Predicting Daily Mean Soil Temperature from Daily Mean Air Temperature in Four Northern Hardwood Forest Stands

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ABSTRACT. Soil temperature is very important in regulating ecosystem processes, yet it is often difficult and costly to measure. Most models that have endeavored to predict soil temperature have either a long time step or several complicated independent variables. Daily mean air and soil temperatures were measured from 1989–1997 in four northern hardwood sites along a 500 km latitudinal gradient in Michigan. These data were used to derive a simple method to predict daily mean soil temperature (depth of 15 cm) using the daily mean air temperature from the previous day and a cosine function of Julian date (R^2 = 0.93–0.96; SEM = 0.98–1.40°C). Predicted values were compared with actual recorded soil temperatures from 1997 at each of the sites, and the average difference between the observed and predicted values ranged from 0.11 to 0.39°C. Different coefficients were estimated for each of the sites; however, this general method of predicting soil temperature appears applicable to any site. Once calibrated for a given site, soil temperature may be simply estimated, thus reducing the need for extended monitoring efforts. This method also allows the reconstruction of soil temperature records beyond the monitoring period. Projecting long-term trends in soil temperature may help to further elucidate several ecosystem processes and also may provide more information on how a changing global climate will impact forest ecosystems. FOR. SCI. 46(2):297–301.

Additional Key Words: Climate, ecosystem monitoring, sugar maple.

Soil temperature is a very important climatic variable affecting ecosystem processes, especially those occurring below ground. Changes in soil temperature have been linked to changes in soil properties such as pH and ion concentrations (Tomlinson 1993). Likewise, changes in soil temperature can affect various components of soil respiration (Boone et al. 1998, Kirschbaum 1995, Raich and Schlesinger 1992), microbial decomposition and mineralization (MacDonald et al. 1995, Bonan and Van Cleve 1992, Van Cleve et al. 1990), and fine root respiration and turnover (Burton et al. 1998, Zogg et al. 1996, Hendrick and Pregitzer 1993). These types of changes could have profound impacts on the carbon balance of forest ecosystems (Bonan and Van Cleve 1992).

The impact of soil temperature on processes such as fine root respiration is often exponential rather than linear (Burton et al. 1998). Therefore, models based on monthly or annual time steps may not accurately predict the dynamic changes in such below-ground processes. Although it is important to have site-specific measurements of daily soil temperature, it is often difficult and costly to monitor soil temperatures for extended periods of time. Continual monitoring also requires continuous maintenance; equipment failure can lead to missing data. Missing climatic data can be approximated using data from a nearby permanent weather station (Kuuseoks et al. 1997, Lane et al. 1993). However, although many of these stations record daily air temperature and precipitation, the majority do not

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record daily soil temperatures. Deriving a method to predict daily mean soil temperature from daily mean air temperature could decrease the amount of time and cost necessary for on-site monitoring of soil temperature. In addition, linking soil temperature with daily air temperature from permanent weather station data could allow researchers to explore historic trends in soil temperature data beyond the period of actual onsite monitoring.

Models do exist to predict soil temperature. However, many of these models are based on monthly time steps (Yin and Arp 1993, Toy et al. 1978), which, as stated above, may not be sufficient to accurately estimate ecosystem processes. Other models require several parameters such as solar radiation, soil thermal diffusivity, soil surface energy balance, and wind speeds (Levine and Knox 1997, Thunholm 1990, Nobel and Geller 1987, Parton 1984). Although these methods may be accurate and precise, they require data that may be difficult and/or costly to monitor on-site. Likewise, historical data sets probably would not include all the necessary data. Therefore, the objective of this study was to develop a simple method to predict daily mean soil temperature (depth of 15 cm) from daily mean air temperature in four northern hardwood forests located along a 500 km latitudinal gradient.

