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Real-Time Web-Based Dissemination of Illinois Soil Temperature

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Abstract

Fall application of nitrogen (N) fertilizer is a common practice in Illinois to help overcome the uncertainties of spring field work and to reduce the potential for delay in planting of spring crops. If, however, the N is applied while soil temperatures are above 50°F, significant N losses can occur before the crop can take up the N. The lost N can pollute the state's water supplies, resulting in harm to the environment. The objective of this work was to provide agricultural community and public access to near real-time, 4-inch bare soil temperatures measured at 10:00 a.m. Central Standard Time (CST) each day. Hourly soil temperatures are measured at 18 automated weather stations in Illinois operated by the Illinois State Water Survey (ISWS). These stations make up the Illinois Climate Network (ICN). Measured weather variables include 4-inch sodded soil temperature, solar radiation, air temperature, relative humidity, barometric pressure, precipitation, and wind speed and direction. These data are collected, quality controlled, and placed on a Web site (http://www.sws.uiuc.edu/warm/soiltemp.asp) for public access. Daily maps of the 4-inch bare soil temperature are derived from a combination of actual 4-inch bare soil measurements at 8 ICN stations and computed bare soil temperature from 4-inch sodded soil temperature measurements from the remaining 10 sites. These maps allow users to see the general pattern of the 10:00 a.m. CST soil temperature from which they can estimate soil temperature at a given location. The other measured weather variables also are presented on the Web site in map format.

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Introduction

Fall field operations in Illinois, consisting of harvest, tillage, and fertilizer application, are generally halted in late fall or early winter when soil moisture has been fully recharged. During the late winter and spring, soils may become saturated, resulting in the delay of spring tillage, fertilizer application, and corn planting. Therefore, fall application of nitrogen (N), in addition to lime, phosphorus, and potassium, is a common practice. Early fall application of N when soils are warm, results in large losses of N and contributes to the degradation of water quality. To limit these losses, fall application of N should be delayed until after the 4-inch soil temperature is less than 60°F (15°C) if a nitrification inhibitor is applied, or after the 4-inch soil temperature is below 50°F (10°C) if no inhibitor is applied (Hoeft, 1998).

The median date of the last 4-inch soil temperature of 60°F during the fall varies from 7 October in northern Illinois to 27 October in southern Illinois (Figure 1). For a soil temperature of 50°F, the dates range from 27 October to 6 November in the north and 16-26 November in the south. These dates occur 5 years in 10. In 1 year in 10, the last 60°F temperature can occur by 17 September in the north and by 7 October in the south. For a 4-inch soil temperature of 50°F, the corresponding dates are 17 October in the north and 27 October in the south. In 8 years in 10, the last 60°F temperature occurs by 17 October in the north and by 6 November in the south; the last 50°F temperature occurs by 16 November in the north and by 6 December in the south.

Because of the wide range in the dates for the last 60°F or 50°F 4-inch soil temperature occurrence, it is necessary to use actual soil temperature measurements to determine when to begin fall N application. The preferred soil temperature measurement is at a 4-inch depth under bare soil at 1000 hours (10 a.m. Central Standard Time or CST; Hoeft, personal communication). Tracking soil temperature changes requires daily measurements. The primary objective of this project was to provide near real-time, bare soil temperature data for Illinois to support timing of fall application of N fertilizer.

Materials and Methods

The Illinois State Water Survey (ISWS) maintains a network of automated weather stations throughout the state (Hollinger et al., 1994). The 18 stations that make up the Illinois Climate Network (ICN) are located at research and education centers or community colleges (Table 1). Variables measured include hourly air temperature, relative humidity, precipitation, solar radiation, wind speed and direction, barometric pressure, soil moisture at 2, 8, 20, 40, and 60 inches, and soil temperature at the soil surface and at approximately 1, 2, 4, 8, 12, 16, 20, 24, 28, 32, 36, and 40 inches. Soil variables are measured under a sodded surface; therefore the values reported are only approximate estimates of bare soil temperature.

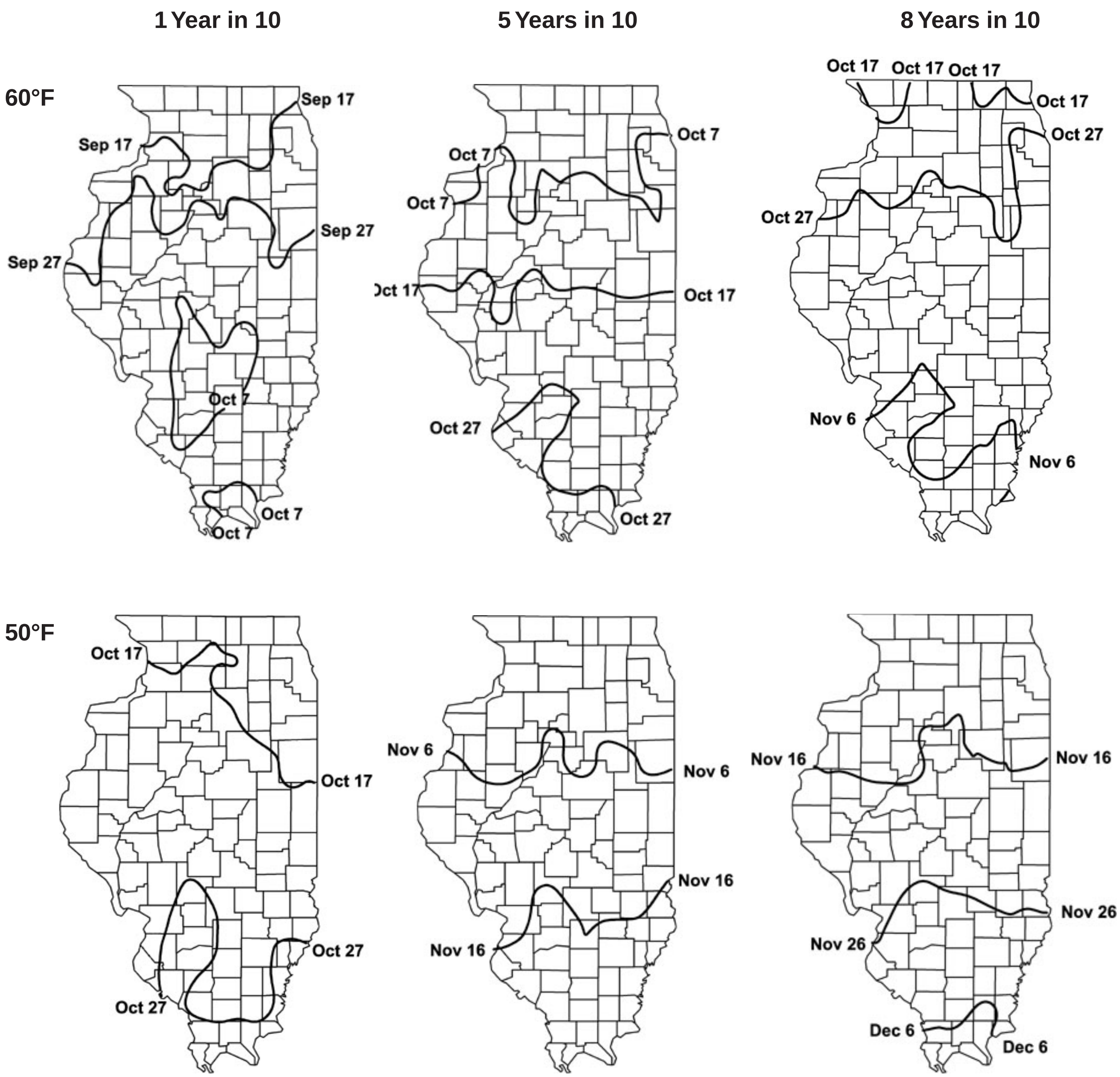


Figure 1. Historically, the last fall 4-inch soil temperatures above 60°F and 50°F occurred on or before dates shown with frequency indicated by label above maps.

