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Mid-Continent Fall Temperatures at the 10-cm Soil Depth

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ABSTRACT

Recommendations for applying nitrogen (N) fertilizer in autumn involve delaying applications until daily soil temperature at 10-cm depth is ≤10°C. Daily soil temperature data during autumn were examined from 26 sites along a transect from 36° to 49° N latitude in mid-continent USA. After soils first cooled to ≤10°C (First10), temperatures usually rebounded for varying amounts of time before the final date, at which they decreased to ≤10°C (Last10) for the remainder of the winter. Because N may be lost during warm episodes between First10 and Last10, understanding the extent, duration, and timing of these warm periods is important. Soils at sites between 41° and 44° N latitude in mid-continent USA accumulated more degree-days (base 10°C) between First10 and Last10 than soils north or south of this region. Thus, if N fertilizer is applied too early, soils in Iowa, South Dakota, and southern Minnesota are more susceptible to N losses compared with soils in Missouri or North Dakota and northern Minnesota. Progressively more conservative guidelines for applying N fertilizer in autumn may be to wait until the dates of (i) average Last10, (ii) Last10 plus one SD, or (iii) Last10 plus two SD units. All of these alternative dates can be estimated reliably through simple polynomial equations for latitudes between 35° and 50°.

Many cropped fields in the corn and wheat belts of the USA receive applications of manure or ammonia-based fertilizers in the autumn. Fall applications are performed primarily to take advantage of drier soils and lower fertilizer prices and to reduce spring work loads (Sawyer 2001). A common recommendation is that these amendments should not be applied until soil temperature at 10-cm depth decreases below 10°C (Creswell et al., 2002, Hanna and Sawyer, 2001, Rehm 2002, NDSU Extension Service, 2006). This restriction on the timing of nitrogen (N)-laden materials to soil is intended to reduce the chances of conversion by soil microorganisms of ammonia-N to nitrate N and N_2, which can be lost through leaching and denitrification, respectively. Most soil microbes are considerably more active above than below 10°C (Alvarez et al., 1995). Although nitrification is a two-step process involving chemoautotrophic and heterotrophic bacteria, the recommendations are based primarily on temperatures that have been observed to inhibit *Nitrosomonas* spp., the primary converters of ammonium into nitrite. For instance, Grunditz and Dalhammar (2001) showed substantially reduced activities of *Nitrosomonas* spp. at temperatures below 10°C, although slight activity continued to 5°C.

Several states provide valuable guides to farmers and fertilizer applicators regarding the dates that soil temperatures at 10 cm (or 15 cm) recede below 10°C. Maps of individual states often are delineated by application zones, typically along north-to-south gradients (e.g., Rehm, 2002; Anonymous, 2005). These zones specify ranges of time in the autumn during which soil temperatures commonly decrease to ≤10°C and when N-fertilizers may be applied with less risk of N losses. Despite such guidelines, N losses remain important environmental and agronomic problems for fall-applied N fertilizers (Randall and Vetsch, 2005a, 2005b; Vetsch and Randall, 2004).

Soil temperature is a highly dynamic microclimatic variable. Soil temperature varies dramatically diurnally and with depth. Temperatures at shallow depths vary much more than those at deeper depths, but even at 10 cm, average soil temperature ranges greatly from one day to the next. Such variability among sequential dates is due primarily to daily differences in solar radiation and air temperature (Spokas and Forcella, 2006) and to precipitation, humidity, and wind speed (Flerchinger and Saxton, 1989). Because several variables contribute to determining the temperature of a soil, the probability is low that a soil will remain ≤10°C on first lowering to this level in the autumn. Indeed, even casual reviewing of average daily soil temperatures (10-cm depth) from Midwestern sites indicates that 10°C often is exceeded after the first occurrence of soil temperature ≤10°C.

Contrasting examples of average daily soil temperatures in autumn are shown in Fig. 1 for Grand Forks, ND, during 2 yr. The ideal situation for fall N-fertilizer applications occurred in 1999. In this year, soil temperature dropped below 10°C on 29 September and stayed below this temperature for the remainder of the autumn and winter. In contrast, in 2003, soil temperature first dropped below 10°C on 25 September but rebounded above 10°C during three episodes (26–27 September, 3–13 October, and 20–21 October). The frequency and extent of these high-temperature episodes are a concern for fall N applications and N losses.

