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A comparison of manual and automated systems for soil CO₂ flux measurements: trade-offs between spatial and temporal resolution

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Abstract

Soil respiration is affected by distributions of roots and soil carbon substrates and by temperature and soil water content, all of which vary spatially and temporally. The objective of this paper was to compare a manual system for measuring soil respiration in a temperate forest, which had a greater spatial distribution of measurements ($n=12$), but poorer temporal resolution (once per week), with an automated system which had poorer spatial distribution ($n=3$) but superior temporal frequency of measurements (hourly). Soil respiration was measured between 18 June and 21 August, 2002, at the Harvard Forest in central Massachusetts, USA. The fluxes measured within 1 h of each other by these systems were not significantly different. However, extrapolations of the mid-morning manual measurements to daily flux values were consistently lower (averaging 13% lower) than the daily estimates obtained from summing the 24 hourly measurements of the automated system. On the other hand, seasonal flux estimates obtained by interpolating between weekly manual sampling dates or by summing the hourly automated measurements were nearly identical. Underestimates by interpolated weekly manual measurements during some periods were cancelled by overestimates during other periods. Hence, a weekly sampling schedule may be sufficient to capture the most important variation of seasonal efflux of CO₂ from the soil. The larger number of chambers that could be measured with the manual system (larger n) resulted in a smaller 95% confidence interval for characterizing spatial variability within the study area on most dates. However, the greater sampling frequency of the automated system revealed rapid responses of soil respiration to wetting events,

which permitted better empirical modelling of the effects of soil temperature and moisture on soil respiration than could have been achieved with the manual sampling system. Most of the positive residuals of a function that predicts soil respiration based on temperature were from fluxes measured within 12 h of a rain event, and the residuals were positively correlated with water content of the O horizon. The automated system also demonstrated that Q_{10} values calculated for diel variation in soil temperature over a few days were not significantly different than Q_{10} values for the entire 3 month summer sampling period. In summary, a manual system of numerous, spatially well-distributed flux chambers measured on a weekly basis may be adequate for measuring seasonal fluxes and may maximize confidence in the characterization of spatial variance. The high temporal frequency of measurements afforded by automation greatly improves the ability to measure and model the effects of rapidly varying water content and temperature. When the two approaches can be combined, the temporal representativeness of the manual measurements can be tested with the automated measurements and the spatial representativeness of the automated measurements can be tested by the manual measurements.

Key words: Automated system, manual system, soil CO₂ flux measurements, soil respiration, spatial resolution, temporal resolution.

Introduction

Soil respiration, a combination of microbial decomposition and root respiration, is an important component of the

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terrestrial carbon cycle. The annual release of carbon from soil can vary significantly among years, and this difference is often attributed to interannual variations in climatic conditions (Savage and Davidson, 2001). Soil respiration is affected both by temperature (Lloyd and Taylor, 1994; Kirschbaum, 1995) and water content (Davidson *et al.*, 2000), which vary hourly, weekly, seasonally, and annually. In previous long-term studies of soil respiration at the Harvard Forest in Massachusetts, USA, an empirical model of soil respiration was developed, based on soil temperature and soil moisture, which revealed that summer droughts reduced soil respiration in many years (Savage and Davidson, 2001). However, the weekly manual sampling schedule precluded an assessment of the importance of wetting events and the empirical model failed to reveal a relationship between soil respiration and soil water content under wet conditions.

Many different methods have been used to measure soil respiration, each with advantages and disadvantages (Davidson *et al.*, 2002; Hutchinson and Livingston, 2002; Rochette *et al.*, 1997). A manual system and an automated system that both use a vented chamber in non-steady-state mode (Livingston and Hutchinson, 1995) with air circulating between an infrared gas analyser and the chamber are compared here. Potential errors of this chamber design are described in detail by Davidson *et al.* (2002). The modifications required to automate it are described here and the advantages afforded by automation are analysed.

Manual chamber measurements are usually made by one person who moves from location to location. Manually based measurements often cannot be sampled frequently due to time constraints of the manual operators. To obtain a daily flux for a site without having a person sample continually throughout the day and night, a measurement is taken within a time period believed to be representative of the mean daily flux. However, the diurnal trend may not be consistent throughout the year and it may be obscured under very dry or wet conditions. The response of soil respiration to precipitation events can be rapid and often missed due to the infrequency of manually sampled chambers. A more frequent measurement schedule is required to capture the diel responses of soil respiration and the rapid responses to precipitation events and to improve models of soil respiration.

