significant amounts of heat transfer down the metal probe over the approximately 1 min it took to make a measurement.

RESULTS AND DISCUSSION

The arrays are rugged, and we have not experienced breakage or electrical malfunctions from driving the arrays directly into field soils. If the soil is dry, dense, or rocky, it is recommended that a pilot hole be created before driving in the array, but in our soils this has only been necessary a few times to penetrate a dry plow pan. It took only a few minutes to install each array. The most important precautions are to dig a small trench to make room for the cable to exit the back side of the array, and to be certain that the top thermistor is located as close as possible to the soil surface.

Measurements shown in Fig. 2 are from sand for a warm, clear day in direct sunlight. The surface 10-cm of the sand was dry, but had been consolidated by rainfall after the installation of the arrays. Below the surface, the individual, un-embedded thermistors in the 5-thermistor array are cooler than the encased arrays nearer the surface but the difference diminishes rapidly with depth (Fig. 2). This may mean that the arrays are conducting heat more rapidly from the hot soil surface downward compared to the dry sandy soil. This is, of course, an undesirable artifact that reduces the accuracy of the near-surface temperature profiles under intense insolation in soils with low thermal conductivity.

The variation in surface soil temperature shown in Fig. 2 are similar in magnitude to those measured by Ham and Senock (1992) when they compared two forms of fine-wire thermocouple to infrared thermometry. We did not measure the time constant of the arrays, but it can be seen in Fig. 2 that measurements at 5-min intervals are sensitive to temperature variations at the surface caused by fluctuations in wind or solar irradiance. In most applications readings will be averaged over relatively long time periods of five to 60 min, so a time constant in the order of a few seconds does not necessarily improve accuracy over a device with a longer time constant.

At 13 cm below the surface of the sand, measurements using the calibrated commercial probe were compared to the encased

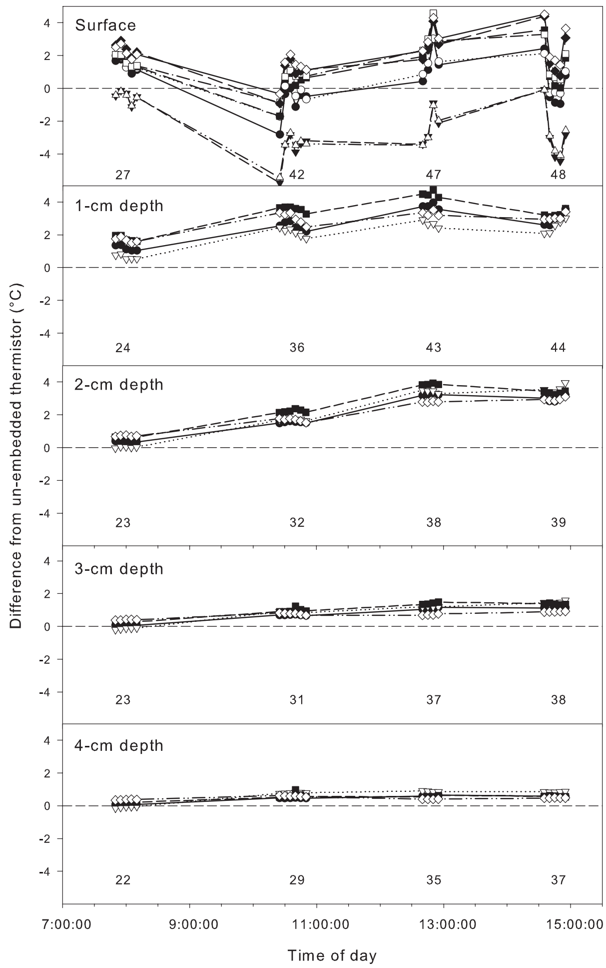

Fig. 2. Differences between bare thermistors and thermistors on four arrays at five depths in dry sand on a clear summer day. Different symbols indicate the four arrays. There are two thermistors located at the soil surface position on each array. Numbers below each measurement group are 5-min averages of the un-embedded thermistor temperature (°C).

array temperatures. The differences ranged from -1.15 to 0.57°C, with an average of -0.30°C and a standard deviation of -0.417°C. This means that on average, at the 13-cm depth, the temperatures sensed by the arrays were slightly cooler than the temperatures sensed by the probe. We do not know which device was closest to the actual soil temperature.

In the field soil with tillage treatments, the array temperatures at the 2- and 5-cm depths averaged about 1°C cooler than soil temperatures taken nearby with reference thermometers (Fig. 3). Soil moisture in the top 10 cm was <0.05 cm^3 cm^{-3}. At the 2-cm depth (solid circles in Fig. 3), the difference ranged from −5.16 to 2.95°C, with an average difference of -0.91°C and a standard deviation of 2.04°C. This is less of a bias than measured at the 2-cm depth in the dry sand (Fig. 2). The large range of difference between the reference thermometers and the arrays reflects the irregularity of the field surface which made it unlikely to find identical conditions at the array and at a location for inserting the reference thermometer a short distance away. At the