The objective of this study was to examine the times and variability of soil temperature dynamics along a transect of sites from northern Minnesota and adjacent North Dakota to southern Missouri (Fig. 2). Of specific interest were the dates when soil temperatures first drop below 10°C in the autumn and stay below 10°C for the remainder of the winter. Other variables of interest included the number of days that soil temperatures exceeded 10°C between the former dates and the heat units associated with those days. The results are expected to be of interest to all those who consider fall application of N-rich materials to soils in mid-continent USA.

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Abbreviations: First10, the first day in autumn that the average soil temperature dropped to or below 10°C; Last10, the last day in autumn that daily temperature was above 10°C.

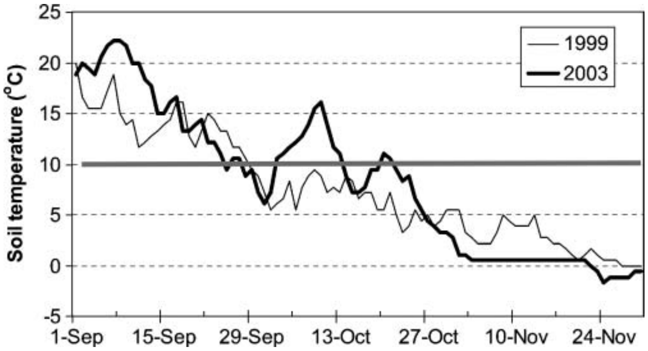

Fig. 1. Average daily soil temperatures at 10-cm depth from Grand Forks, ND, during autumn in 1999 and 2003. In 1999, once soil temperature dropped below 10°C, it stayed low for the remainder of the cold season, which is the desired scenario for fall-applied nitrogen fertilizer. In contrast, in 2003, after first dropping below 10°C, soil temperature rose above this level three times, which possibly enhanced nitrogen losses.

MATERIALS AND METHODS

Electronic databases of temperatures of bare soils at 10-cm depth were downloaded from the World Wide Web. The web sites included Iowa Environmental Mesonet, NDAWN, SD-AWDN, Missouri Historical Agricultural Weather Database, Soil Climate Analysis Network (Missouri only), and three research farms in Minnesota. Specific information for each weather station is listed in Table 1. Only databases with ≥3 yr of observations were used.

Hourly soil temperature data of many databases were converted to daily averages using the Pivot Table option in MicroSoft Excel. Five types of data were generated. For each year, the dates were recorded for the first instance of daily average soil temperature dropping to or below 10°C in the autumn (First10) and the last day in autumn that daily temperature was above 10°C (Last10). The differences between these first and last dates were calculated. Additionally, the number of days was counted between the First10 and Last10 that soil temperature exceeded 10°C. Finally, heat units (degree-days; base = 10°C) associated with these latter days were summed for each site and year. Within each site, averages and SDs were calculated across years for each type of data. These simple statistics were plotted against latitudes of their respective sites, and, when of interest, linear and polynomial regressions were performed using standard options in MicroSoft Excel and Statistix 8 software (Anonymous, 2003).

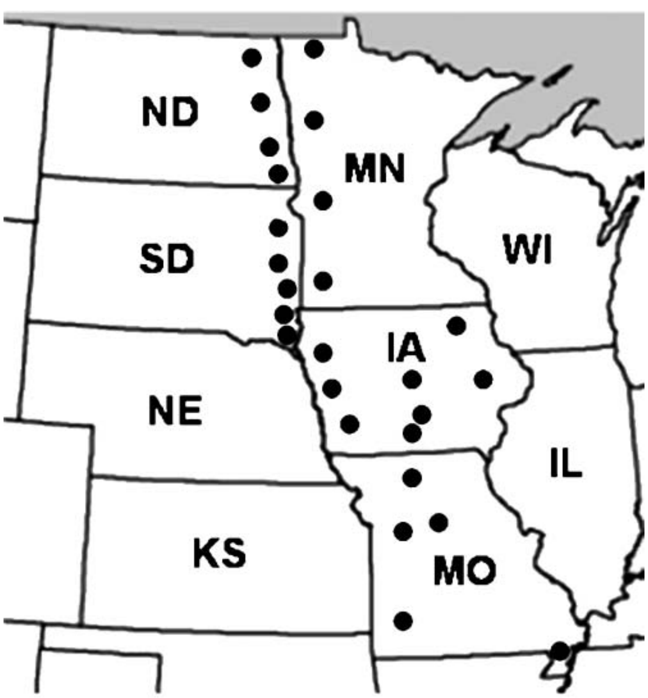

Fig. 2. Locations of sites from which soil temperature data were recorded and analyzed.

