ELECTRICAL DETERMINATION FOR SOIL FROST

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Studies have shown that abrupt changes in soil electrical conductivity can be used to indicate if soil is frozen or thawed. Advances in digital recording systems make it possible to automatically record electrical conductivity. Parallel steel rods driven into the soil were used to continuously monitor changes in electrical conductivity during periods of seasonal frost for 2 yr. Thermocouples attached to a wooden dowel were used to monitor soil temperatures simultaneously. When soil temperature dropped below 0°C, electrical conductivities dropped correspondingly to 0 mS.

INTRODUCTION

A knowledge of whether soil water is frozen in the top 10 cm is required for predicting snowmelt runoff (Burgess and Hanson 1979). Studying soil erosion, scheduling late fall harvesting and assessing potential damage to rooting systems of crops can all benefit from depth of frost information. Since the temperature at which freezing occurs varies with soil properties, monitoring characteristics which change significantly when the soil water freezes or thaws may be preferable to temperature measurements. Sartz (1967) found that the abrupt increase in electrical resistance when soil water freezes and the corresponding decrease when it thaws could be effectively used to determine depth of frost. Harlan et al. (1971) performed laboratory tests of the response of electrical resistance measurements to soil water freezing and thawing using soil moisture blocks. Banner and van Everdingen (1979) designed and tested, under field conditions, multisensor electrical resistance freezing gauges. Burgess and Hanson (1979) developed an automatic soil-frost measuring system which used gypsum soil moisture blocks to monitor changes in electrical conductivity. Brach et al. (1985) used a capacitance meter and a sensing probe with multiple electrodes to electrically determine frost depth.

In this study, a Campbell Scientific CR5 digital recorder with an AC conductivity signal conditioner module was used to record the electrical conductivity of the soil water system using stainless steel rods driven to various depths in the soil. Soil temperature was monitored simultaneously over the period and used to evaluate estimates of seasonal frost penetration determined by electrical conductivity readings.