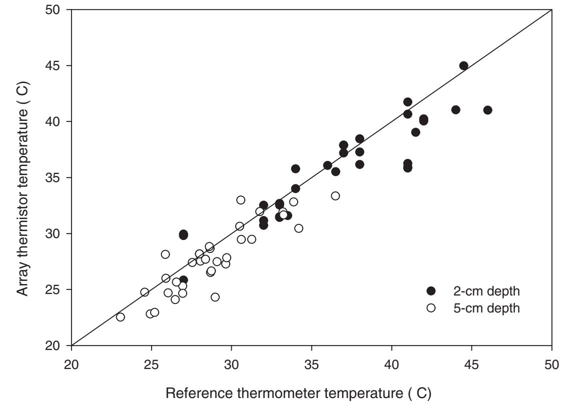

Fig. 3. Comparison of temperatures from 15 arrays versus reference temperatures at the 2- and 5-cm depths in the Ritzville silt loam soil. This is the same array installation as the data in Fig. 4. The 2-cm depth reference thermometer was a fine-wire thermocouple, and the 5-cm depth reference thermometer was a calibrated commercial probe. The reference thermometers were placed about 1- to 5-cm horizontal distance from the arrays, at similar depth and surface condition. The measurements were made at about 1100 h and 1400 h on a clear summer day.

5-cm depth (Fig. 3), the range was 2.4 to −4.67°C, with an average difference of -1.14°C and standard deviation of 1.49°C.

We would expect some differences due to lack of precision of calibration or measurement error of different types. To recheck for consistency between arrays and thermistors within arrays after field deployment, the 16 arrays of various ages and different calibration runs were compared by placing all of them in a tub of water and mixing the water until the temperature was stable. Differences from the water temperature (26°C) ranged from -0.97 to 0.84°C, with a standard deviation of 0.134°C. This is a very large range given the small standard deviation. It indicates the presence of a few thermistors with poor calibration (deviations of as much as ± 1°C), but the majority of thermistors being within about 0.1°C. Out of 480 thermistors in the 16 arrays, 7 were not included in any of the data reported in this paper because of errant readings due to defects in construction.

We believe that with very careful technique the thermistors can be reliably calibrated to >0.1°C, and perhaps even 0.01°C. Under most research requirements, this might not be necessary, especially if the interest is in changes in temperature or ratios of temperatures at different depths rather than absolute temperature differences. Individual thermistors, regardless of small errors in calibration, give extremely consistent response to changes in temperature, so that if the change in temperature is calculated, or a ratio of temperatures is calculated, the results are extremely accurate.

A primary goal of the development of these arrays was to be able to search for important discontinuities in heat and water movement which are responsible for the effect of tillage on evaporation. An example of the ability of the arrays to detect the depth of these discontinuities and subtle differences in heat movement through the surface profile is shown in Fig. 4. Another example of temperature profile comparisons made using this array design can be found in Wuest (2010).

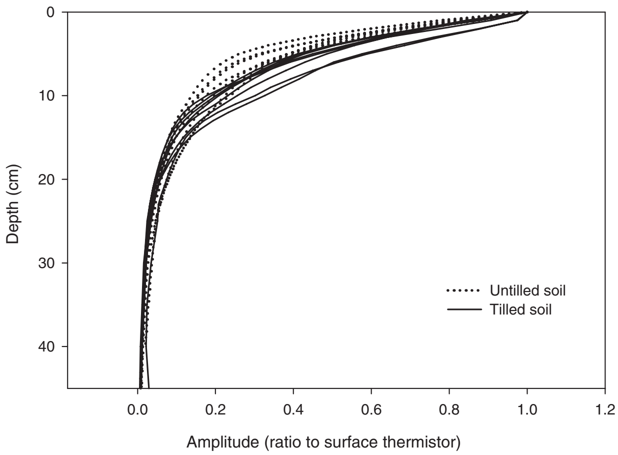

Fig. 4. An example of the capacity of detailed temperature profiles to detect differences between soil treatments in a Ritzville silt loam. The tillage was one pass with a sweep at about 13 cm that did little soil mixing, and did not substantially change surface residue conditions. The temperature amplitude from each array was measured during one clear summer day starting at 0400 h (PDT). This is the same array installation as the data in Fig. 3.

Some readers might be interested in making deeper measurements, perhaps at 0.5 or 1 m. We have built probes with single thermistors mounted on the end of carbon-fiber tubing. Since temperatures vary less at deep depths, thermistors with greater sensitivity in a chosen temperature range can be used, and more precise calibration is possible. In deep loess soils, for example, if the compacted plow pan is not too dry, we can usually insert a 1-cm-diam. probe by hand to 1-m depth without creating a starter hole. The timing and amplitude of diurnal temperature waves are readily apparent.

A modification suggested by the test data would be to reduce the thermal mass in the top 10 cm of the array on the side where the thermistors are located. This portion of the array does not receive much force during installation, and could probably be reduced in thickness by 50% or more. Materials with lower thermal conductivity could also be substituted for some of the glass fiber and epoxy matrix.

Many cropped and most tilled soils have uneven surfaces. This makes it difficult to determine a precise soil surface and to get uniform surface temperature readings. Variations in surface temperatures recorded using this array design were similar to reported variations in temperature recorded by researchers using other devices, but may introduce a bias for several centimeters below the soil surface in certain soils during intense surface heating.

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