Methods

Daily mean air temperatures at 2 m above the ground and daily mean soil temperatures at a depth of 15 cm were recorded in four northern hardwood stands from 1989 through 1997. The four stands extend along a 500 km latitudinal gradient from northern to southern Michigan (map displayed in Burton et al. 1991a). These sites are second-growth forests dominated by sugar maple (*Acer saccharum* Marsh.) and are similar in age, basal area, species composition, soils, physiography, and stand structure (Table 1; Burton et al. 1991a). Yearly precipitation is fairly consistent among the sites (810–870 mm); however, the mean annual temperature (7.6–4.3°C) decreases from the southern to northern sites (Burton et al. 1991b).

Air temperatures at three different locations within each site were recorded at 2 m above the ground every 30 min. using thermistors (Model ES-060-SW, Omnidata, Logan, Utah). Averages were recorded every 3 hr by data loggers (Model 925, Omnidata, Logan, Utah), and these 3 hr averages were then used to calculate the average daily air temperature for each location. The average daily temperature for a site was calculated using the average of the three sampling locations. Air temperatures for approximately 15% of the total number of days were missing due to occasional equipment failure. Regression equations and coefficients derived by Kuuseoks et al. (1997) that utilized data from nearby NOAA stations were used to estimate missing air temperatures.

Soil temperatures were measured near the same three locations as air temperature at each of the sites. These temperatures were recorded at a depth of 15 cm using thermistors (Model ES-060-SW, Omnidata, Logan, Utah). Soil temperatures were recorded every 30 min. The average daily soil temperature for each location was calculated from these 30 min. averages, and the average daily soil temperature for each site was calculated as the average of the three locations Similar to air temperature, approximately 15% of the total number of days were missing due to occasional equipment failure. Some missing values could be filled in using soil temperature data from nearby plots within the same site—however, the following method had to be used to fill in most of the data.

The complete air temperature and soil temperature data sets for each site from 1989 through 1997 were used to formulate a regression equation to predict missing soil temperatures from air temperature. Several different estimations of air temperature were tested: daily mean air temperature, mean air temperature from the previous day, and 3, 5, 7, 10, 14, and 20-day running mean air temperatures. Air temperature increases faster than soil temperature in the spring and decreases faster than soil temperature at the end of the growing season. A second variable, cosine ((JD-220)/220), incorporating Julian date (JD) and the JD at which the average high soil temperature was reached (JD 220) was used to remove the seasonal trend in over- and under-estimation of soil temperature. Hence the following general equation was generated to predict soil temperature (ST):

$$ST = \beta_0 + \beta_1 * \phi + \beta_2 * \gamma + \varepsilon; \qquad (1)$$

where ϕ = daily mean air temperature of the previous day and γ = cosine ((JD-220)/220).

Different coefficients were calculated for each site. Daily mean soil temperatures recorded at each of the sites during 1997 were compared to predicted soil temperatures to validate the above equation. Only JD 91 through JD 334 (April 1 through November 30; the growing season plus some time at either end of the season) were considered in the models. Since all of these sites experience snow coverage during the

Table 1. Location and stand characteristics of the four sites used in this study. Stand characteristics are based on measurements made in 1993. Values for stand characteristics are presented as means with standard deviations in parentheses.

	Site A	Site B	Site C	Site D	Literature source
Latitude	46°52'N	45°33'N	44°23'N	43°40'N	
Longitude	88°53'W	84°51'W	85°50'W	86°09'W	
Stand density (tree ha^{-1})	696 (177)	759 (172)	811 (100)	907 (93)	MacDonald et al. (1998)
Basal area (m^2 ha^{-1})	33.4 (0.4)	30.7 (1.4)	31.8 (2.5)	32.2 (1.9)	MacDonald et al. (1998)
Soil families	Sandy, mixed, frigid Alfic & Typic Haplorthod	Sandy, mixed, frigid Alfic & Typic Haplorthod	Sandy, mixed, frigid Alfic & Typic Haplorthod	Sandy, mixed, mesic Typic Haplorthod	MacDonald et al. (1994)
Soil texture	Loamy sand	Sand	Sand	Sand	MacDonald et al. (1992)
pH	4.4	4.7	4.3	4.3	MacDonald et al. (1995)

winter months, and the observed soil temperatures did not change during this winter period, these starting and ending dates were chosen based on the average dates at which soil temperature began fluctuating in the spring and stopped changing in the fall. Also, descriptive statistics were calculated for annual air and soil temperatures, and daily mean air and soil temperatures for JD 91 through JD 334.

