Field measurements of root respiration indicate little to no seasonal temperature acclimation for sugar maple and red pine

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Summary Increasing global temperatures could potentially cause large increases in root respiration and associated soil CO₂ efflux. However, if root respiration acclimates to higher temperatures, increases in soil CO₂ efflux from this source would be much less. Throughout the snow-free season, we measured fine root respiration in the field at ambient soil temperature in a sugar maple (Acer saccharum Marsh.) forest and a red pine (Pinus resinosa Ait.) plantation in Michigan. The objectives were to determine effects of soil temperature, soil water availability and experimental N additions on root respiration rates, and to test for temperature acclimation in response to seasonal changes in soil temperature. Soil temperature and soil water availability were important predictors of root respiration and together explained 76% of the variation in root respiration rates in the red pine plantation and 71% of the variation in the sugar maple forest. Root N concentration explained an additional 6% of the variation in the sugar maple forest. Root N concentration was higher for red pine than sugar maple at the same soil moisture and temperature conditions. Experimental N additions did not affect root respiration rates measured in the field at ambient soil temperature. Soil temperature and soil water availability were important predictors of root respiration and together explained 76% of the variation in root respiration rates in the red pine plantation and 71% of the variation in the sugar maple forest. Root N concentration explained an additional 6% of the variation in the sugar maple forest. Root N concentration was higher for red pine than sugar maple at the same soil moisture and temperature conditions. Experimental N additions did not affect root respiration rates measured in the field at ambient soil temperature. Soil temperature and soil water availability were important predictors of root respiration and together explained 76% of the variation in root respiration rates in the red pine plantation and 71% of the variation in the sugar maple forest. Root N concentration explained an additional 6% of the variation in the sugar maple forest. Root N concentration was higher for red pine than sugar maple at the same soil moisture and temperature conditions. Experimental N additions did not affect root respiration rates measured in the field at ambient soil temperature.

Introduction Root respiration often comprises from one third to more than one half of total soil CO₂ efflux in forest ecosystems (Edwards and Harris 1977, Nakane et al. 1983, Behera et al. 1990, Bowden et al. 1993). If root respiration rates increase rapidly with temperature, as would be predicted from typical Q₁₀ values of 2 or greater, higher temperatures could cause large increases in root respiration and associated soil CO₂ efflux (Boone et al. 1998). However, if root respiration acclimates to temperature, increases in soil CO₂ efflux due to climate warming might be small.

Temperature acclimation has been commonly reported for dark respiration of foliage (Rook 1969, Sorensen and Ferrell 1973, Teskey and Will 1999, Tjoelker et al. 1999a, 1999b, Atkin et al. 2000b, Gunderson et al. 2000, Will 2000), and mechanisms that could account for an acclimation response have been proposed. Changes in adenylate control (turnover of ATP to ADP) of respiration could occur in association with an altered demand for ATP or a change in the activity of the nonphosphorylating alternative pathway. Variation in soluble carbohydrate concentrations could also cause acclimation by altering substrate availability or respiratory gene expression, or both (Atkin et al. 2000a). However, the actual mechanisms underlying temperature acclimation of respiration remain unclear, and the degree of acclimation can vary widely from complete acclimation, or homeostasis, to slight or nonexistent (Larigauderie and Körner 1995). Nevertheless, for many plants, acclimation of foliar dark respiration can result in CO₂ losses in a warmer environment that are significantly less than would be predicted from instantaneous temperature response curves (Larigauderie and Körner 1995, Tjoelker et al. 1999a).

Less is known about temperature acclimation of root respiration, but it has been observed in roots of seedlings in the laboratory (Bryla et al. 1997, 2001, Tjoelker et al. 1999a), and in young citrus trees (Bryla et al. 2001) and grass species in the field (Fitter et al. 1998). In contrast, temperature acclimation of root respiration was not observed in small Picea engelmannii Parry or Abies lasiocarpa (Hook.) Nutt. trees (Sowell and Spomer 1986), or in roots of Picea glauca (Moench) Voss seedlings (Weger and Guy 1991). To our

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Effect of soil temperature and soil water availability on root respiration in red pine (Pinus resinosa Ait.) and sugar maple (Acer saccharum Marsh.) forests: a common garden experiment. Tree Physiology 25, 19–31
knowledge, respiratory temperature acclimation has not been assessed in roots of mature trees in natural ecosystems.