Baker (1965) reported that soil temperatures under sod had a smaller diurnal range than bare soil temperatures. In July, bare soil temperatures were warmer than temperatures under sod. In January, bare soil temperatures were cooler than temperatures under sod. Rodskjer and Tuvesson (1976) reported fall mean temperature under newly sown wheat (bare soil) was about 1 C (1.8°F) cooler than similar observations under short grass. From these measurements, it is expected that 4-inch soil temperatures under sod should be different than bare soil temperatures throughout the year.

Table 1. Locations and Starting Dates of Automated 4-inch and 8-inch Soil Temperature Data Collection Records at Illinois Climate Network Weather Stations

No.	*Code*	*Name*	*Latitude (deg)*	*Longitude (deg)*	*Altitude (m)*	*Start date soil temperature records*
1	BVL	Bondville	40.05	88.37	213	20 Aug 1990
2	DXS	Dixon Springs	37.45	88.67	165	9 Feb 1990
3	BRW	Brownstown	38.95	88.95	177	25 Aug 1989
4	ORR	Perry	39.80	90.83	206	1 Jul 1989
5	DEK	DeKalb	41.85	88.85	265	1 Jan 1989
6	MON	Monmouth	40.92	90.73	229	21 Jul 1989
7	SFM	Kilbourne	40.17	90.08	152	1 Jan 1989
8	ICC	E. Peoria	40.70	89.52	207	1 Jan 1989
9	LLC	Springfield	39.68	89.62	177	1 Jan 1989
10	FRM	Belleville	38.52	89.88	133	16 Nov 1989
11	SIU	Carbondale	37.70	89.23	137	14 Dec 1989
12	OLN	Olney	38.73	88.10	134	24 Oct 1989
13	FRE	Freeport	42.28	89.67	265	1 Jul 1989
14	RND	Rend Lake	38.13	88.92	130	18 Apr 1990
15	STE	Stelle	40.95	88.17	213	1 Jan 1989
20	STC	St. Charles	41.90	88.37	226	1 Jan 1988
34	FAI	Fairfield	38.38	88.38	136	14 Sep 1991
81	CMI	Champaign	40.08	88.23	219	16 Feb 1989

Temperature differences also should occur during the fall (spring) when the soil is cooling (warming). The trend of these comparisons in fall when N application is under consideration was not known. Therefore, soil temperature sensors were installed at a depth of 4 inches under bare soil plots at eight ICN sites in close proximity to the existing temperature sensors 4 inches below a sod surface. Bare soil temperature sensors were installed at Brownstown, Bondville, DeKalb, Dixon Springs, Perry (Orr), Rend Lake, Kilbourne (Sand Farm), and Stelle. These stations were selected to form north to south and east to west transects across the state and to represent all major soil types in Illinois (Table 2).

Soil temperatures at a depth of 4 inches under sod and bare soil conditions were measured continuously at these locations and were analyzed to develop an adjustment for soil temperatures under sod representing bare soil temperatures. Linear regression was used to determine the relationship between the maximum, minimum, and 10:00 a.m. CST daily bare soil and sod temperatures. From the resulting equations, estimates were made for 4-inch bare soil temperatures at the ten remaining ICN stations where bare soil temperature sensors were not installed. Independent relationships between the daily maximum and daily minimum 4-inch bare soil and sod soil temperature were developed using temperature data from 1994 to 2000, recorded at West Lafayette, Indiana.

Weather data from the ICN stations were measured automatically, stored on a site data logger, and retrieved each day. To ensure high-quality information, computer programs were written to automate quality control and archival procedures for all weather data. The process consisted primarily of checking data for errors due to sensor or equipment failure in order to identify erroneous information and prevent it from being added to the long-term data records (Hollinger et al., 1994).

A structured Web site was developed to disseminate the ICN soil temperature and weather data to the agricultural community and the public. The Web site allows users to see maps, graphs,

Table 2. Soil Characteristics at Illinois Climate Network Sites

Name	*Soil Type*	*Family*	*Texture*
Bondville	Flanagan/	fine, montmorillonitic, mesic Aquic Argiudolls	Silt loam
	Elburn	fine, silty, mixed, mesic Aquic Argiudolls	Silt loam
Dixon Springs	Grantsburg	fine, silty, mixed, mesic Typic Fragiudalfs	Silt loam
Brownstown	Cisne	fine, montmorillonitic, mesic Mollic Albaqualfs	Silt loam
Orr (Perry)	Clarksdale	fine, montmorillonitic, mesic Udollic Ochraqualfs	Silt loam
DeKalb	Flanagan/	fine, montmorillonitic, mesic Aquic Argiudolls	Silt loam
	Drummer	fine, silty, mixed, mesic Typic Haplaquolls	Silt clay loam
Kilbourne	Plainfield	mixed, mesic, Typic Udipsamments	Loamy sand
Monmouth	Muscatine	fine, silty, mixed, mesic Aquic Hapludolls	Silt loam
Peoria	Clinton	fine, montmorillonitic, mesic Typic Hapludalfs	Silt loam
Springfield	Ipava	fine, montmorillonitic, mesic Aquic Argiudolls	Silt loam
Belleville	Weir	fine, montmorillonitic, mesic Typic Ochraqualfs	Silt loam
Carbondale	Parke	fine, silty, mixed, mesic Ultic Hapludalfs	Silt loam
Olney	Bluford	fine, montmorillonitic, mesic Aeric Ochraqualfs	Silt loam
Freeport	Dubuque	fine, silty, mixed, mesic Typic Hapludalfs	Silt loam
Rend Lake	Cisne	fine, montmorillonitic, mesic Mollic Albaqualfs	Silt loam
Stelle	Monee	fine, illitic, mesic Mollic Ochraqualfs	Silt loam
Fairfield	Cisne	fine, montmorillonitic, mesic Mollic Albaqualfs	Silt loam
Champaign	Drummer	fine, silty, mixed, mesic Typic Haplaquolls	Silt clay loam

and tables of current and historic soil temperature and weather data. Historic data also can be downloaded for further analysis.

Results and Discussion

The Web Site

The initial soil temperature Web site (http://www.sws.uiuc.edu/warm/soiltemp.asp) became available in mid-October 2001. A portion of the Web site is updated daily and provides maps of the previous day's 10:00 a.m. CST 4-inch bare soil temperature and of the daily maximum and daily minimum 4-inch bare soil temperatures. A six-day history of soil temperature maps is also available. Included on the opening page of the soil temperature Web site is the following description and caution.

> "The Illinois State Water Survey, through a grant from the Illinois Department of Agriculture Fertilizer Research and Education program, has initiated daily dissemination of maps showing 4-inch bare soil temperatures across the state based on observations taken at selected Illinois Climate Network sites. These data are intended to assist Illinois farmers with timing of post-harvest nitrogen (N) fertilizer application. The information displayed is specifically representative of the actual locations where soil temperature observations are made. Elsewhere, these data should be viewed as a guide to general soil temperatures within a given region, and as indicative of current temperature trends progressing across the state. Farmers and applicators should monitor the soil temperature of each field before fall application of N fertilizer.