Results

Air temperatures predicted using coefficients and algorithms developed by Kuuseoks et al. (1997) were deemed accurate at a particular site for any given date. The comparison of actual temperatures and predicted values for these dates indicated that the equations accounted for 96 to 99% of the variation in air temperature and were consistent with the performance recorded by Kuuseoks et al. (1997). Therefore, missing air temperature data were replaced using the equations from Kuuseoks et al. (1997) in conjunction with records from nearby NOAA stations, and the complete air temperature data set (observed merged with predicted) was used in these analyses.

Equation (1) was used to predict soil temperatures for individual sites across an entire season. The use of the cosine function eliminated seasonal over- and under-estimation of soil temperatures associated with using air temperature alone. For example, increases in soil temperature in the spring and decreases in the fall lagged behind the changes in air temperature (note the range of air temperatures with soil temperatures < 5°C in Figure 1). Although many expressions of air temperature were tested, daily mean air temperature from the previous day yielded the best empirical fit. This, along with the cosine function of JD in Equation (1), successfully predicted daily mean soil temperature for 1997 (R^2 = 0.93 to 0.96; SEM = 0.98 –1.40°C) for each of the sites (Figure 2). Equations developed using the other expressions of air temperature did not predict daily soil temperatures as successfully (maximum R^2 = 0.88 to 0.90 using the 3-day

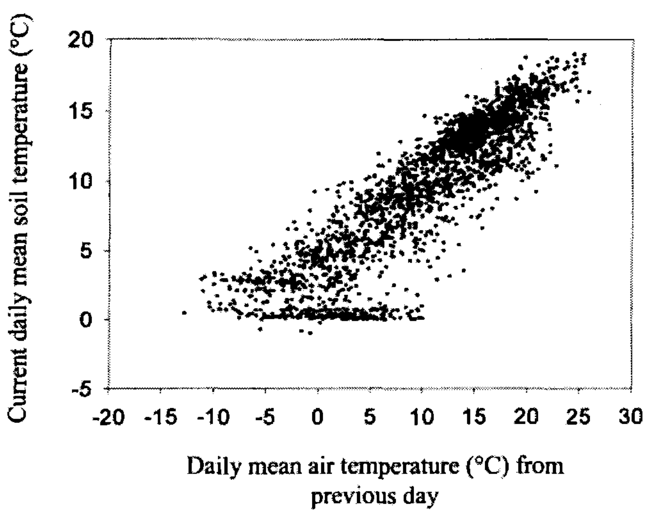

Figure 1. Relationship between daily mean soil temperature at time *t* and daily mean air temperature from the previous day (*t* – 1) recorded at site A from 1989–1997. Increases in spring soil temperatures and decreases in fall soil temperatures lag behind changes in air temperature.