Automated systems can sample at a much higher temporal frequency without having personal attention (Goulden and Crill, 1997; King and Harrison, 2002) and can operate during rain events. These automated soil respiration systems are more expensive and require greater infrastructure (i.e. power, housing) to operate than do the manual measurements. Due to these constraints the automated systems are more poorly spatially distributed than the manual sampling systems. In summary, the manual system can more easily address the spatial

heterogeneity of an area, while the automated system affords greater temporal frequency of sampling. The objective of this paper is to examine the trade-off between the spatially superior manual chamber sampling system and a temporally superior automatic soil respiration sampling system.

Materials and methods

Site description

Soil respiration was measured at the Harvard Forest near Petersham, Massachusetts USA (42°32' N, 72°11' W; see descriptions in Davidson *et al.*, 1998; Savage and Davidson, 2001). Data are presented here for the period from 18 June through 21 August, 2002. A mixed hardwood forest, approximately 60 years old, is growing on well drained sandy loam soils. The mean annual temperature is +8.5 °C and the mean annual precipitation is 1050 mm.

Three separate plots (5×5 m) were selected within an apparently homogeneous area of about 20×20 m². Four manual soil respiration collars and one automated soil respiration collar were randomly placed within each plot. Soil pits were excavated at each of the three plots, probes for measuring temperature (Type T thermocouple) and volumetric water content (Campbell Scientific Water Content Reflectometers, Logan, Utah, USA) were installed at 4.5, 8.5, 14, 36, 44, and 61 cm depths, and then the pits were backfilled. Only data from the 4.5 cm depth are reported here. Litter layer gravimetric water content was measured using DC-half bridge sensors (Borken *et al.*, 2003; Hanson *et al.*, 2003). Throughfall, air temperature, soil volumetric water content, soil temperature, and litter layer gravimetric water content were measured hourly at the site.

Manual measurements of soil respiration

Manual measurements of soil respiration, using a vented, flow-through, non-steady-state system (Livingston and Hutchinson, 1995), were made once per week between 09.00 h and 12.00 h. This time was previously determined as being representative of the mean flux rate for the day, based on a previous manual sampling of diel variation (Davidson *et al.*, 1998). Soil respiration was measured using a Li-Cor 6252 portable Infrared Gas Analyzer (IRGA, Lincoln, NE, USA) mounted on a backpack frame (Fig. 1). The calibration of the IRGA was checked before each measurement using a zero CO₂ standard and a 523 µl l⁻¹ CO₂ certified standard. The IRGA was connected to a vented white acrylonitrile-butadiene-styrene (ABS) chamber top (10 cm in height) that is placed over a collar already in the ground. A pump circulates the air at a rate of 0.5 l min⁻¹ from the chamber top to the IRGA and back to the chamber top. The IRGA and the pump are both run from a 12 V battery. The collars, 25 cm in diameter (0.05 m² surface area), made from thin-walled PVC tubing were cut into 10 cm lengths and inserted into the ground to a depth of approximately 5 cm. Pressure differences between the chamber headspace and ambient air outside the chamber were below detection limits (0.1 Pa measured by an Infiltec micromanometer) (Davidson *et al.*, 2002). The chamber top was left on the collar for 5 min, and the change in CO₂ concentration within the chamber was recorded using a Hewlett-Packard HP 200LX palmtop. A linear regression was performed on the increasing concentration to determine a flux rate, which was corrected for atmospheric pressure and chamber air temperature. Daily flux values were calculated by extrapolating this flux measurement to 24 h. To calculate fluxes for the entire sampling period, fluxes were linearly interpolated between sampling days.

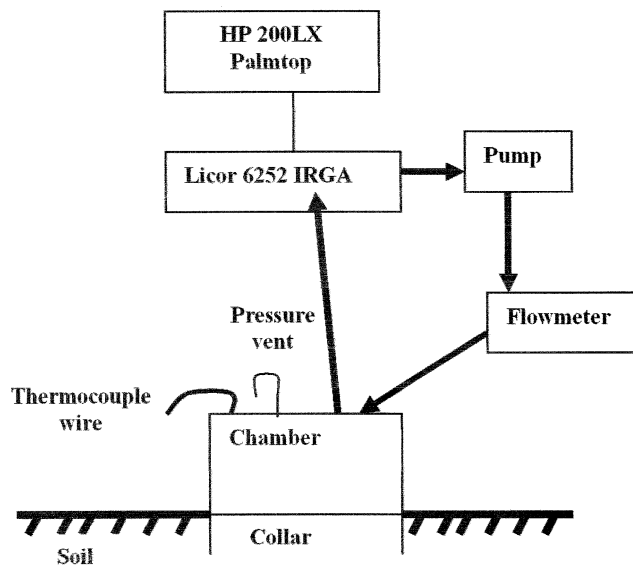


Fig. 1. The manual system for measuring soil respiration rates. All equipment is mounted on a backpack frame and operated with batteries. Thick black lines indicates one-quarter inch OD, one-eighth inch ID urethane tubing and arrows indicated the direction of flow. The HP palmtop is connected to the IRGA and records all data.