Individual daily maps are analyses of the observed soil temperatures across Illinois on the previous day at a depth of 4 inches below a bare soil surface. Figures show:

- soil temperature between 9:00 - 10:00 a.m. (Central Standard Time) on the previous day
- daily (midnight to midnight) maximum soil temperature on the previous day
- daily (midnight to midnight) minimum soil temperature on the previous day

Charts will be updated by 4 a.m. C.S.T. each day.

Users should be aware that soil temperature fluctuations during the fall may result in periods with soil temperatures below the accepted threshold for N application followed by an extended period with soil temperatures above the accepted threshold. Therefore, users are advised to be aware of both the current soil temperature and short- to long-term weather forecasts.

The *Illinois Agronomy Handbook* states that soil temperatures in autumn determine when ammonium, containing nitrogen fertilizer may be applied without excessive nitrification. At 50°F and below, the rate of nitrification is reduced. At soil temperatures below 60°F, anhydrous ammonia application with a nitrification inhibitor can begin. The mean dates when soil temperatures drop and remain below 60°F and 50°F are shown on separate maps, respectively. The *Illinois Agronomy Handbook* recommends that no fall N application should occur south of Illinois Route 16, roughly the southern third of Illinois."

In addition to the maps of the sod and bare soil temperature at 4 inches, maps of soil temperature at 8 inches under sod, as well as maps of weather variables for the previous day are displayed. These include the maximum and minimum air temperature, maximum wind gust, total solar radiation in Mega-joules per square meter per day, average wind speed and direction, average dew point temperature, potential evapotranspiration, and precipitation. Eventually, hourly and historical data for a station will be available for viewing in a two-dimensional graphical form.

Sod and Bare Soil Temperature Relationship

Two independent data sets were used to develop a relationship between the 4-inch bare soil temperature and the 4-inch sod temperature. The first method involved data collected as a part of this project. The second method involved historical 4-inch bare soil and sod temperature data collected at the West Lafayette, Indiana weather station, part of the National Weather Service Cooperative Observer Network. The current evaluation period covers an entire year and is an extension to that reported in an earlier summary (Hollinger and Scott, 2002). Because all seasons are included here, some results from the previous report have been modified.

Current Data

The 4-inch bare soil sensors were installed at the eight selected stations in spring 2001. Hourly data became available on 1 August 2001 after the grass had been removed from the soil surface and the soil around the sensors had time to stabilize. Data from 1 August 2001 through 31 July 2002 were used to develop a relationship between the 4-inch bare soil and 4-inch sod temperatures measured at 10:00 a.m. CST and the daily maximum and minimum temperature values.

Analyses of the bare soil and sod temperatures show some commonalities at each site and some distinct differences due to specific site conditions (Table 3). Without exception, the highest and lowest 10:00 a.m. temperatures at each site were found under bare soil. Sod cover served as an insulator, moderating temperature extremes at all locations. All standard deviation values over the one-year period for bare soil temperatures were higher than the sodded soil temperatures. In addition, the average temperatures were higher under sod at five sites and under bare soil at three sites, indicating that the positive departures between the sodded and bare soil temperatures during warm periods were balanced fairly equally by the negative departures during cold periods.

Visual observations were made at each station of the type of vegetation cover. Grass at Rend Lake is not mowed. Bondville and Stelle, although mowed a few times each summer at a height of 4 to 6 inches, historically have been unmowed sites, allowing a thick mat of prairie grass cover to develop over the sod sensor. The heavy sod mat at Bondville and Stelle moderates soil temperatures more than that expected by the lawn grass surface. The difference between the high 10:00 a.m. bare soil and sod temperatures at each of these sites in mid-summer when vegetation was highly developed ranged from 6 to 7°F. The low temperature differences during the cold season ranged from 3.4 to 7.1°F. Conversely, the surface cover (basically lawn grass) at DeKalb, Dixon Springs, and Perry was mowed frequently. Data from these sites yielded a bare soil/sod high temperature difference of 1.8 to 4.2°F, and a bare soil/sod low temperature difference range from 0.7 to 4.9°F. Smaller temperature differences observed on the lawn type sod covers at Dixon Springs, DeKalb, and Perry, and larger temperature differences at prairie sites (Bondville, Brownstown, Rend Lake, and Stelle) during both the summer and winter demonstrate insulation effects of vegetation.

The surface cover at Kilbourne is sparse, weedy vegetation on a sandy loam. The sod plot is not too different visually from the site's bare soil location, although the vegetation casts a shadow at the surface above the sod sensor. This created a difference in high temperatures observed between the bare and sodded soil of 4.3°F, and a difference in the low temperatures of

Table 3. Site Absolute Maximum and Minimum 10:00 a.m. Central Standard Time, Average, and Standard Deviation 4-inch Sod and Bare Soil Temperature Values at Illinois Climate Network Sites with Both Soil Temperature Observations, August 2001-July 2002

		Maximum		*Minimum*		*Average*		*Standard deviation*	
Site	*Surface cover*	*Sod (°F)*	*Bare (°F)*	*Sod (°F)*	*Bare (°F)*	*Sod (°F)*	*Bare (°F)*	*Sod (°F)*	*Bare (°F)*
DeKalb	lawn	80.7	82.5	28.7	26.2	51.4	51.1	15.29	16.08
Stelle	prairie	79.1	85.1	31.3	24.2	53.0	51.8	14.90	16.88
Perry	lawn	81.6	85.8	30.0	25.1	54.6	53.9	15.53	17.01
Kilbourne	sparse	83.6	87.9	25.8	21.2	55.4	55.9	16.40	18.51
Bondville	prairie	75.2	82.2	29.2	25.7	52.0	53.2	13.61	16.21
Brownstown	prairie	84.6	88.4	35.8	29.2	61.7	57.4	15.13	16.82
Rend Lake	prairie	78.6	85.4	32.3	28.9	56.3	57.2	13.84	16.60
Dixon Springs	lawn	80.4	83.1	32.8	32.1	56.3	55.3	14.64	16.18

4.6°F. Part of this difference was also due to the sandy loam soil. The sandy soil tends to dry more quickly than silty loam, allowing faster accumulation and transport of heat downward due to less partitioning of solar energy to evaporation and a lower specific heat capacity of the sandy soil system. This was further supported by the larger bare soil and standard deviation values at Kilbourne: temperature changes were larger and more rapid. This suggests that sandy soils are more sensitive to solar radiation and air temperature differences.