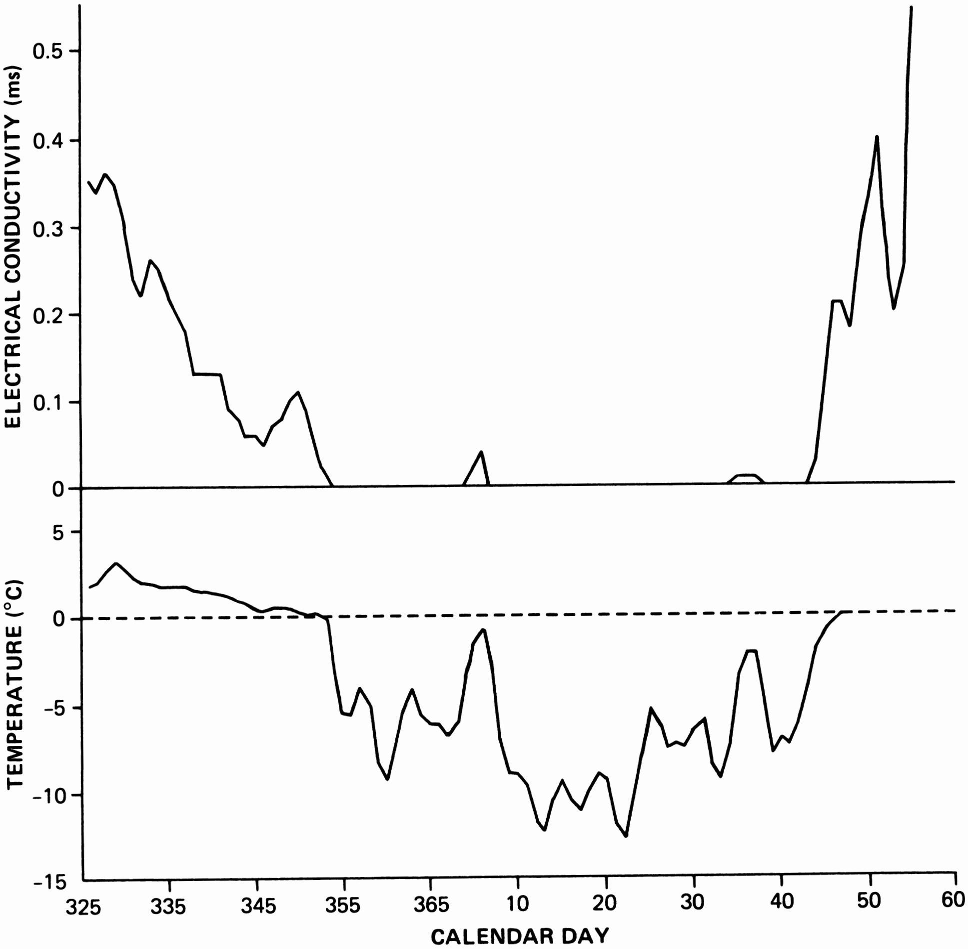

Figure 1. Daily soil temperature at 0.3 m depth and electrical conductivity measured with 0.3-m electrode during the period of seasonal frost in 1983–1984.

METHOD

The experiment was conducted at Ottawa, Ontario on a medium sand soil of the Uplands Association with a mean bulk density of 1.6 t m^{-3} (Hayhoe et al. 1986). Prior to freeze-up in 1983, the volumetric water content averaged 27% in the top 0.5 m and 18% in the lower 0.5 m. In 1984 the corresponding values averaged 24% in the top 0.5 m and 17% in the lower 0.5 m. The plot was manually cleared of snow during the winters of 1983–1984 and 1984–1985.

In November 1983, stainless steel rods 3 mm in diameter were installed. One rod 1.0 m long was driven into the soil to a depth of 1.0 m. Six additional steel rods 0.1, 0.2, 0.3, 0.5, 0.75 and 1.0 m long

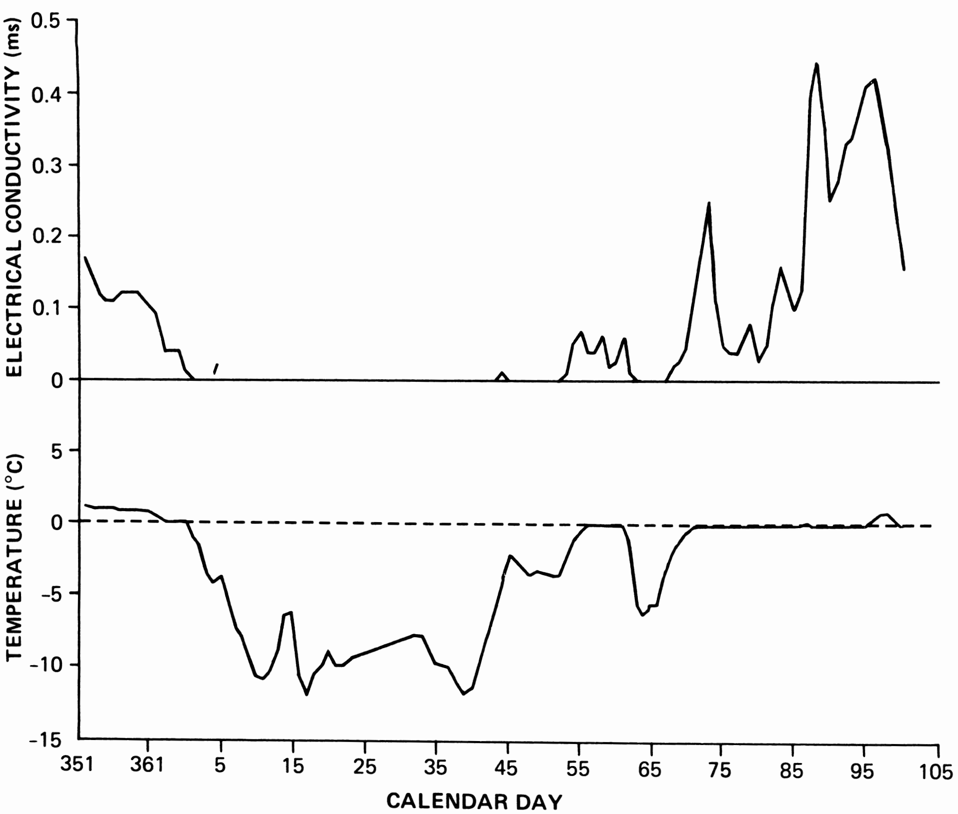

Figure 2. Daily soil temperature at 0.3 m depth and electrical conductivity measured with 0.3-m electrode during the period of seasonal frost in 1984–1985.