Table 1. Locations and number of years for which soil temperature data were analyzed.

Weather station	State	Datasets	Latitude	Elevation
		yr		m
Roseau	MN	4	48°50′	318
Cavalier	ND	13	48°45′	269
Grand Forks	ND	13	47°55′	252
Crookston	MN	4	47°46′	269
Fargo	ND	13	46°53′	275
Wyndmere	ND	13	46°16′	320
Swan Lake (ARS)	MN	9	45°35′	343
South Shore	SD	4	45°06′	564
Brookings	SD	4	44°18′	495
Lamberton	MN	7	44°13′	347
Dell Rapids	SD	3	43°50′	468
EROS	SD	3	43°44′	479
Calmar	IA	4	43°12′	382
Beresford	SD	3	43°05′	456
Sutherland	IA	8	42°58′	432
Castana	IA	8	42°05′	349
Ames	IA	8	42°00′	286
Cedar Rapids	IA	7	42°00′	240
Rhodes	IA	7	41°55′	312
Lewis	IA	8	41°18′	358
Chariton	IA	7	41°02′	311
Spikard	MO	4	40°15′	358
Sanborne Field	MO	6	38°55′	311
Powell Gardens	MO	4	38°52′	261
Mt Vernon	MO	3	37°04′	219
Portageville	MO	5	36°25′	243

RESULTS AND DISCUSSION

The first day during autumn that average daily soil temperatures at 10-cm depth fell to or below 10°C followed a consistent curvilinear pattern associated with latitude (Fig. 3). The pattern fit a simple polynomial

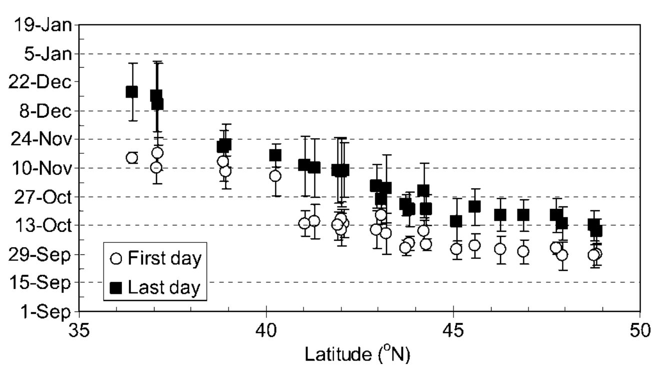

Fig. 3. Average dates (±SD) of the first day in autumn that soil temperature at 10-cm depth dropped below 10°C and the last day in autumn that soil temperature exceeded 10°C. Data are for 26 sites with weather stations along a north-south transect between 36° and 49° N latitude, approximating the mid-continent of the USA.

equation well ($r^2 = 0.90$, $p < 0.01$), which had the following form:

$$\text{First10: DoY} = 0.3173 \times \text{Lat}^2 - 31.369 \times \text{Lat} + 1045 \quad [1]$$

where DoY is day of year, and Lat is degrees north latitude, with minutes in fractions of a degree. On average, the initial dates at which soil temperature first was ≤10°C were 27 September at 49° latitude and 23 November at 36° latitude (Table 2). Site elevations ranged from 85 to 564 m, but elevation did not account for additional variation in multiple regressions with latitude.

An almost identical pattern occurred for the last day during autumn that soil temperature rose above 10°C. The form of this pattern also fit a polynomial function ($r^2 = 0.96$; $p < 0.01$), whose form was

$$\text{Last10: DoY} = 0.3348 \times \text{Lat}^2 - 33.810 \times \text{Lat} + 1137 \quad [2]$$

The final dates at which soil temperature was >10°C were, on average, 10 October at 49° latitude and 18 December at 36° latitude.