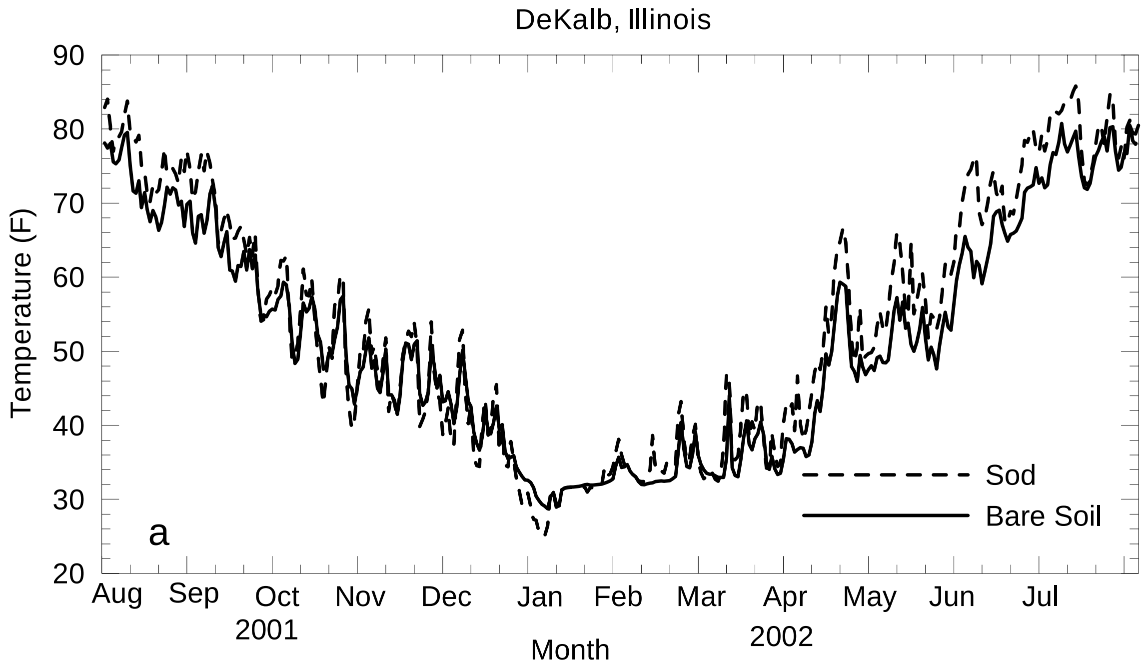
Two stations, Perry (Orr) and Brownstown, tend to differ from the other stations with similar vegetation. Temperature differences between the two surface types at Perry (Orr) tend to be larger than at other locations with lawn type surfaces. Temperature differences at Brownstown were less than those observed at other prairie sites. The reason for this lack of conformity at these two stations is not known.

Records of snow cover are not generated at ICN locations. When snow is present, it increases the insulation of both surfaces from incoming solar radiation and terrestrial heat loss. Winter of 2001-2002 was exceptional in that there was very little snow in Illinois; thus, the impact of snow insulation on these data was likely low.

Station time series show the variability of the 10:00 a.m. CST bare soil and sod temperatures throughout the one-year period of analysis (Figure 2). As seasons progress from summer to winter, bare soil temperatures are cooler than sod temperatures. Similarly, these data show that as seasons progress from winter to summer, bare soil temperatures were warmer than sod temperatures, agreeing with Baker (1965). Throughout nearly all records, bare soil temperatures are colder than sod temperatures in fall and winter and warmer than sod temperatures in spring and summer.

Bondville (Figure 2e), Rend Lake (Figure 2g), and Stelle (Figure 2b) displayed the expected temperature trends for sensors at sites under heavy sod, showing colder bare soil temperatures in fall and winter, and warmer bare soil temperatures in spring and summer. Kilbourne (Figure 2d) appeared to closely follow the trends at these sites. DeKalb (Figure 2a) and Perry (Orr, Figure 2c) displayed lesser bare/sod surface temperature differences that were typical of lawn grass sites. However, Dixon Springs (Figure 2h) with lawn grass, and Brownstown (Figure 2f) with prairie sod both showed colder bare soil temperatures in fall and winter than sodded soil temperatures. Brownstown showed nearly equal sod and bare soil temperatures in spring and summer. Dixon Springs tended to have cooler bare soil temperatures, just the opposite of prevailing trends at most sites.

A scattergram of the 10:00 a.m. CST bare soil and sod temperatures for the full year of data collection showed that the two soil surface temperatures were linearly related (Figure 3). The coefficient of variation (R^2) defines the proportion of the variance in sodded soil temperatures attributable to the variance in bare soil temperatures. The R^2 of 0.97 showed the strong statistical relationship between the bare and sodded soil temperatures, indicating that the same physical principles and weather variables control the temperature changes. The slope of the plotted data (heavy solid line) indicates a trend close to a 1:1 relationship (thin solid line). However, a distinct difference between these two lines is noted, and the data confirm that the temperature under sodded soil was cooler than bare soil during warm soil conditions, and warmer than bare soil during cold weather. The point at which sod and bare soil temperatures were equal was approximately 62°F. Thus, since all applications of N fertilizer should occur only when soil temperatures are below 60°F, monitoring of 4-inch temperatures under sod to determine whether application is appropriate, typically will result in values marginally warmer than values under bare soil.