TABLE I. DAILY ELECTRICAL CONDUCTIVITY AND SOIL TEMPERATURE FROM DECEMBER 1983 TO FEBRUARY 1984

Depth (m)	Month/day								
	12/8	12/11	12/20	12/22	1/12	1/18	2/19	2/24	2/25
(a) Electrical conductivity (mS)									
0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.35	0.28
0.2	0.02	0.00	0.00	0.00	0.00	0.00	0.31	0.53	0.54
0.3	0.09	0.06	0.00	0.00	0.00	0.00	0.33	0.51	0.49
0.5	0.14	0.11	0.03	0.00	0.00	0.00	0.38	0.64	0.62
0.75	0.19	0.16	0.11	0.08	0.00	0.00	0.37	0.61	0.59
1.0	0.24	0.21	0.16	0.13	0.03	0.00	0.42	0.77	0.76
(b) Soil temperature (°C)									
0.0	−5.9	−8.1	−13.4	−8.4	−16.5	−11.1	1.4	3.7	0.3
0.1	−2.5	−4.0	−10.5	−8.0	−15.4	−11.0	0.1	1.2	0.0
0.2	0.0	−0.8	−6.7	−7.1	−13.6	−10.6	0.0	0.3	0.0
0.3	1.1	0.4	−3.0	−5.6	−11.7	−10.0	0.0	0.1	0.0
0.5	2.4	1.9	1.1	−0.5	−7.2	−8.1	0.0	0.1	0.0
0.75	3.8	3.4	2.8	2.1	−1.0	−4.3	0.0	0.1	0.0
1.0	5.2	4.8	4.2	3.8	1.6	0.0	0.0	0.1	0.1

were driven into the soil to a depth equal to their length. They were equally spaced in a circle with a radius of 25 mm with the 1.0-m rod being at the center. Brass nuts were used to attach shielded 300 Ω TV wire from the steel rods directly to the recorder. The AC conductivity between each rod and the central 1.0 m rod was automatically recorded each hour. Temperatures were recorded simultaneously adjacent to the steel rod installation by means of a single probe consisting of thermocouples positioned on a wooden dowel.

RESULTS

The electrical conductivity measured between each of the six rods and the center rod consistently dropped to 0 mS as temperatures dropped significantly below 0°C throughout the depth range containing the outer rod. This result supports previous studies which indicate that as temperature drops below 0°C there is an abrupt drop in the electrical conductivity of the soil water (Banner and Van Everdingen 1979; Burgess and Hanson 1979).

Figures 1 and 2 illustrate the correspondence of soil temperature and average conductivity within the top 0.3 m of the soil between the 0.3 and 1.0-m steel rods. The soil temperature is the value recorded at 0.3 m. Both conductivity and temperature are daily averages calculated from hourly observations. As the freezing front progressed through the top 0.3 m the measured conductivity dropped (Tables I and II). By the time it had progressed to the 0.3 m depth as indicated by the temperature, the electrical conductivity approached zero as shown in Figs. 1 and 2.

The profiles of electrical conductivity and temperature during freezing for the fall and winter 1983–1984 show the temperature to be less than or equal to 0°C at all depths when the conductivity dropped to 0 mS. A conductivity of 0.0 mS was taken as an indication of frost penetration to that depth at that time (Fig. 3). Similar results were observed in 1984–1985 (Fig. 4) but the delay between the time at which the temperature reached 0°C and the time the conductivity reading indicated 0.0 mS was longer, particularly at the 0.75 and 1.0 m depths.

Previous studies have demonstrated that the temperature at which freezing occurs may be depressed due to soil properties and ionic concentration (Harlan et al. 1971). Therefore, the electrical conductivity dropping off below 0°C but not at 0°C could be attributed to a depressed freezing point. Some differences indicated in Figs. 3 and 4 between the 0°C isotherm and the depth of zero conductivity could be attributed to spatial variability since the temperature measurements were made approximately 1 m from the conductivity measurements.