The SDs of First10 and Last10 averaged 6.2 and 11.6 d, respectively. Standard deviations also showed trends with latitude, with relatively high variation at low latitudes and low variation at high latitudes. In other words, once soils chill in the north, they tend to stay cold, whereas autumn soil temperatures are more variable in the south. Nevertheless, even in northern sites, considerable variation occurred from one year to the next in terms of when soils initially and finally fell below 10°C.

The difference between the initial and final dates (i.e., the range of days between First10 and Last10) was nearly always >10 d (Fig. 4A). These ranges were inconsistent in the south (low or high) and lower and more uniform in the north. When the CVs for ranges were plotted against latitude, no latitudinal trend was apparent (Fig. 4B) because the slope of this possible relationship was near zero, r^2 was 0.01, and $p > 0.1$. This suggested that large ranges reflected late dates for Last10 and not latitude. Thus, the magnitudes of all of the calculated ranges indicated that regardless of latitude, considerable amounts of time can occur between First10 and Last10. Site elevation had no bearing on the range of days between First10 and Last10.

Table 2. Estimated dates of average first occurrence of soil temperatures ≤10°C (First10), average last occurrence of temperatures >10°C (Last10), Last10 plus 1 SD, and Last10 plus 2 SD.

	Date			
Degrees latitude	**First10**	**Last10**	**Last10+1SD**	**Last10+2SD**
35	**2 Dec.**	**28 Dec.**	**12 Jan.**	**26 Jan.**
36	**23 Nov.**	**18 Dec.**	**2 Jan.**	**15 Jan.**
37	**15 Nov.**	**9 Dec.**	**23 Dec.**	**6 Jan.**
38	**8 Nov.**	**30 Nov.**	**14 Dec.**	**27 Dec.**
39	**1 Nov.**	**22 Nov.**	**6 Dec.**	**19 Dec.**
40	**25 Oct.**	**15 Nov.**	**28 Nov.**	**11 Dec.**
41	**20 Oct.**	**8 Nov.**	**21 Nov.**	**3 Dec.**
42	**15 Oct.**	**2 Nov.**	**15 Nov.**	**26 Nov.**
43	**10 Oct.**	**28 Oct.**	**9 Nov.**	**19 Nov.**
44	**7 Oct.**	**23 Oct.**	**3 Nov.**	**13 Nov.**
45	**3 Oct.**	**19 Oct.**	**30 Oct.**	**8 Nov.**
46	**1 Oct.**	**16 Oct.**	**26 Oct.**	**3 Nov.**
47	**29 Sept.**	**13 Oct.**	**22 Oct.**	**30 Oct.**
48	**28 Sept.**	**11 Oct.**	**19 Oct.**	**26 Oct.**
49	**27 Sept.**	**10 Oct.**	**17 Oct.**	**23 Oct.**
50	**27 Sept.**	**9 Oct.**	**15 Oct.**	**20 Oct.**

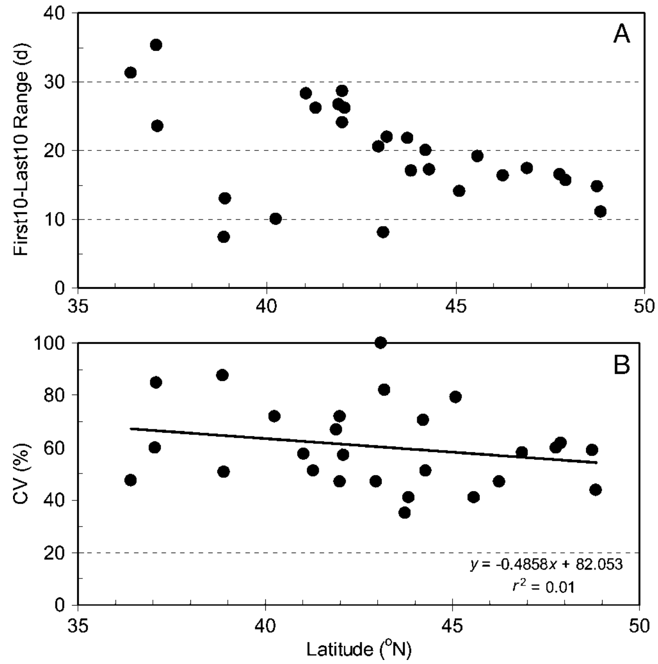

Fig. 4. (A) Average ranges of days between the first day in autumn that soil temperature at 10-cm depth dropped below 10°C (First10) and the last day in autumn that soil temperature exceeded 10°C (Last10) among 26 weather stations along a latitudinal transect. (B) Coefficients of variation associated with averages in Fig. 4A.