The possible existence of temperature acclimation of root respiration has a variety of implications. If root respiration acclimates to seasonal changes in temperature, as has been observed for foliar dark respiration (Pereira et al. 1986), then estimates of annual root respiration fluxes based on temperature response curves made at one point in time will be in error. To accurately estimate annual root respiration, many individual measurements would have to be made at ambient temperature over the course of the year.

The degree to which root respiration acclimates to climate warming could affect the global C balance which, in turn, could affect the extent of climate change. Recent evidence suggests that ecosystem respiration, not photosynthesis, may be the main determinant of net ecosystem C exchange in many forests (Valentini et al. 2000), and the degree to which respiration rates increase as temperatures increase will determine the sink strength of terrestrial ecosystems (Grace and Rayment 2000). If respiration rates increase rapidly as temperatures increase (i.e., no acclimation), a positive feedback could occur, causing atmospheric CO₂ concentration, and subsequently global temperatures, to increase more rapidly (Woodwell and Mackenzie 1995). If acclimation of the components of soil respiration occurs, this feedback loop will be weakened (Luo et al. 2001), reducing the potential temperature increase. Cox et al. (2000) recently predicted mean global warming of 5.5 °C by 2100 when feedback between the C cycle and climatic warming was included, compared with a 4 °C increase without the feedback. Increases for mean land temperature were even more extreme: 8 °C from 1860 to 2100 with the feedback. Cox et al. (2000) predicted that the sink strength of terrestrial ecosystems would decrease by 20% for every 1 °C increase in temperature.

In 1998 and 1999, we measured root respiration in the field at ambient soil temperature throughout the snow-free season in a northern hardwood forest dominated by sugar maple (Acer saccharum Marsh.) and in a red pine (Pinus resinosa Ait.) plantation in Michigan. Objectives of the research included: (1) determining the effects of temporal variations in soil temperature and soil matric potential on specific respiration rates for the two forest types; and (2) testing for evidence of temperature acclimation in response to seasonal changes in soil temperature by comparing field respiration rates measured at ambient soil temperature over time to previous respiration measurements made in the laboratory using a temperature series on a single date. A further test for acclimation of sugar maple root respiration utilized previous and new data for respiration rates determined in the laboratory at constant reference temperatures of 6, 18 and 24 °C. These measurements were made at various times during the year when field soil temperatures varied from 0.4 to 16.8 °C. Lower respiration rates at a reference temperature during periods of high soil temperatures would indicate the existence of partial acclimation. Each of the study sites had both control and N-amended study plots, so the effects of long-term N additions on root respiration rates were also assessed.

Materials and methods

Study sites

The study sites were a 90-year-old second-growth sugar maple forest and a 50-year-old red pine plantation in Michigan’s Upper Peninsula. The sugar maple forest had a basal area of 35 m² ha⁻¹, of which 90% was sugar maple. The red pine plantation had a basal area of 34 m² ha⁻¹ comprised entirely of red pine. Each study site contained six 30 m × 30 m study plots, three of which were control plots and three of which received N additions. At the sugar maple site, 30 kg N ha⁻¹ as NaNO₃ was added in six 5-kg increments per year beginning in 1994. At the red pine site, 100 kg N ha⁻¹ was added in four 25-kg increments per year beginning in 1998. The red pine plantation had virtually no understory or ground vegetation. In the sugar maple forest, the sapling and seedling layers had sugar maple dominance similar to that occurring in the overstory. Thus fine roots sampled for respiration contained virtually no roots other than those of the study species.

Field root respiration at ambient soil temperature

During the 1998 and 1999 growing seasons, root respiration rates were measured in the field at ambient soil temperature 17 times at the sugar maple site and 9 times at the red pine plantation. Root respiration measurement dates included the months April through November at the sugar maple site and June through November at the red pine plantation. Onset Computer).
sisted of five to seven excised root mats, each comprising an intact network of root segments containing primarily first-, second- and third-order roots (see Pregitzer et al. 1998 for an illustration of a typical root mat). During excision, roots were damaged only at the locations where the intact root networks were detached (i.e., five to seven locations per sample). Detailed examinations of similar root mats suggest that first-order roots contributed about 50% of the root length sampled and second-order roots contributed about 25% (Pregitzer et al. 2002). Typically, one sample was analyzed from each plot at a site on each measurement date. In the two cases where two samples from a plot were analyzed on a given date, mean values for the two samples were used in subsequent repeated measures analysis of variance.