Automated measurements of soil respiration

The automated soil respiration measurement system consisted of a Li-Cor 6252 IRGA, two sets of Campbell relay controllers, three sets of solenoid manifolds and a Campbell multiplexer, which were all controlled by a Campbell CR10X datalogger (Fig. 2). There were two sets of controls for this system, those that controlled the movement of the chamber top (relay controller 2) and those that controlled the flow to and from the chambers (relay controller 1). Relay controller 2 controlled the solenoid manifold, which was responsible for supplying the pistons with pressurized air to raise and lower the chamber tops. The other two sets of solenoids, connected to relay controller 1, controlled the flow from the chamber top to the IRGA, through the pump and flowmeter, and back to the chamber top. The flow rate through the system was 0.71 min^{-1} . The IRGA was calibrated weekly using a zero CO₂ standard and a $523 \mu\text{l l}^{-1}$ CO₂ certified standard. Air temperature for each chamber was measured using a Type T thermocouple wired to the multiplexer. The collars were constructed from a 30.5 cm (0.07 m^2 surface area) diameter schedule 80 PVC collar cut to 6.5 cm depth. A stainless steel tube (5 cm long, 2.16 mm ID) served as a chamber vent to equalize pressure between the inside and outside of the chamber. One end of the collar was bevelled so that it could be inserted into the ground approximately 2 cm. The chamber top was made of schedule 40 PVC and was 35.5 cm diameter and 15 cm tall. Automobile window weather stripping was applied to the top of the collar to form an O-ring, such that when the chamber top was lowered by applying 70 psi of pressure to the piston, the chamber top sealed against the weather stripping on the collar. Each automated chamber was activated for 10 min. The first 2 min were to flush out the tubing with ambient air. Ambient air concentrations were logged during the 3rd minute. The chamber top was then lowered onto the collar and the headspace concentration was logged for 7 min. At the end of this 10 min period the chamber top was raised and the next chamber activated. One flux measurement from each of the three automated chambers was sampled each hour over the course of a day. Changes in headspace concentration were converted to flux rates in the same manner as the manual flux values.

Data analysis and modelling

The temperature model: $\text{respiration} = A \times \exp(B \times \text{soil temperature})$ was fit using non-linear least squares regression. The Q_{10} value, which represents the temperature response of soil respiration, was calculated as: $Q_{10} = e^{B \times 10}$.

Results and discussion

Observed patterns of soil respiration and environmental variables

The triplicate autochambers and the mean of the 12 manual chambers showed good agreement throughout most of the sampling period (Fig. 3a). On 8 August autochamber No. 1 began exhibiting extremely high soil respiration rates compared to the other two automated chambers. It was suspected that this was due to the presence of a large mushroom inside the collar. Significantly higher rates of soil respiration have previously been observed when a mushroom appears in a collar. Soil respiration rates followed a generally increasing trend with increasing soil temperature (Fig. 3a, e). The gravimetric water content of the Oi horizon responded immediately to all throughfall events, whereas the soil moisture in the A horizon responded only to large throughfall events (Fig. 1b–d). The duration of the wet-up observed in the Oi horizon was dependent upon the magnitude of the event. Soil respiration decreased as the Oi moisture content decreased, as observed between 4 July and 10 July. Respiration increased immediately after the small wet-up on 11 July. Larger throughfall events, such as those on 18 July and 17 August produced larger respiration responses. Soil respiration rates remained high as long as the gravimetric water content in the Oi was elevated (18 July through 5 August).

The manual soil respiration measurements made on a weekly sampling schedule also generally follow the soil temperature and soil moisture patterns. During periods when the Oi horizon was wet, the manual respiration measurements exceeded those sampled during the drier periods. However, the rapid responses to throughfall events were missed.

Spatial and temporal variability

The automated system makes one soil respiration sample per hour for each of the three collars. To determine the precision, measurements were made six times for 1 h on one automated collar. This experiment was conducted on two separate collars and on four different hours throughout a 1 d period. The average coefficient of variation for soil respiration rates was 8% ($n=48$) with a range of 4–16%. This indicates that there is up to 16% variation in measured soil respiration of a single fixed collar within a 1 h period.