During these periods between First10 and Last10, typically only on some days did soil temperature exceed 10°C. The summation of this variable averaged 9.1 d across all sites. Relatively low values (≤10 d) occurred at the northern and southern extremes of the latitudinal transect (Fig. 5A), whereas from 41° to 44° latitude, ≥10 d occurred with soil temperatures >10°C. More important than the number of days that soil temperature surpassed 10°C are perhaps, the extent and duration that this temperature was exceeded. Accumulated degree-days (base 10°C) between First10 and Last10 are shown in Fig. 5B. Sites at latitudes from 41° to 44° not only accumulated more degree-days on average, but the variances associated with this variable were considerably greater for these mid-latitude sites. The high variances from 41° to 44° latitude may reflect the fact that this region is midway between the Gulf of Mexico (30° N) and Hudson Bay (55° N), where persistent tropical and polar air masses, respectively, likely help to dampen short-term temperature fluctuations.

The importance of soil temperature exceeding 10°C for the microbial processes of nitrification and denitrification depends on the magnitude and duration of the high temperatures. For instance, Ernst and Massey (1960) examined ammonia losses from urea-amended soils over the course of 10 d in a laboratory at temperatures of 7.5° to 32°C. The results can be summarized by converting the temperatures and durations to accumulated degree-days (base 10°C) and regressing against

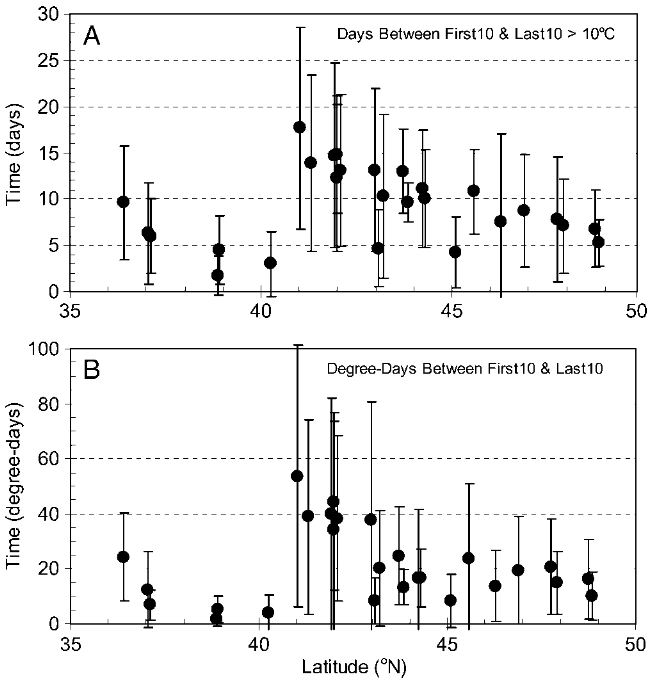

Fig. 5. (A) Cumulative number of days between the first day in autumn that soil temperature at 10-cm depth dropped below 10°C (First10) and the last day in autumn that soil temperature exceeded 10°C (Last10) during which average daily soil temperature at 10-cm depth exceeded 10°C along a latitudinal transect of weather stations. (B) Cumulative degree-days (base 10°C) associated with Fig. 4A.

ammonia losses. The resulting summary is as follows: accumulated thermal times of 5, 10, 20, 30, 40, 50, 60, 80, and 100 degree-days were associated with ammonia losses of about 1, 2, 3, 5, 6, 7, 8, 11, and 12%, respectively. Based on this information and that of Fig. 5B, sites from 41° to 44° latitude often could lose 5 to 12% of fall-applied urea in autumn, whereas sites above and below these latitudes typically lose ≤5% of fall-applied urea. The above estimates are solely for illustrative purposes; actual field losses likely are different. Nevertheless, comparison of the relative magnitudes of potential losses among sites along this transect may be meaningful.