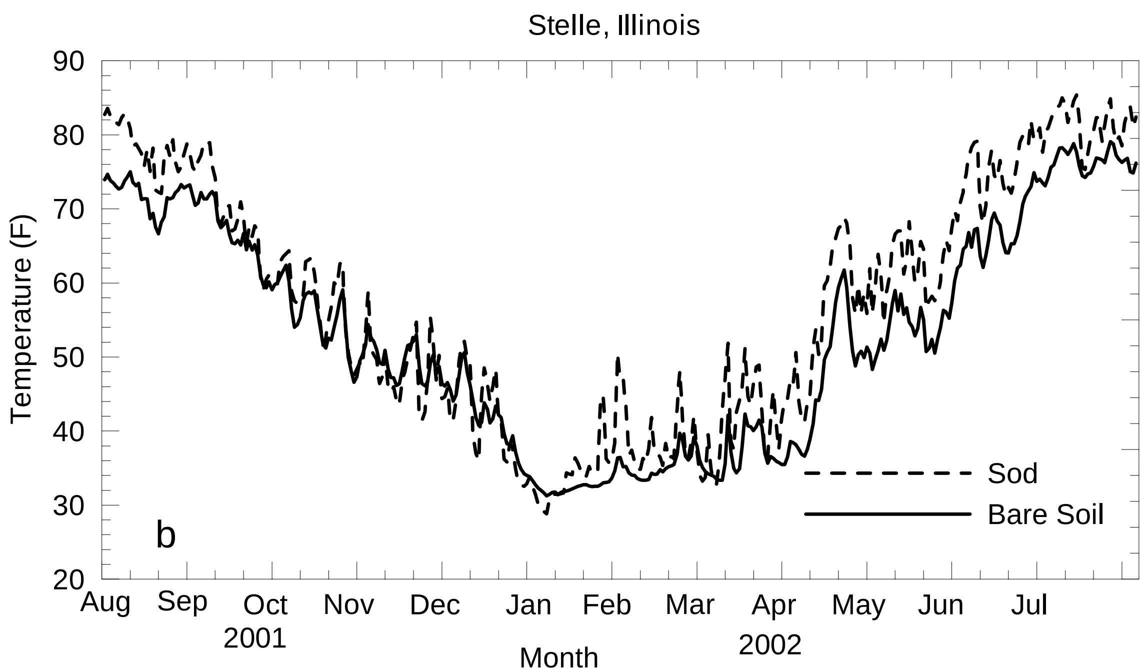
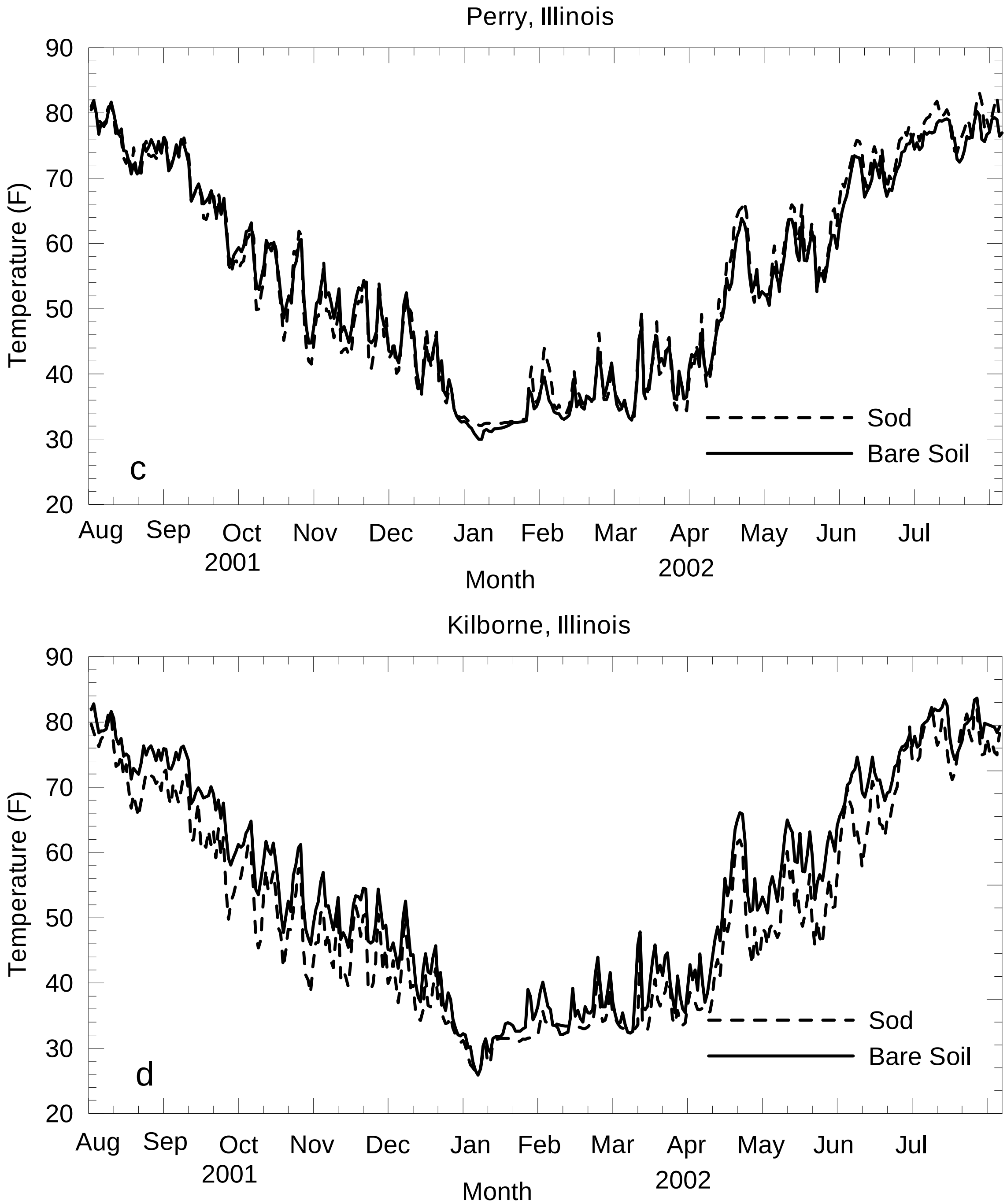


Figure 2. Time series of 10 a.m. Central Standard Time bare soil and sod temperatures, August 2001-July 2002. Station graphs are ordered from north to south and west to east.



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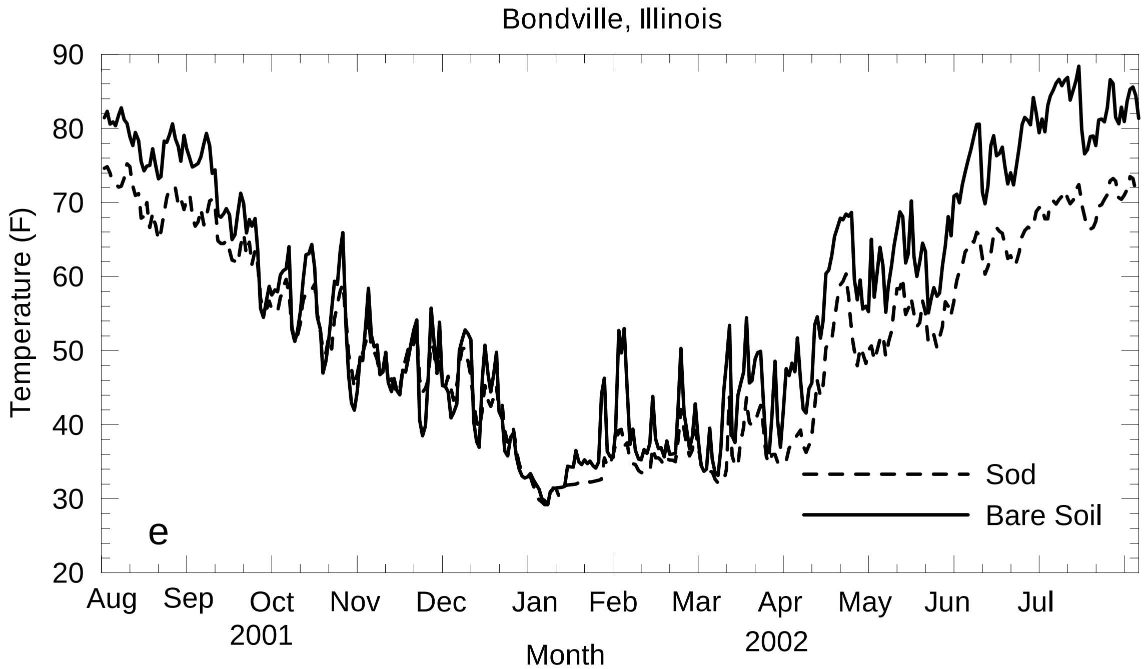