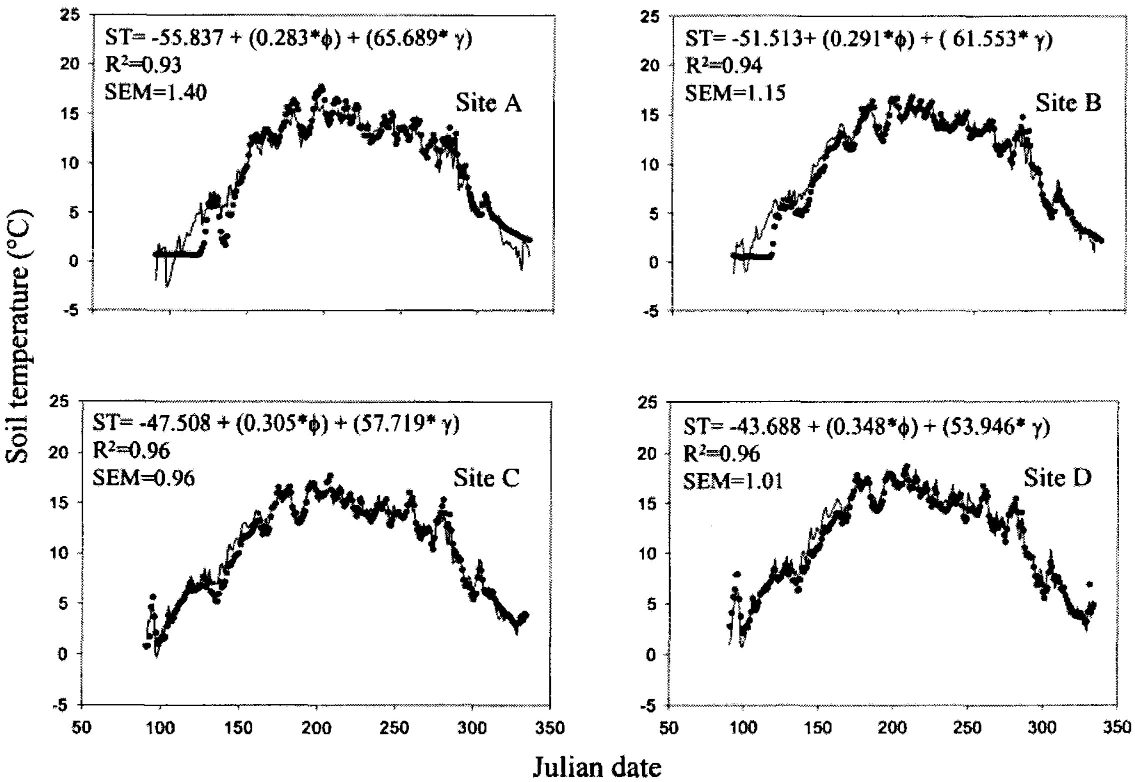

Figure 2. Recorded and predicted daily mean soil temperatures from April 1 through Nov. 30, 1997 for four sites along a latitudinal gradient in Michigan. Each graph contains a series of dots depicting the recorded daily mean soil temperatures, and a line depicting the predicted daily mean soil temperatures. The general equation used to predict soil temperature is as follows: $ST = \beta_0 + \beta_1 * \phi + \beta_2 * \gamma$, where ϕ = daily mean air temperature at time $t - 1$, and γ = cosine ((JD–220)/220). The specific equation, coefficients of determination (R^2) and standard error of the estimates (SEM) are given for each site.

running mean air temperature, for example). Thus the previous day air temperature, along with the cosine of JD, was used to predict daily mean soil temperatures.

Different coefficients were derived for each site. These coefficients in the equations for each of the sites varied consistently with latitude (Figure 2). For example, β_0 and β_2 decreased from north to south, whereas β_1 increased from north to south. This latitudinal relationship is also reflected in the descriptive statistics, which showed an increase in the annual and seasonal daily mean air and soil temperatures from north to south (Table 2). This, not surprisingly, implies that latitude may be significant in the relationship between air and soil temperature. Latitude was tested as both a separate independent variable and as an interaction term with air temperature and the cosine function of JD. However, adding latitude to Equation (1) did not increase its predictive ability. Therefore, it was not used in the final equation predicting daily mean soil temperature.

Discussion

Use of air temperature from the previous day and a cosine function of JD to predict soil temperature was as accurate and, in some cases, more precise than predictions from studies that used a greater number of meteorological parameters (Levine and Knox 1997, Zheng et al. 1993). Thus, this general empirical method could lead to reasonable estimates of soil temperature without constant on-site monitoring or calculation of many variables. Using fewer variables increases the probability that necessary information will be available to estimate missing values.

An important consideration is the estimation of winter soil temperature. Equation (1) predicts temperatures for the months of May through November. Winter soil temperatures did not change at these sites. Therefore, a constant soil temperature could be reasonably used during the winter months. However, the success of using a constant temperature during the winter for other areas will depend on the specific length and characteristics of the winter period.