Total root collection time was about 15 min, and samples (about 2–4 g fresh weight) were immediately placed in a respiration cuvette attached to an infrared gas analyzer (IRGA, CIRAS-1 portable gas analyzer, PP Systems, Haverhill, MA). The IRGA and cuvette were configured in an open system, with root respiration rate determined as the difference between the amounts of CO2 entering and leaving the cuvette. Steady respiration rates were achieved within 15 to 20 min after placing a sample in the cuvette. The input CO2 concentration ([CO2]) for the cuvette was maintained at 1000 µl l–1 to approximate soil [CO2]. This value is slightly lower than the [CO2] typically found near the soil surface where our root samples were taken (1200 µl l–1, Burton et al. 1997; 1350 µl l–1, Yavitt et al. 1995; and 1023 µl l–1, Fernandez et al. 1993).

The one-piece base of the aluminum root respiration cuvette was 5 cm in diameter, with an internal chamber for roots that was 5 cm in depth with a volume of 76 cm3. Beneath the respiration chamber was a solid aluminum plug 12 cm in length. The entire 17 cm-long aluminum base was inserted into the soil, with only the upper 1 cm of the base and the cuvette top above the soil surface. This allowed roots inside the cuvette to be maintained at ambient soil temperature during measurement (verified by comparing temperatures measured by a thermometer inside the cuvette, in contact with the root sample, to soil temperatures adjacent to the cuvette).

Following respiration measurements, root samples were placed on ice in coolers until they could be returned to the laboratory (less than 3 h). In the laboratory, root samples were frozen until a later date when they were cleaned of any adhering soil and organic debris (<5% of sample mass), dried, and analyzed for N with an elemental analyzer (Carlo Erba NA 1500 NC, CE Elantech, Lakewood, NJ). Microbial respiration in the adhering soil and organic debris would have been measured as root respiration, but rates of microbial respiration per gram of forest soil material (Zak et al. 1999) are often orders of magnitude less than those we measured per gram of root tissue. Thus the contribution of these materials to measured root respiration rates should be less than 5% of the reported values.

The [CO2] at which measurements are made can potentially affect root respiration rates of tree species (Qi et al. 1994, Burton et al. 1997), with higher measurement [CO2] resulting in lower respiration rates. However, recent reports suggest that this CO2 effect does not exist for roots of many species (Bouma et al. 1997a, 1997b, Bryla et al. 2001, Burton and Pregitzer 2002). We tested a subset of our field root samples for a possible [CO2] effect by determining respiration rates at both 350 and 1000 µl l–1, and found no effect of [CO2] on root respiration rates of either sugar maple or red pine measured in the field (Burton and Pregitzer 2002).

Laboratory root respiration at constant reference temperatures

In previous work, we measured root respiration of sugar maple trees in the laboratory at fixed temperatures of 6, 18 and 24 °C (Site A in Burton et al. 1996, Burton et al. 1998). The measurements were made at various times of the year during 1994, 1995 and 1996, with ambient soil temperatures during the preceding 4 days ranging from 6.1 to 16.8 °C. These data and data from two additional sampling dates in 1997 (ambient soil temperatures of 0.4 and 14.3 °C) were examined for evidence of temperature acclimation. The site did not experience dry soil conditions during any of these sampling dates (Burton et al. 1998).

Roots for these experiments were obtained from 10-cm deep by 5.4-cm diameter soil cores collected from four random locations per plot and transported in coolers to the laboratory for processing (less than 30 min travel time per site). In the laboratory, the four cores per plot were combined. Fine (<1.0 mm), non-woody, live roots were then sorted by hand from the composite sample and rinsed free of soil and organic matter with deionized water. Respiration of 0.5 g (fresh mass) subsamples was measured as O2 consumption with gas-phase O2 electrodes (Model LD 2/2, Hansatech Instruments, Norfolk, U.K.) connected to constant temperature circulating water baths (Burton et al. 1996, Zogg et al. 1996). Root samples were allowed to equilibrate to the measurement temperature for 20 min, before O2 consumption was monitored for 40 to 60 min. During this period, O2 consumption rates declined only slightly (less than 5%). Three complete O2 electrode systems were run simultaneously, allowing respiration measurements to be performed on separate root samples at 6, 18 and 24 °C within 3 h of sample collection. A complete instantaneous temperature series was performed for all six plots on each of the 10 measurement dates. A similar temperature series was determined for the red pine plantation on a single measurement date in 1997 (Burton et al. 2002).