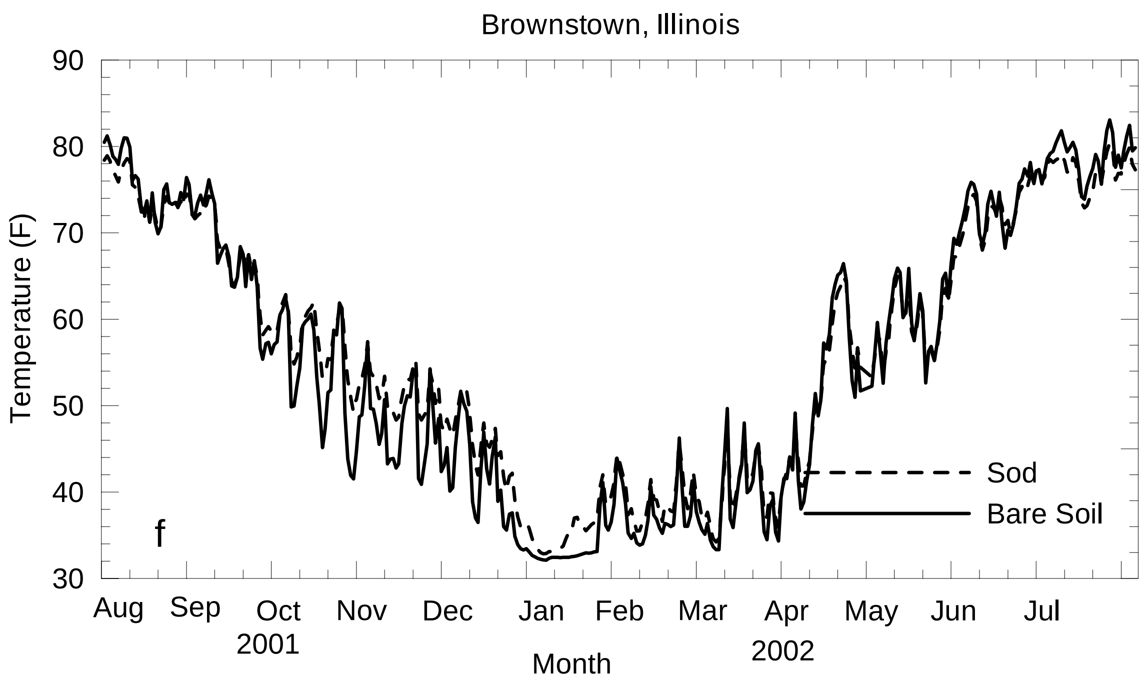

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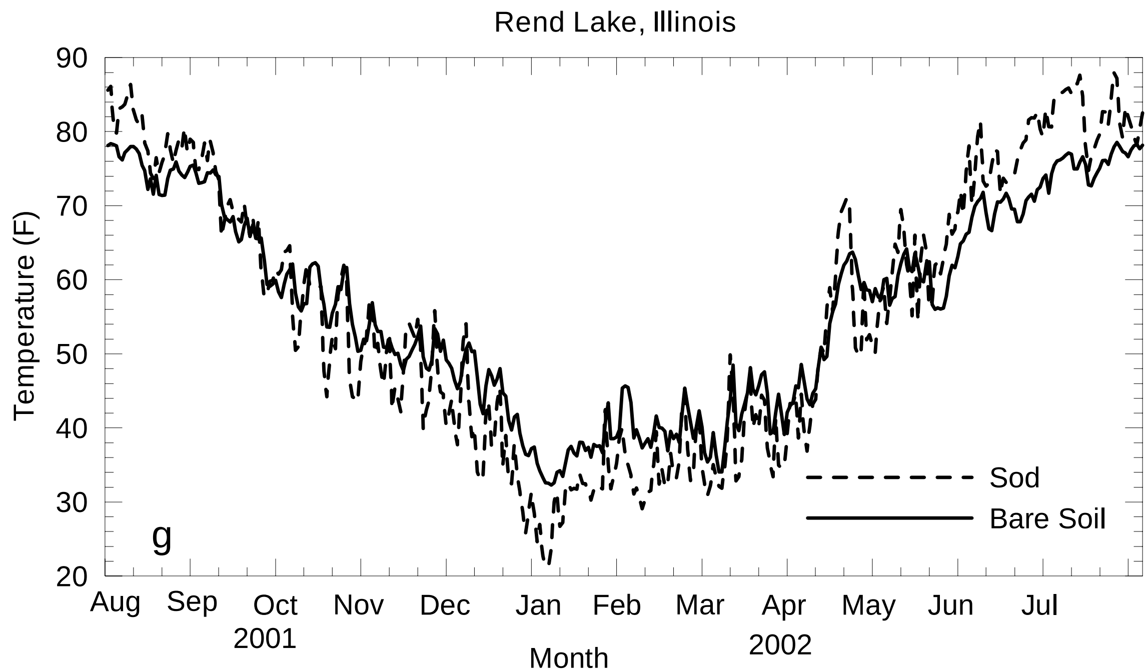

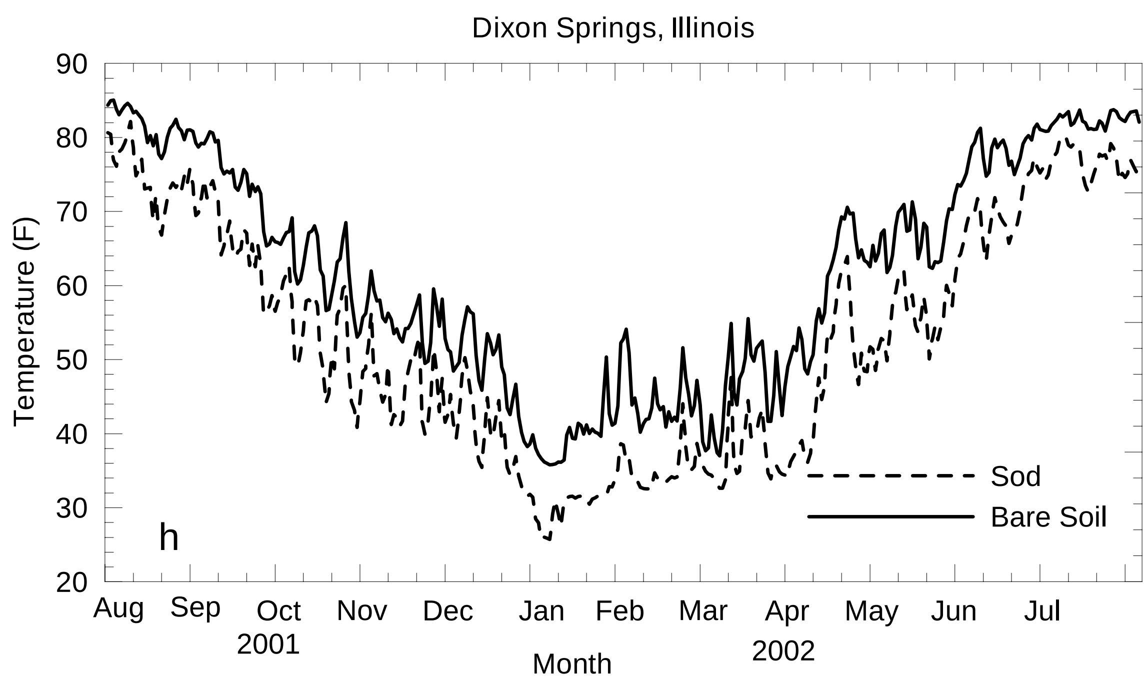

Figure 2. Concluded.

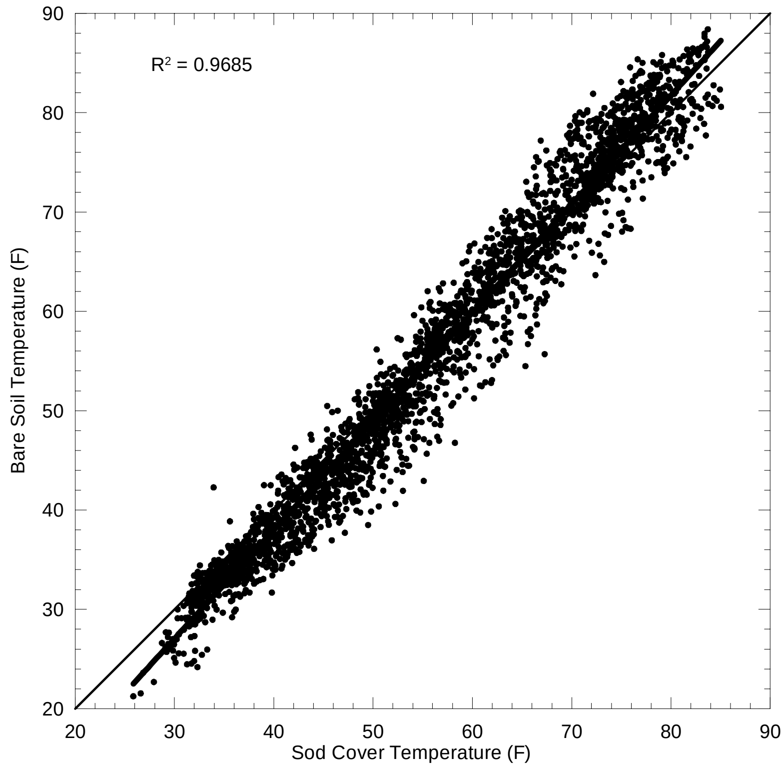

Figure 3. Relationship between 10:00 a.m Central Standard Time 4-inch bare soil and 4-inch sod temperatures.