Nitrification inhibitors applied with autumn soil N can help minimize N losses. Several classes of compounds can inhibit nitrification, such as acetylene, amino triazoles, dicyandiamides, gaseous hydrocarbons, pyridines, pyrimidines, pyrazoles, thiazoles, thiadiazoles, and other sulfur compounds (e.g., ammonium thiosulfate or sulfur coated urea), among several others (Prasad and Power, 1985; Paul and Clark, 1996). Only nitrapyrin is used commercially in the USA. Application of nitrapyrin in the autumn has been shown to help to improve yields the following growing season (Wolt, 2004; Randall and Vetsch, 2005b). Although use of nitrapyrin or a similar product may protect against nitrification during periods of fall and early spring soil warming, inhibitors are not guaranteed to stabilize N fertilizers above the 10°C benchmark.

To guard against losses of fall-applied N fertilizers, with or without nitrification inhibitors, applications should be made only after the date that soil temperatures remain below 10°C. However, the variability surrounding such dates is high; therefore, the accuracy of recommended dates remains elusive. One strategy to overcome this uncertainty may be to determine the length of delay of fertilizer applications by using specific probabilities of temperatures remaining below 10°C. For instance, if average Last10s are increased by the magnitudes of their associated SDs, the resulting sums represent dates at which the probability is 0.95 that subsequent autumn soil temperatures will remain below 10°C in two-thirds of all years. The addition of two SD units to average Last10s results in dates on which soil temperatures would not be expected to exceed 10°C in 95% of all years. These dates of Last10, Last10+1SD, and Last10+2SD represent increasingly conservative approaches to applications of fall-applied N fertilizers. They are listed in Table 2 for latitudes between 35° to 50° N. These dates also can be estimated from the following equations:

$$\text{Last10+1SD: DoY} = 0.3058x^2 - 31.913x + 1121\ (r^2 = 0.90;\ p<0.01) \quad [3]$$

$$\text{Last10+2SD: DoY} = 0.2767x^2 - 30.017x + 1104\ (r^2 = 0.83;\ p<0.01) \quad [4]$$

Soil temperature is not the sole variable that governs the timing of fall N fertilizer applications. Other important variables include labor constraints, equipment availability, harvesting schedules, costs, precipitation, soil type, and soil drainage. The values of all of these latter variables may supersede the importance of autumn soil temperatures for deciding when to apply N fertilizer in any particular year, but they do not diminish the risk of a fall N application that is too early. When managers can use soil temperature in their decision processes, some discretion is advisable. Simple observance of First10 is not a reliable cue for when to apply N fertilizer, especially for sites between 41° to 44° N latitudes. These areas include Iowa, adjacent Nebraska, South Dakota, and southern Minnesota. In these regions, soil temperatures have a very high probability of returning to levels above 10°C long enough to elicit substantial N losses. Areas north and south of these mid-latitude regions (North Dakota and northern Minnesota, and Missouri, respectively) have soils with lower probabilities of rising above 10°C after initially falling below this threshold in autumn. Nevertheless, all soils from 36° to 49° N latitude have some chance of warming after an initial chilling. A more reliable rule of thumb may be desirable for determining fall N-fertilizer application times.

One possible alternative is to use Last10, but even this relatively conservative date is surrounded by a level of variability and cannot be estimated with certainty. To overcome uncertainty, even more conservative dates can be estimated by adding one or two SD units to the average dates of last occurrences of 10°C. These dates, listed in Table 2 for latitudes between 35° and 50°, may be useful for helping managers choose levels of risk with which they feel comfortable to make decisions on the timing of fall N-fertilizer applications to field soils in mid-continent USA.

Elevations of most of the sites examined were 200 to 500 m, and they had no obvious effects on fall temperatures of these mid-continent soils. Latitudinal fall temperature relationships for higher elevation sites to the west are unknown, as are those for low-elevation sites along the Atlantic and Pacific coastal plains, and both would make interesting comparisons to that for mid-continent USA.

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