Because there were slight differences in the plumbing and flow rates of the manual and automated design, these two systems were compared on the same collar at approximately the same time. No significant difference

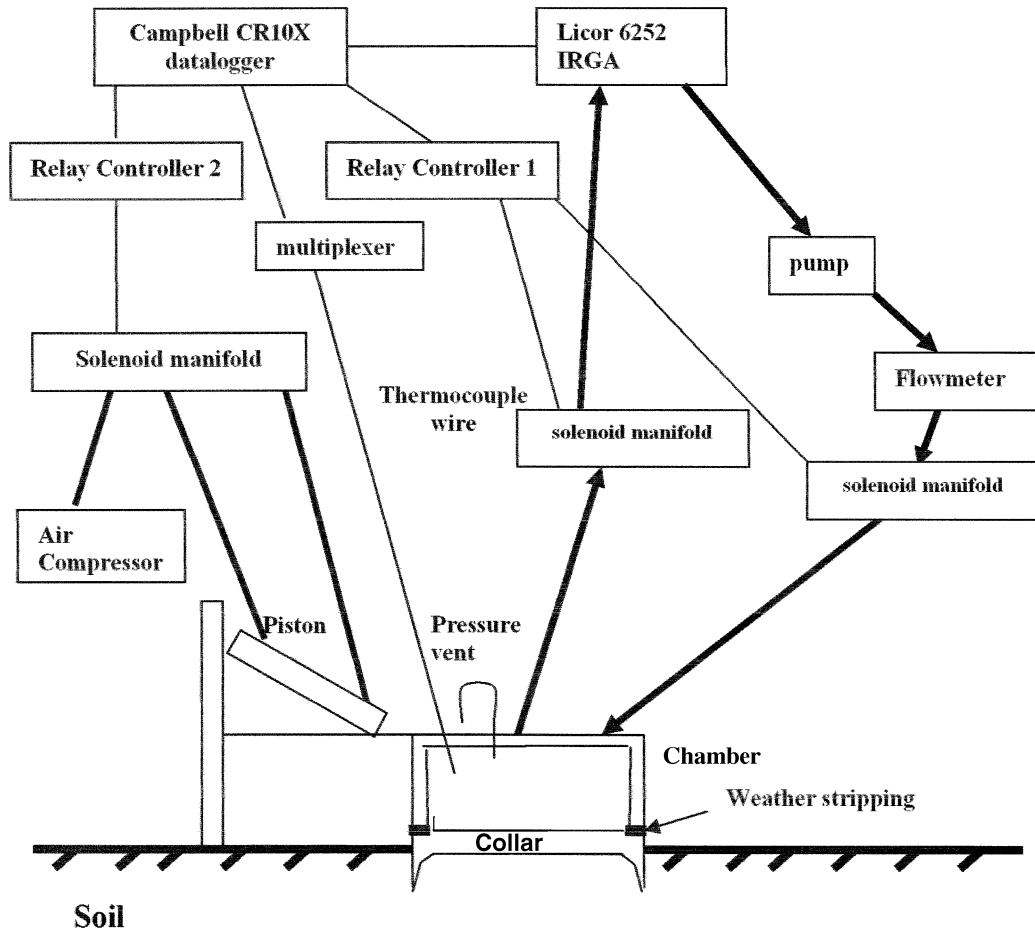


Fig. 2. Flow and wiring diagram for the automated soil respiration system. Thick black lines indicate one-quarter inch OD, one-eighth inch ID tubing and fine black lines are wire connections from the CR10 datalogger. Arrows indicate the direction of flow to and from the chamber. This system operated from line power (not shown). The structure holding the chamber top is fixed to the ground in four locations with 30 cm steel tent pegs (not shown).

was found, and the coefficients of variation were within the 4–16% range previously observed. The two systems also produced similar results when measurements were compared across plots and across the nine sampling dates when the manual measurements overlapped with the automated respiration samples (Fig. 3a). For these 9 d, 77% of the plot means of manual measurements were not significantly different than the automated soil respiration measurement made within the same hour, on the same plot (Table 1). Similarly, Irvine and Law (2002) found good agreement between manual and automated soil respiration measurements on 14 out of 19 dates in Ponderosa pine forests of Oregon.

The larger number of manual collars permitted greater spatial distribution of flux measurements than obtained with the three automated collars. A larger sample size can increase the variance about the mean, but, if the variance is not much larger, a larger sample size can also reduce the standard deviation. Although the 95% confidence intervals for the means of 12 manual and three autochambers were

comparable for several dates, the confidence intervals for the mean fluxes of the entire sampling period were consistently smaller for the manual than the automated system (Table 1, bottom row). Also, when one of the three autochambers was affected by an event such as the mushroom appearance in autochamber 1, this had a greater impact on the site mean and 95% confidence interval (Table 1, 15 Aug and 20 Aug, right-hand column). Based on an analysis of the variance among a population of 36 manual flux estimates, Davidson *et al.* (2002) estimated that ten chamber measurements are sufficient to obtain a mean that is $\pm 20\%$ of the full population mean with a 95% confidence interval, and that only three chamber measurements will provide an estimate of $\pm 40\%$ of the full population mean with a 95% confidence interval.