Another important consideration is the latitudinal differences in the constants and coefficients derived for the different sites using Equation (1). These differences suggest that these particular coefficients are only applicable to these sites. Likewise, the JD of the mean peak soil temperature (JD 220 in this study) may change with major shifts in latitude. Although this general method is likely applicable for most sites, individual coefficients and constants will have to be calculated for each site. Moreover, changes in the amount and type of vegetative cover can cause differences in soil thermal regimes (Balisky and Burton 1993, Flerchinger and Pierson 1991). Different species assemblages can have different canopy architectures, which can impact the amount of radiant energy reaching the forest floor (Balisky and Burton 1993). Also, the removal of the canopy during a disturbance such as clearcutting can change the thermal dynamics of the soil (Liechty et al. 1992). It is important to consider these elements when deriving coefficients for different sites; both soil and air temperatures will need to be monitored for a period of time and compared in order to derive the correct coefficients for a particular site.

Once coefficients for Equation (1) are derived for the sites of interest, soil temperature may no longer need to be monitored on these sites. This will decrease cost and equipment maintenance. Likewise, air temperature data from historical sources could be used to estimate trends in soil temperature over longer periods of time. This could prove invaluable in research addressing trends in ecosystem processes, especially those integrally linked with soil temperature. However, long-term extension of the soil temperature record in this way would assume that vegetative thermal cover was constant over time. This may be appropriate for short time periods, but over longer time periods changes in the vegetative community might upset

Table 2. Descriptive statistics for: annual air temperature, air temperature for JD 91-334 (April 1–Nov. 30), annual soil temperature, and soil temperature for JD 91-334.

	Site A	Site B	Site C	Site D
Annual air temperature (°C)				
N	9	9	8	8
Mean	4.224	5.473	6.302	7.106
Standard error	0.191	0.222	0.197	0.202
Minimum, maximum	3.18, 5.06	4.60, 6.59	5.46, 7.37	6.31, 7.96
Air temperature (°C); JD 91-334				
N	9	9	8	8
Mean	9.814	11.004	11.405	12.176
Standard error	0.173	0.227	0.469	0.241
Minimum, maximum	9.15, 10.58	10.08, 12.16	10.86, 12.03	11.17, 13.16
Annual soil temperature (°C)				
N	9	9	8	8
Mean	6.373	6.919	7.607	8.327
Standard error	0.114	0.112	0.100	0.165
Minimum, maximum	5.76, 6.75	6.27, 7.49	7.24, 8.11	7.69, 9.09
Soil temperature (°C) JD 91-334				
N	9	9	8	8
Mean	9.285	10.095	10.754	11.746
Standard error	0.150	0.181	0.140	0.690
Minimum, maximum	8.52, 9.94	9.22, 10.95	10.27, 11.30	10.75, 12.84

the relationship between air temperature at 2 m and soil temperature. However, this type of effect could be documented through further field investigation.

The ability to estimate soil temperatures could be important in studies addressing global warming. Projected increases in global air temperatures have been linked to possible forest decline through decreases in forest productivity and changes in forest composition (Jones et al. 1994, Jones et al. 1993, Tomlinson 1993). Predicting how soil temperature will fluctuate with changing air temperature could further explain how ecosystem processes may be affected by a changing global climate.

Conclusions

Soil temperature, although integral in many ecosystem processes, is often difficult and costly to observe. The approach in this study provides a simple method to estimate soil temperature using daily air temperature from the previous day and a cosine function of Julian date. Although the coefficients and constants were estimated for each of the sites in this study, this general method of estimating soil temperature appears applicable to any site once the relationship between air and soil temperature is initially established. In contrast to other models, this approach reduces the number of variables needed to predict soil temperatures. It also decreases the impact of equipment failure and makes it more likely that needed information will be available from other sources, such as permanent weather stations. Successful prediction of soil temperature can lead to a decrease in the time, cost, and equipment maintenance necessary for on-site monitoring and allow researchers to use data from other sources. Projecting long-term trends in soil temperature may help to elucidate ecosystem processes, and clarify how these processes may be affected by changes in climate.

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