The increase in electrical conductivity which occurs during thawing provides an indication of the phase change of the soil water and may be influenced by infiltration of rainfall and snowmelt water. Although no limiting value for the electrical conductivity at which soil water has completely thawed can be specified, the magnitude as well as the rate of increase can provide insight into the degree of thaw penetration (Banner and van Everdingen 1979; Burgess and Hanson 1979). Winter thaws produced small increases in electrical conductivity which appear as the peaks in Figs. 1 and 2. From 4 to 6 Jan. 1984, air temperature was above 0°C. Although the soil temperature at 0.3 m remained below 0°C, the 0.1 m soil temperature reached 0°C and the conductivity of the 0.0 to 0.3 m depth range rose to 0.04 mS (Fig. 1). During a thaw in February 1984 the soil temperature at 0.3 m went above 0°C to 0.1°C and the conductivity simultaneously reached a maximum of 0.51 mS (Fig. 1). In the spring of 1985 maximum conductivity of 0.44 mS occurred on 29 Mar. the day after the temperature went above 0°C to 0.1°C (Fig. 2).

TABLE II. DAILY ELECTRICAL CONDUCTIVITY AND SOIL TEMPERATURE FROM DECEMBER 1984 TO APRIL 1985

Depth (m)	Month/day									
	12/19	12/27	1/1	1/7	1/17	2/3	3/14	3/29	4/6	4/15
(a) Electrical conductivity (mS)										
0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.20	0.11	0.04
0.2	0.09	0.00	0.00	0.00	0.00	0.00	0.25	0.48	0.43	0.25
0.3	0.12	0.09	0.00	0.00	0.00	0.00	0.25	0.44	0.42	0.22
0.5	0.25	0.16	0.05	0.00	0.00	0.00	0.26	0.45	0.62	0.46
0.75	0.31	0.21	0.12	0.06	0.00	0.00	0.27	0.51	0.81	0.54
1.0	0.37	0.30	0.21	0.13	0.03	0.00	0.29	0.63	0.91	0.71
(b) Soil temperature (°C)										
0.0	−1.2	−6.8	−6.0	−13.0	−15.8	−12.5	2.1	3.3	4.7	12.2
0.1	0.0	−3.7	−4.5	−11.1	−14.7	−11.1	0.9	2.5	3.9	9.0
0.2	0.3	−0.7	−2.8	−9.1	−13.4	−10.0	0.0	1.0	2.1	5.7
0.3	1.0	0.4	−1.0	−7.2	−12.0	−8.9	0.0	0.0	0.5	3.5
0.5	2.0	1.6	1.0	−2.7	−7.7	−6.7	0.0	0.0	0.0	0.1
0.75	3.3	2.9	2.6	1.2	−1.5	−3.4	0.0	0.0	0.3	0.9
1.0	4.6	4.2	3.9	3.0	1.5	0.0	0.5	1.0	1.2	1.5

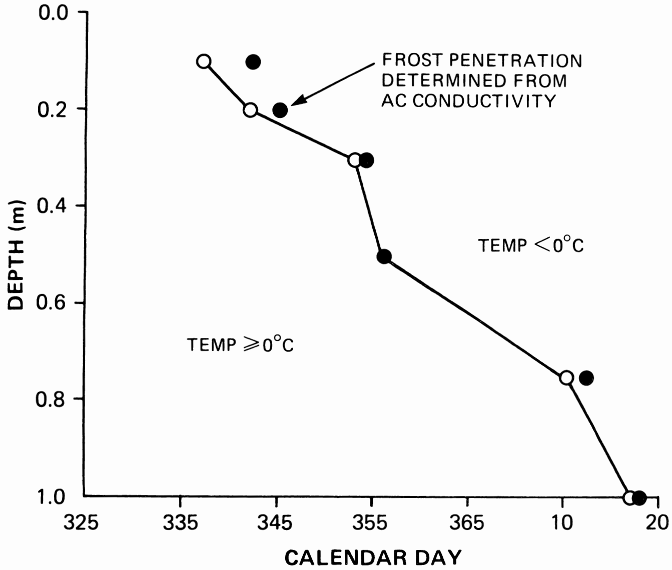

Figure 3. Seasonal frost penetration during 1983–1984 as determined using temperature and electrical conductivity.