In addition to uncertainties resulting from spatial heterogeneity within a study site, temporal variation can be important for determining daily fluxes. Daily flux estimates from these manual measurements are made simply by multiplying the measured hourly flux value by

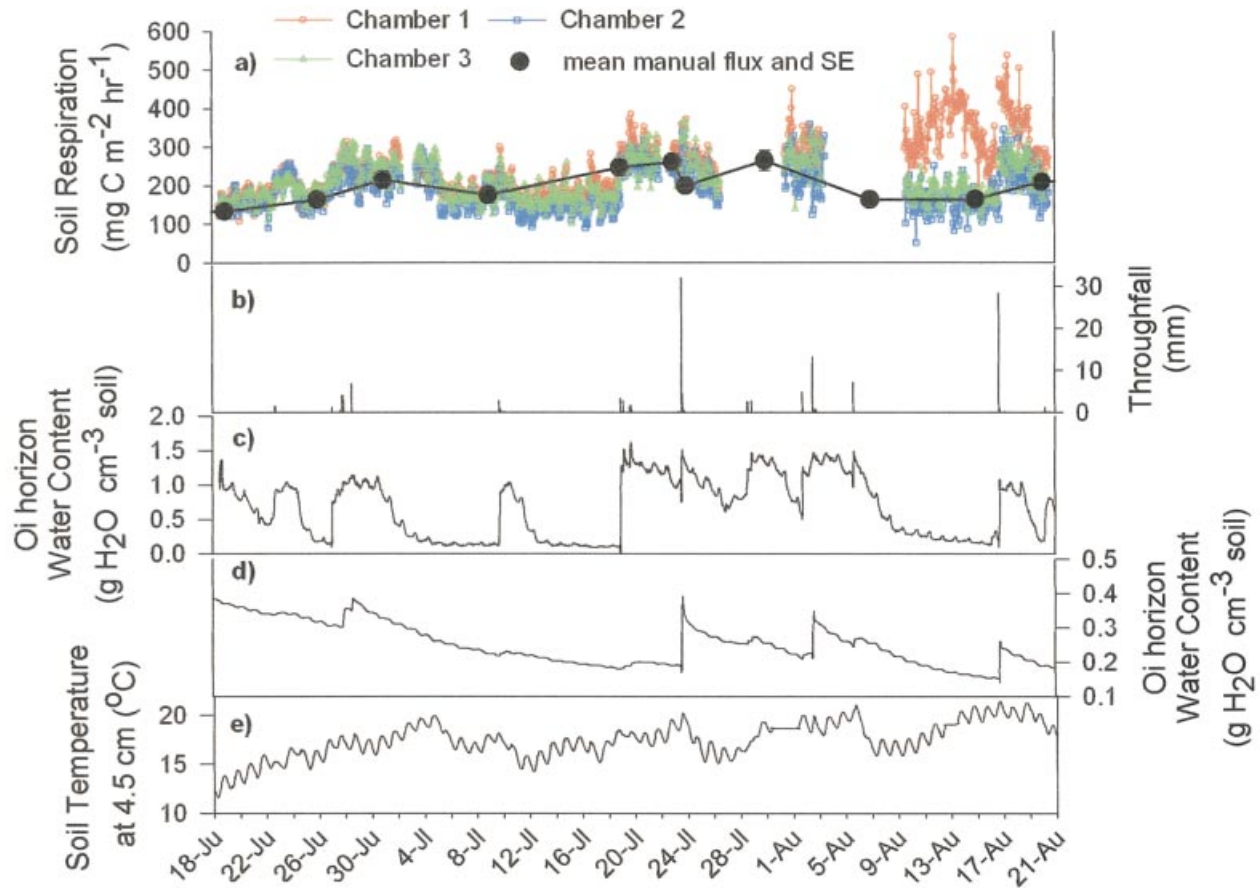


Fig. 3. (a) Hourly soil respiration for each of the three automated chambers (coloured lines) and the mean respiration rate for the manual chambers ($n=12$; black circles with connecting solid lines; error bars are standard errors), (b) hourly throughfall totals, (c) mean ($n=12$) h gravimetric water content of the Oi horizon, (d) soil moisture at 4.5 cm depth, (e) soil temperature at 4.5 cm depth. This depth represents the interface of the O and A horizons.

24. With an automated system, in contrast, the measurements taken during each of the 24 h are summed to determine a daily total respiration rate. A comparison of the mean extrapolated manual daily flux estimates ($n=12$) and the mean summed automated hourly flux estimates ($n=3$) reveals that the automated system gave a consistently and significantly greater daily flux value than the manual daily flux extrapolation. This could mean that the assumption that the period between 09.00 h and 12.00 h is representative of the daily mean flux was incorrect. The underestimation of daily flux by the manual method ranged from 2–30% with a mean of 13%. By contrast, Irvine and Law (2002) found that daily estimates based on two manual measurements made at times expected to represent the diel minimum and maximum fluxes overestimated the mean daily flux by 7% compared to estimates based on 16 automated measurements d^{-1} .