Additional statistics (Table 4) expanded on these and earlier results employing seasonal comparisons of the data sets. In keeping with climatological convention, the following seasonal definitions were used: fall (September - November), winter (December - February), spring (March - May), and summer (June - August). Separate relationships were developed for each of the eight stations within every season, and an overall relationship using all data from the eight stations was formulated. Stations in the table are ordered from north to south. The west to east transect of bare soil temperatures (Perry to Bondville) are inserted at the appropriate latitude along the north-south transect.

Slopes of the relationship between bare and sodded soil temperatures in all seasons generally reflect the overall trend shown in Figure 3. However, slopes at four sites in winter, and three sites in summer, and the "all site" category for both seasons showed the opposite of what was normally expected. Rather they indicate that as air temperatures increase (decrease), soil temperatures under sod are cooler (warmer) than bare soil temperatures. This relationship was possibly due to overall temperature trends in these hot and cold seasons that were considerably smaller than the rapidly changing temperature values observed during transition seasons of spring and fall. This allowed for a similar scatter of points to have a greater masking effect on the results. Similarly, R^2 values that were relatively high in transition seasons were lower in winter and considerably lower in summer, again reflecting the flat temperature trend during winter and summer.

Over all seasons, the standard error between bare soil and sodded temperatures at 10:00 a.m. CST for the eight stations ranged from ±1.63°F at DeKalb in northern Illinois to ± 2.91°F at

Table 4. Seasonal Statistical Comparisons between 10:00 a.m. Central Standard Time 4-inch Sod and Bare Soil Temperatures, August 2001 - July 2002

	Autumn				*Winter*			
Site	*Intercept (°F)*	*Slope*	R^2	*Std. err. (°F)*	*Intercept (°F)*	*Slope*	R^2	*Std. err. (°F)*
DeKalb	-9.08±2.10	1.15±0.04	0.98	1.46	1.73±2.19	0.93±0.06	0.91	1.28
Stelle	-10.39±3.95	1.12±0.07	0.92	2.66	-0.98±3.41	0.94±0.09	0.82	2.09
Orr (Perry)	-8.91±1.72	1.12±0.03	0.98	1.27	-1.90±2.36	1.00±0.06	0.92	1.49
Kilbourne	-8.55±2.21	1.13±0.04	0.98	1.63	-4.41±2.82	1.07±0.08	0.90	1.91
Bondville	-15.44±2.67	1.28±0.05	0.97	1.72	-0.46±1.93	0.97±0.05	0.94	1.26
Brownstown	-18.96±2.95	1.28±0.05	0.97	1.80	0.44±2.57	0.93±0.06	0.90	1.49
Rend Lake	-14.98±2.79	1.25±0.05	0.97	1.78	-9.15±3.39	1.17±0.08	0.90	1.84
Dixon Springs	-15.0±3.06	1.13±0.05	0.96	2.03	-8.72±2.68	1.07±0.06	0.93	1.60
All sites	-7.8±1.47	1.10±0.03	0.91	3.00	0.84±1.02	0.91±0.03	0.86	2.05

	Spring				*Summer*			
Site	*Intercept (°F)*	*Slope*	R^2	*Std. err. (°F)*	*Intercept (°F)*	*Slope*	R^2	*Std. err. (°F)*
DeKalb	-3.12±1.60	1.09±0.03	0.98	1.45	0.65±5.01	1.00±0.07	0.90	1.80
Stelle	-4.69±2.50	1.08±0.05	0.95	2.31	-10.96±9.18	1.18±0.13	0.79	2.61
Orr (Perry)	-4.32±1.55	1.07±0.03	0.98	1.42	-15.35±8.75	1.23±0.12	0.83	1.95
Kilbourne	-6.67±2.62	1.17±0.05	0.96	2.53	7.19±7.77	0.95±0.10	0.79	1.92
Bondville	-3.12±1.60	1.09±0.03	0.98	1.45	5.87±8.84	0.99±0.13	0.72	2.16
Brownstown	-4.60±1.34	1.09±0.03	0.99	1.24	-15.64±4.90	1.22±0.07	0.94	0.89
Rend Lake	-7.36±2.35	1.17±0.04	0.97	1.95	6.53±1.13	0.98±0.15	0.65	2.27
Dixon Springs	-4.37±4.27	1.00±0.07	0.90	3.49	-26.94±18.6	1.32±0.23	0.59	2.60
All sites	-2.67±0.93	1.05±0.02	0.95	2.60	13.33±3.10	0.85±0.04	0.69	2.86

	All seasons			
Site	*Intercept (°F)*	*Slope*	R^2	*Std. err. (°F)*
DeKalb	-2.67±0.59	1.05±0.01	0.99	1.63
Stelle	-7.58±1.11	1.12±0.02	0.97	2.91
Perry (Orr)	-5.54±0.66	1.09±0.01	0.99	1.76
Kilbourne	-6.02±0.86	1.12±0.01	0.98	2.38
Bondville	-8.12±0.92	1.18±0.02	0.98	2.26
Brownstown	-6.44±0.81	1.10±0.01	0.99	1.98
Rend Lake	-9.70±0.98	1.19±0.02	0.98	2.27
Dixon Springs	-10.33±1.12	1.10±0.02	0.98	2.59
All sites	-5.76±0.41	1.09±0.01	0.97	3.00

Stelle in east-central Illinois (Table 4). When data from the eight stations were combined into a single linear relationship, the standard error increases to ±3.00°F. At the same time, the intercept increased from north to south. These results may be due to the varying conditions across the state discussed earlier. Nevertheless, the R^2 over the whole year was very high.

Statistical relationships between bare soil and sod temperatures developed using their daily maximum and minimum values responded similarly to the 10:00 a.m. CST relationship (Table 5). Standard errors of both values were slightly greater than the standard error for the 10:00 a.m. CST relationship. Maps of daily maximum and minimum 4-inch bare soil temperatures computed from the 4-inch sodded soil temperature will, therefore, have a greater error than the 10:00 a.m. CST map. Thus, maximum and minimum maps only should be used as general estimates of daily extreme soil temperatures across the state.

Historical Data

Concurrent 4-inch bare soil and 4-inch sodded soil temperatures were not readily available for Illinois stations. However, such observations were available from the National Weather Service Cooperative Weather Station located at the Purdue Agronomy Farm near West Lafayette, Indiana. Data from this station were obtained for the period of 1 January 1994 through 31 December 2000. Because only the daily maximum and minimum temperatures were available, the equation developed from these data cannot be used for this study. However, the regression coefficients for the daily maximum and minimum soil temperatures can be used to verify the robustness of the equations developed for the limited Illinois data.