Statistical analyses

The effect of N additions on root respiration rates measured in the field was analyzed by repeated measures analysis of variance. Separate analyses were used for the sugar maple and red pine sites, because the N additions differed in form, duration and rate of application. Linear regression was used to model the effects of temperature, soil matric potential and fine root N concentration on specific root respiration rates measured in the field at each site, with the natural log of respiration as the response variable. Regression models were estimated based on data for all individual samples from a site. The temperature slope coefficient for each forest type was then used to calculate its respiratory Q10 (Q10 = e10(T slope)). Differences between
$Q_{10}$ values calculated from field respiration measurements made across the growing season (long-term $Q_{10}$) and those calculated for instantaneous laboratory temperature series (short-term $Q_{10}$) were assessed by comparing regression slope coefficients for temperature by the Student’s t-test in a fashion analogous to that for testing differences between population means (Zar 1984). Regressions of respiration rate versus ambient soil temperature during the previous 4 days were used to examine respiration rates measured in the laboratory at constant temperatures of 6, 18 and 24 °C for evidence of seasonal acclimation of root respiration.

Results

For both forest types, root respiration rates in the field followed changes in soil temperature when soils were moist and were reduced when soils were dry (Figure 1). Because root respiration was unaffected by N additions at either site (Table 1), data from all samples were used to develop single regression relationships for each site. Fine root respiration rates for sugar maple were best predicted by the relationship:

$$\ln(R) = -0.41 + 0.055Z + 0.55M + 0.086T$$

($r^2 = 0.77, P < 0.0001, N = 104$)

where $R$ is specific root respiration (nmol CO$_2$ g$^{-1}$ s$^{-1}$), $N$ is tissue N concentration (g kg$^{-1}$), $M$ is soil matric potential (MPa), and $T$ is temperature (°C). Soil temperature and soil matric potential explained most of the variation among sample dates, whereas tissue N concentration primarily explained variation among individual samples within sampling dates. This effect was not a result of the N additions, because root N concentration varied more within treatments than between treatments and was not significantly affected by N additions ($P = 0.11$ for repeated measures analysis of variance).

For the red pine site, specific respiration rates in field samples were predicted by the relationship:

$$\ln(R) = -0.13 + 0.67M + 0.109T$$

($r^2 = 0.76, P < 0.0001, N = 54$)

The long-term $Q_{10}$ values calculated from the slope coefficients for temperature were 2.4 for sugar maple and 3.0 for red pine. Ignoring root N concentration at the sugar maple site decreased the predictive ability of the relationship by about 6%, but did not affect the calculated long-term $Q_{10}$ value. Ignoring soil matric potential reduced the amount of variation accounted for at both sites by about 8% and caused the long-term $Q_{10}$ values to decline to 2.2 and 2.4 for sugar maple and red pine, respectively.

Laboratory measurements of root respiration made at different times of the year indicated no relationship between mean ambient soil temperature during the 4 days before sampling and root respiration rates at reference temperatures of 6 and 18 °C (Figure 2), and indicated only a very weak relationship between ambient soil temperature and root respiration at 24 °C ($P = 0.08, \text{slope} = -0.09$). Short-term $Q_{10}$ values were calculated for each of the 10 sample dates portrayed in Figure 2. These short-term $Q_{10}$ values averaged 2.7, and they were unrelated to mean soil temperature during the preceding days ($P = 0.22$). The 4-day period for soil temperature was chosen based on the number of days needed for acclimation to occur in laboratory studies in which acclimation of root respiration has been observed (Bryla et al. 1997, 2001, Gunn and Farrar 1999). The use of shorter time periods or same-day soil temperatures did not alter the results.