The diel pattern of soil respiration measured by the automated system was variable. Peak respiration rates usually occurred in the late afternoon (17.00–19.00 h) and

the lowest respiration rates usually appeared in the early morning (04.00–07.00 h). However, the responses of soil respiration to wetting events were usually much greater than the diel variation, thus obscuring the diel pattern for several hours depending on the duration and magnitude of the rainfall. The diel pattern was also weaker under very dry soil moisture conditions.

Having addressed the hourly and daily flux estimates, variation over the entire 3 month sampling period is now considered. To determine a respiration rate for the site using weekly manual measurements, sampling dates and summed over the period were interpolated (Fig. 3a, solid line). For the automated system, all of the hourly measurements were summed. These two estimates were compared for the 58 d when the automated system was operating (Fig. 3a). The total interpolated manual flux estimate is 0.26 kg C m^{-2} per 58 d and the summed autochamber flux estimate for the same period is 0.27 kg C m^{-2} per 58 d. The close correspondence is due to the fact that the higher and lower flux values measured by the

Table 1. Mean fluxes (and 95% confidence intervals) for automated and manual flux measurements made during the same hour on each of 9 dUnits are mg C m⁻² h⁻¹. Significant differences are indicated by an asterisk (*) two-tailed one-sample *t*-test (Zar, 1974).

Date	Plot 1		Plot 2		Plot 3		Combined	
	Manual (n=4)	Auto C-1 (n=1)	Manual (n=4)	Auto C-2 (n=1)	Manual (n=4)	Auto C-3 (n=1)	Manual (n=12)	Auto C (n=3)
19 June	136 (66)	168	106* (13)	160	159 (71)	146	134 (27)	158 (21)
26 June	194 (82)	153	127 (65)	134	170 (23)	166	164 (31)	151 (30)
1 July	261 (129)	198	149* (28)	191	236 (77)	216	215 (48)	202 (24)
9 July	237 (91)	178	100* (20)	151	189 (49)	141	175 (45)	156 (32)
19 July	293 (84)	278	171* (55)	250	277 (104)	248	247 (49)	259 (31)
23 July	274 (95)	268	210 (28)	210	300 (131)	245	261 (46)	241 (53)
24 July	230 (74)	258	157 (59)	196	212 (65)	253	200 (34)	235 (63)
15 Aug	196* (116)	322	115 (33)	122	*181 (22)	132	164 (37)	192 (208)
20 Aug	242 (162)	242	180 (52)	157	207 (26)	203	210 (4)	201 (78)
Seasonal mean	229 (27) n=36	229 (43) n=9	147 (15) n=36	174 (31) n=9	215 (22) n=36	194 (37) n=9	197 (14) n=108	199 (21) n=27

Table 2. Comparison of daily estimates derived by multiplying by 24 the mean manual measurements made in the late morning and by summing mean automated measurements made once every hour over 24 hThe automated estimates are significantly higher according to a paired 2-tailed *t*-test ($p < 0.001$). Units are g C m⁻² d⁻¹.

Sample date	Manual daily flux (n=12)	Automated daily flux (n=3)	Difference (% greater than manual daily flux)
19 June	3.2	3.8	0.6 (18%)
26 June	3.9	4.3	0.4 (10%)
1 July	5.2	5.7	0.5 (10%)
9 July	4.2	4.9	0.7 (16%)
19 July	5.9	6.5	0.6 (10%)
23 July	6.3	6.7	0.4 (7%)
24 July	4.8	6.2	1.4 (30%)
15 Aug	3.9	4.7	0.8 (19%)
24 Aug	5.0	5.1	0.1 (2%)
Mean	4.7	5.3	0.6 (13%)

autochamber for certain intervals between manual measurements cancelled each other out. This cancelling of overestimates and underestimates by the manual interpolation method could be fortuitous for this particular dataset, but if it is generally characteristic of synoptic scale temporal variation, it indicates that a seasonal flux could reasonably be estimated with a weekly manual sampling schedule. Indeed, the narrower confidence intervals affected by spatial variation in the weekly manual measurements (Table 1), suggest that the manual approach has some advantage for estimating spatial heterogeneity across seasons and years without creating a large error due

to limited temporal resolution. The lack of temporal resolution could become more important, however, if the manual sampling regime were reduced to biweekly or monthly estimates.