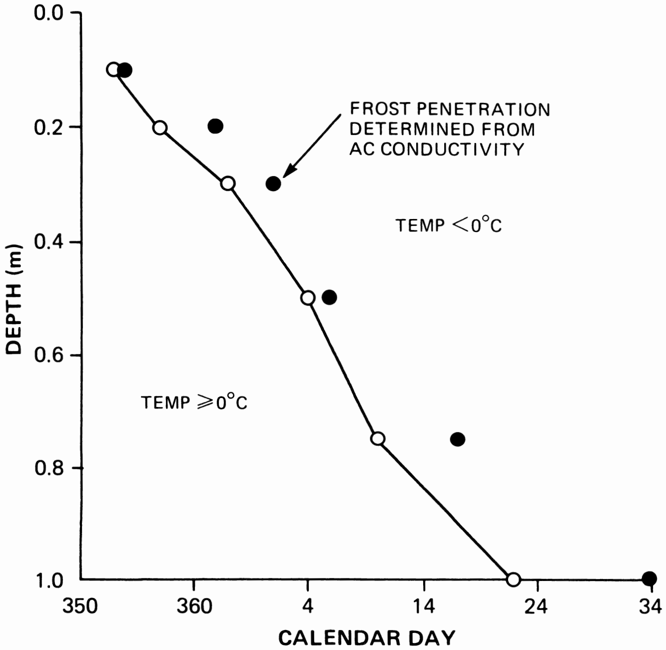

Figure 4. Seasonal frost penetration during 1984–1985 as determined using temperature and electrical conductivity.

The increase in electrical conductivity indicated in Figs. 1 and 2 is attributed to an increase in liquid water adjacent to the electrodes. Hayhoe et al. (1986) suggested that with an apparent capacitance technique the soil water adjacent to the electrodes could be assumed thawed when the apparent capacitance reached a local maximum following an abrupt increase associated with thawing. Figures 1 and 2 and Tables I and II suggest that a similar approach could be useful here. Electrical conductivity tends to peak as soil temperatures rise above 0°C through a given depth range due to an increase in liquid water. For example, the temperature and conductivity profile on 24 Feb. indicate thawing accompanied with an increase in unfrozen water content (Table I).

Freezing and thawing occurred in the 0.0 to 0.3 m depth range as indicated by the abrupt increases and decreases in the conductivity during March 1985 (Fig. 2). The drop in conductivity resulted from daily mean air temperature dropping to a low of −8.2°C on 18 Mar. which produced freezing in the upper part of the 0.0 to 0.3 m depth range. Following this the electrical conductivity rapidly increased and reached a maximum of 0.44 mS on 29 Mar. (Fig. 2). The temperature and conductivity profiles on 29 Mar. are given in Table II. They indicate that by 29 Mar. the 0.0 to 0.3 m depth range was largely thawed.

Tables I and II suggest that by determining the difference in electrical conductivity between depth ranges, it is possible to examine the degree of freezing and thawing at intermediate depth intervals provided there is not too much variation in soil conditions. For example, on 19 Feb. 1984 the electrical conductivity measured from 0.0 to 0.5 m was 0.38 mS and the conductivity for 0.0 to 0.75 m was 0.37 mS (Table I). This is interpreted to indicate that the depth range from 0.5 to 0.75 m was not thawed. On 29 Mar. 1985 the electrical conductivity was 0.44 mS in the 0.0 to 0.3 m depth range and 0.45 mS in the 0.0 to 0.5 m depth range (Table II). The difference of 0.01 mS suggests the 0.3 to 0.5 m depth had not thawed. By 6 Apr. 1985 this difference had increased to 0.20 mS, suggesting thawing had progressed in that depth range.

DISCUSSION AND CONCLUSIONS

The steel rod electrodes used in this study combined with a commercially available digital recorder provide an automatic method of recording abrupt changes in electrical conductivity which have been shown to occur when soil water freezes or