Discussion

Acclimation of respiration to high temperatures can result in either a lower slope ($Q_{10}$) for the temperature-response curve of acclimated tissue or a reduction in the intercept (Atkin et al. 2000a). In either case, the effect of acclimation in laboratory
studies is a long-term $Q_{10}$ (determined by measuring respiration at growth temperatures for plants grown at different fixed temperatures) that is lower than the short-term $Q_{10}$ (derived from instantaneous temperature series conducted on individual plants). For example, Tjoelker et al. (1999a) found that foliar respiration of five tree species grown under controlled conditions acclimated to elevated temperatures, resulting in long-term $Q_{10}$ values for foliar respiration that ranged from 1.1 to 1.9 compared with short-term $Q_{10}$ values, determined for the same plants, of 2.1 to 2.4. Similarly, if plant tissues acclimate quickly to seasonal changes in temperature in the field, the net result should also be a long-term $Q_{10}$ (determined from measurements made at ambient temperature throughout the growing season) that is lower than the short-term $Q_{10}$ value (determined using temperature series at individual points in time). In the extreme case of rapid, full acclimation (homeostasis), respiration rates measured in the field at ambient temperature would produce a long-term $Q_{10}$ of 1.0.

For the sugar maple and red pine study sites, we periodically measured respiration rates in the laboratory across a temperature series from 6 to 24 °C. Short-term $Q_{10}$ values determined from these measurements were 2.6 (Burton et al. 1996) to 2.7 (based on all data summarized in Figure 2) for the sugar maple forest and 3.0 for the red pine plantation (Burton et al. 2002). The long-term $Q_{10}$ values determined in this study (based on respiration rates measured at ambient temperature over the growing season) were slightly, but not significantly lower for the sugar maple forest (2.4) and unchanged for the red pine plantation (3.0). The long-term $Q_{10}$ for sugar maple would need to be 0.7 units lower than the short-term $Q_{10}$ to be significantly different at the 0.05 level of probability.

Table 1. Repeated measures analysis of variance of the effects of N additions (30 kg N ha$^{-1}$ year$^{-1}$ as NaNO$_3$ for sugar maple and 100 kg N ha$^{-1}$ year$^{-1}$ as NH$_4$NO$_3$ for red pine) on root respiration rates measured in the field at ambient soil temperature during 1998 and 1999.

<table>
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<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>$F$ ratio</th>
<th>$P &gt; F$</th>
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</thead>
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<td></td>
<td></td>
</tr>
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<td>64</td>
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<td>0.68</td>
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</table>

For root respiration, evidence of seasonal acclimation to shifts in ambient soil temperature has been found for grassland species (Fitter et al. 1998), but not for roots of woody perennials. Fairly rapid temperature acclimation of root respiration has been seen in tree seedlings grown at one constant temperature and then shifted to another constant temperature (Bryla et al. 1997, 2001) and in 9-year-old grapefruit (Citrus paradisi Macf.) trees in which soil was heated to approximately 10 °C above ambient but allowed to fluctuate naturally.

Figure 2. Relationship between sugar maple root respiration as O$_2$ consumption, at reference temperatures of 6, 18 and 24 °C, and mean ambient soil temperature (15 cm) during the previous 4 days. Relationships were not significant at any temperature ($P$ values were 0.37, 0.86 and 0.08 for 6, 18 and 24 °C, respectively). Each symbol represents a mean value for samples from six plots. Soil matric potential did not significantly affect the results, because dry conditions did not occur at the site for any of the sample dates involved (Site A in Burton et al. 1998).
In this latter study, however, acclimation occurred only above 23 °C. A variety of factors may have contributed to the failure of root respiration to acclimate to seasonal changes in soil temperature in our study. In experiments that held elevated temperatures constant, acclimation of root respiration took 4 to 5 days to occur (Bryla et al. 1997, 2001, Gunn and Farrar 1999). Time spans of several days for acclimation have also been reported for temperature-step experiments examining foliar dark respiration (Atkin et al. 2000b). Natural fluctuations in soil temperatures in the field may reduce the degree of acclimation that can occur. Roots within 5 cm of the soil surface at both of our sites experienced temperature shifts of 5 to 10 °C over time spans of one to several days throughout the growing season (Figure 3), which may have prevented discernible acclimation from occurring. There may also be a temperature threshold below which acclimation of root respiration does not occur. Bryla et al. (2001) did not find temperature acclimation of citrus root respiration below a temperature of 23 °C, and soil temperatures at 5-cm depth in the heated treatment in which they found acclimation were often in the 32 to 37 °C range. Soil temperatures at the 5-cm depth for our sites reached maxima of 19.9 °C at the sugar maple site and 22.0 °C at the red pine plantation. Adjacent to the soil surface, temperatures were occasionally higher, but never for longer than 10 h during the day, after which they decreased considerably overnight (1-cm depth in Figure 3). Finally, root respiration of some species simply may not acclimate to temperature. For example, there have been reports of no temperature acclimation in root respiration for Picea engelmannii, Abies lasiocarpa and Picea glauca (Sowell and Spomer 1986, Weger and Guy 1991). Larigauderie and Körner (1995) studied foliar respiration of 19 species and found a range from full to no temperature acclimation. Gunderson et al. (2000) reported only a small (10%) temperature acclimation for foliar dark respiration of sugar maple saplings grown at temperatures 4 °C above ambient.