Modelling respiration responses to soil temperature and moisture

It is evident from the automated soil flux data (Fig. 3) that soil respiration responds both to soil temperature and to throughfall events. With the manual measurements, sampling during precipitation events is missed and so many of these short-term responses are missed. The previous

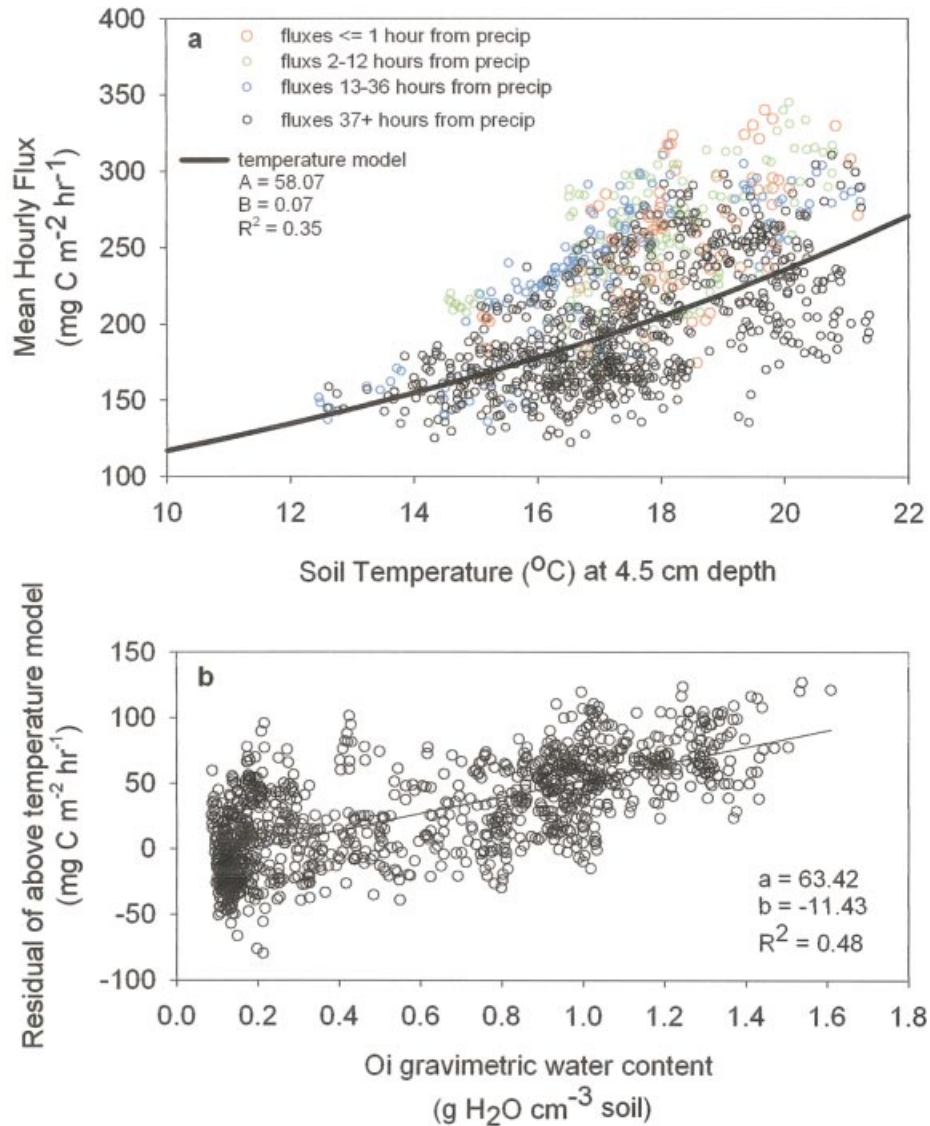


Fig. 4. (a) Mean hourly soil respiration and soil temperature model, (b) residuals of the temperature model plotted against mean hourly gravimetric water content in the Oi horizon. Temperature model is $respiration = A \times \exp(B \times \text{soil temperature})$. The gravimetric Oi horizon water content (WC) model is: $residual\ of\ the\ temperature\ model = a \times WC + b$.

attempts to model soil respiration using weekly manual measurements produced a model explaining the seasonal temperature response and the effects of long-term drought conditions, but failed to predict responses of soil respiration to variations in soil water content rates during non-drought periods (Savage and Davidson, 2001). This variation during non-drought conditions may be rapid, which the automated soil respiration system provides a better chance to reveal.

Soil temperature and mineral soil water content often covary, confounding their effects on respiration (Davidson *et al.*, 1998), but the soil temperature and gravimetric soil moisture content in the Oi horizon were not significantly

correlated in the present study. Soil temperature measured at 4.5 cm depth (below the litter layer) was strongly correlated with soil respiration over the measurement period (Fig. 4a). The fitted Q_{10} value of 2.0 is relatively low, but the temperature range is relatively small and includes only summertime temperatures (12–21 °C).