The Indiana daily maximum temperature equation had an intercept of –2.53±0.50°F, and a slope of 1.11±0.01. This equation used all 365 days of data each year. The Indiana daily maximum equation coefficients were significantly different than the Illinois coefficients. However, their standard errors are similar to the standard error of the all site coefficients (Illinois). Differences in the Indiana daily minimum temperature equations show the same response and may be due to the different types of instruments used to collect the soil temperature data. Indiana data were collected using mercury in steel thermometers that were read manually and entered into the record. Illinois data were collected using thermistors, which have a lower time constant and are automatically recorded using a data logger.

2001 Bare Soil Temperature

The pattern of the bare soil temperature change during fall 2001 shows that the temperature dropped below 60°F in the northern two-thirds of the state during the week of 26 September (Figure 2 and Table 6), rebounded above 60°F during the week of 3 October, and returned to below 60°F during the week 10 October. The 4-inch bare soil temperature fell below 50°F for the first time during the week of 17 October, rebounded above 50°F the week of 24 October, and fell below 50°F during the week of 31 October.

This sequence of soil temperatures was typical for any given year; however, the exact timing of soil temperature fluctuations can vary considerably. A major concern about the use of the daily soil temperature maps would be the tendency to assume that N application is permissible the first time the soil temperature drops below a threshold. To evaluate how this might

Table 5. Annual Statistical Comparisons of Maximum and Minimum 4-inch Sod and Bare Soil Temperatures

	Maximum				*Minimum*			
Site	*Intercept (°F)*	*Slope*	R^2	*Std. err. (°F)*	*Intercept (°F)*	*Slope*	R^2	*Std. err. (°F)*
DeKalb	-4.85±0.71	1.13±0.01	0.99	1.88	-3.44±1.07	1.00±0.02	0.97	2.60
Stelle	-13.25±1.38	1.31±0.03	0.97	3.37	-6.31±1.07	1.08±0.02	0.97	2.58
Orr (Perry)	-8.00±1.64	1.18±0.03	0.96	4.04	-3.71±1.45	1.03±0.03	0.95	3.53
Kilbourne	-4.51±1.43	1.18±0.02	0.97	3.71	-4.95±0.84	1.05±0.02	0.98	2.17
Bondville	-11.15±1.11	1.29±0.02	0.98	2.48	-8.04±1.01	1.18±0.02	0.98	2.22
Brownstown	-8.19±1.01	1.18±0.02	0.98	2.33	-5.66±0.95	1.07±0.02	0.98	2.11
Rend Lake	-13.00±1.56	1.33±0.03	0.97	3.20	-8.97±1.06	1.16±0.02	0.98	2.20
Dixon Springs	-18.05±3.80	1.29±0.06	0.86	7.79	-10.23±3.03	1.06±0.05	0.85	6.44
All sites	-8.52±0.52	1.21±0.01	0.97	3.53	-4.84±0.46	1.05±0.01	0.96	3.07

Table 6. First and Last Dates of 60°F and 50°F 10:00 a.m. Central Standard Time Bare Soil Temperatures during Fall 2001 and Sring 2002 at Illinois Climate Network Sites Where Fall N Application is Acceptable

	First fall date below 60°F	*Last fall date above 60°F*	*First fall date below 50°F*	*Last fall date above 50°F*	*First spring date above 50°F*	*Last spring date below 50°F*	*First spring date above 60°F*	*Last spring date below 60°F*
DeKalb	20 Sep	4 Oct	25 Sep	5 Dec	15 Apr	22 May	17 Apr	6 Jun
Stelle	24 Sep	4 Oct	6 Oct	5 Dec	12 Apr	21 May	16 Apr	26 May
Perry	24 Sep	24 Oct	6 Oct	5 Dec	12 Apr	28 Apr	15 Apr	23 May
Kilbourne	25 Sep	24 Oct	16 Oct	5 Dec	9 Apr	23 Apr	14 Apr	18 May
Bondville	25 Sep	24 Oct	6 Oct	5 Dec	12 Apr	2 May	16 Apr	26 May

affect nitrification, a closer analysis of the 4-inch bare soil temperature time series data was made. Bondville (Figure 2e) was selected as an example.

The first day that the 10:00 a.m. CST 4-inch bare soil temperature at Bondville was below 60°F was 25 September, and the last day it was above 60°F was 24 October (Table 6). Between 25 September and 24 October, the bare soil temperature was above 60°F four times, with 4.8 degree-days above 60°F. Most of this occurred before 4 October. The first day that the 4-inch bare soil temperature at Bondville was below 50°F was 6 October, and the last day it was above 50°F was 5 December. Between 6 October and 5 December, the bare soil temperature was above 50°F on 19 days, with 93.2 degree-days above 50°F, of which all but four days (6.5 degree-days) occurred before 3 November. In retrospect, it might concluded from these data that with the use of a nitrification inhibitor, N application would have been permissible near Bondville after about 4 October, but without the inhibitor, not before 3 November. If N application were started before these dates, there would have been additional loss of N. Therefore, monitoring of temperatures in individual fields and keeping abreast of local weather forecasts for warmer weather in the near future are important to be sure that soil temperatures do not rise above the threshold temperatures after fall N has been applied.

Summary

The ISWS network of 18 climate-monitoring stations has measured, in addition to aboveground weather variables, hourly soil temperature under a sod surface since the late 1980s. Temperatures under sod closely approximate soil temperatures under field soils covered by crop residue. However, planting and fall N fertilizer application decisions are based on bare soil temperatures. While these climate data have been gathered for many years, they are not immediately available to agricultural producers or the general public. Therefore, they are not useful in real-time planning decisions.

In this project, a Web site was created to disseminate daily and hourly summaries of the historical and current climate data from the ISWS network. Maps and hourly data are available for the previous day by 4:00 a.m. CST each day. In addition to the Web site, soil temperature sensors were installed at eight of the climate monitoring stations to measure 4-inch bare soil temperature along with the 4-inch temperature under a sod surface. These data were used to create a relationship to convert the sodded soil temperature measured at 4 inches to an equivalent 4-inch bare soil temperature.

Beginning the second week of October 2001, maps generated were available on the Internet (http://www.sws.uiuc.edu/warm/soiltemp.asp). The maps showed the previous day's 10 a.m. 4-inch soil temperature at the eight climate monitoring stations where the 4-inch bare soil temperatures were measured. Other weather variables measured at the stations were available on the Web site in early January 2002. During summer of 2002, the maps of 4-inch soil temperatures used both the measured 4-inch bare soil temperature at ICN stations with bare soil plots and 4-inch bare soil temperatures computed from the measured 4-inch sodded soil temperature at the other ICN stations.

The maps allow users to see the relative pattern of the different weather variables across Illinois. Hourly weather also may be viewed in either tabular or graphic form for individual stations. The tables and graphs eventually will allow access to hourly data for the complete climate record of each station. Hourly data and daily summaries will eventually be available for users to download for additional analysis.

Before release, data collected each day undergo quality control procedures by automated computer programs developed as part of this project. Potential errors or data problems identified by the computer program are checked manually to ensure capture of all questionable data. This combined method also ensures that equipment malfunctions are detected and repaired in a timely manner.

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