It is likely beneficial for acclimation of foliar dark respiration to occur. The same may not be true for root respiration, at least relative to seasonal changes in soil temperature. Availability of resources for photosynthesis (light, CO₂) at the leaf surface would not be greatly changed by a warm period in the middle of the growing season. However, the supply rate of nutrients to roots could be significantly increased by an increase in soil temperature through effects on mineralization of organic nutrients (MacDonald et al. 1995, Zak et al. 1999) and ion diffusion. Down-regulation of foliar dark respiration during such a warm period might limit C losses without greatly affecting the rate of photosynthesis. In roots, high metabolic activity (respiration rates) during warm, moist conditions would allow for rapid nutrient uptake and assimilation during the co-occurring periods of enhanced nutrient supply (Pregitzer et al. 2000). Temperature acclimation during such times and the accompanying reduction in metabolic activity could reduce nutrient uptake. Acclimation to seasonal changes in temperature in foliage, but not in roots, might allow both leaves and roots to efficiently match their activity to the availability of growth-limiting resources. In temperature-step laboratory experiments that have shown acclimation, availability of N and other nutrients was typically not increased with temperature (Bryla et al. 1997, Tjoelker et al. 1999a) as might be expected to occur under field conditions.

It is possible that roots of some temperate tree species would not acclimate to seasonal changes in soil temperature, but would acclimate to increases in annual temperatures associated with global warming. If annual temperatures increased, but total annual nutrient requirement did not, then root metabolic uptake potential would exceed demand on an annual basis. In this case, downward adjustment of annual root system metabolic activity might be beneficial. This could occur through the construction of roots with lower protein nitrogen and amino acid concentrations. Such roots would presumably have a low respiration rate, in agreement with the many reports of strong correlations between root tissue N and respiration rate (Burton et al. 1996, 2002, Ryan et al. 1996, Zogg et al. 1996). Essentially, these tree roots would contain less metabolic machinery that would function at a higher rate because of elevated temperatures and could therefore accomplish similar amounts of work as roots with higher N concentrations in a cooler environment. If such a longer-term change occurred in
combination with acclimation of foliar respiration, it would result in the ratio of respiration to photosynthesis remaining relatively constant as climate warmed, as proposed by Dewar et al. (1999). We note that Tjoelker et al. (1999b) found that conifer seedlings grown at elevated temperatures had lower foliar N concentrations and lower dark respiration rates at a given temperature.

The response of root respiration to altered climatic conditions will also depend on changes in soil water availability. Dry soil conditions significantly reduced root respiration rates for both sugar maple and red pine, and similar effects of drought have been reported previously for a variety of species (Bryla et al. 1997, 2001, Burton et al. 1998). We note that ignoring the effects of soil matric potential resulted in a mean decrease of 0.4 units in the calculated long-term $Q_{10}$. Because dry soils and high temperatures often occur together, ignoring the effects of soil water availability could result in attributing the effects of drought on root respiration to temperature acclimation.

Conclusions

Specific root respiration rates in sugar maple and red pine forests in Michigan were highly correlated with both soil temperature and soil water availability. Long-term $Q_{10}$ values (based on field measurements of root respiration) were similar to short-term $Q_{10}$ values (based on instantaneous temperature series in the laboratory) for both species, and sugar maple root respiration at constant reference temperatures did not vary significantly as ambient soil temperature changed. This suggests that root respiration in these species undergoes little, if any, acclimation to seasonal changes in soil temperature. For both sugar maple and red pine, results from laboratory temperature series performed at a single point in time appeared to be applicable to field conditions throughout the year, although a series of field measurements spaced over the growing season would be preferable. Our results for two growing seasons do not preclude possible adjustment of root system activity to the sustained increases in mean annual temperature predicted in global climate change scenarios. Such adjustment could cause large increases in ecosystem C losses from root respiration unless there are reductions in either root biomass or root metabolic capacity.

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