The time since the last throughfall event is also indicated by the colour of the plotting symbol in this graph, revealing that the highest fluxes, and, hence, those with the greatest deviation above the regression line, often occurred within 12 h of a throughfall event (Fig. 4a). Fluxes can remain high up to 3 d following the precipitation event. The residuals of the temperature function in Fig. 4a were

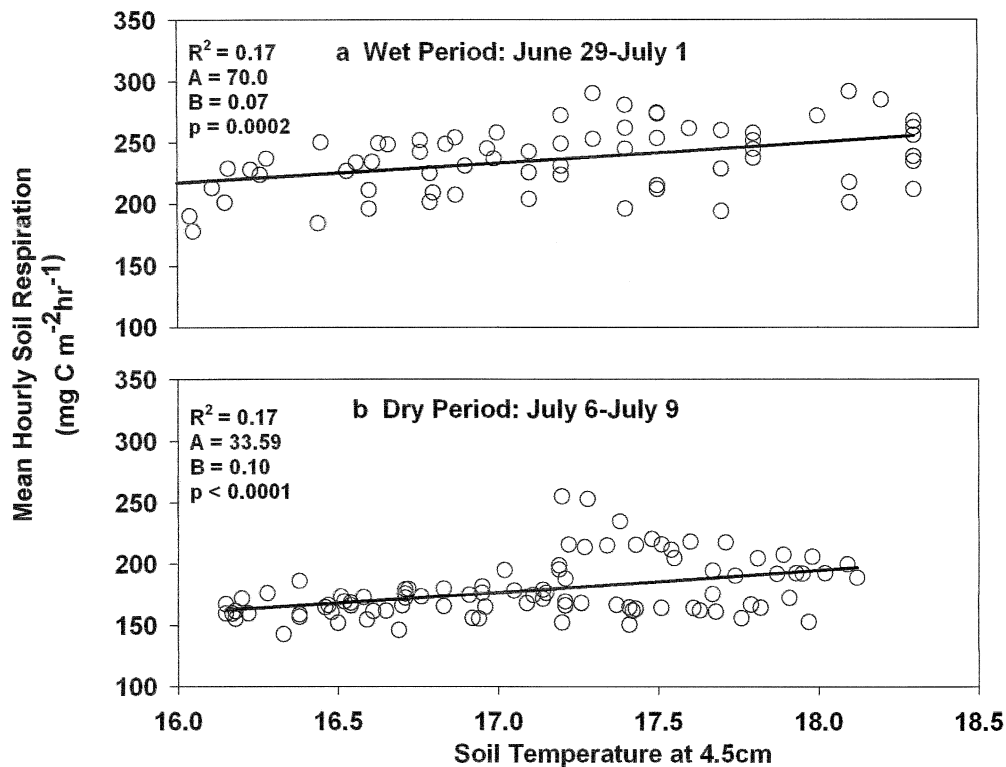


Fig. 5. Mean hourly soil respiration and temperature for a wet period (a) and dry period (b). Temperature model is: $respiration = A \times \exp(B \times soil\ temperature)$.

positively correlated with the gravimetric water content of the Oi horizon (Fig. 4b). The combined temperature and soil moisture function:

$$R = 58.07 \times \exp^{(0.07T)} + 63.42 \times WC - 11.43$$

where R = soil respiration in ($\text{mg C m}^{-2} \text{h}^{-1}$), T = soil temperature ($^{\circ}\text{C}$) and WC = gravimetric water content ($\text{g H}_2\text{O g}^{-1}$ O horizon material) accounted for 65% of the variation in the variability of soil respiration throughout the season. By contrast, the temperature function alone accounted for only 35% of the variation during the summer sampling season. The relatively fast response of the Oi horizon wetness and soil respiration to wetting events would be more difficult to quantify using a manual sampling regime.

The autochamber data also afforded the opportunity to examine whether the response of soil respiration to temperature over the sample period of early to later summer is similar to the diel response. Automated flux data were selected from periods of several days when the soil temperature varied only 2–3 degrees and when soil water content was also relatively constant (Fig. 5a, b). Using the automated soil respiration rates between 29 June and 1 July as a relatively wet period, the Q_{10} was 2.0 (Q_{10} range of 1.4–2.9, 95% confidence). During the relatively dry period between 6–9 July, the Q_{10} was 2.7 (Q_{10} range 1.8–4.2, 95%

confidence). These Q_{10} values are not significantly different from each other or from the temperature response for the entire study period (Fig. 4a), indicating that the diel Q_{10} response of soils during the summer period is not significantly different than the Q_{10} response over the entire summer period.

Conclusions

The manual and automated systems tested here agreed well when measurements were made during the same hour. The larger number of measurements possible with the manual system narrowed the standard deviation of the mean, thus increasing the confidence in the site mean estimate with respect to spatial heterogeneity. On the other hand, extrapolation of manual measurements made in the late morning to a daily flux consistently underestimated the more reliable daily sum afforded by the automated system. However, when interpolated and summed over a 58 d period, the two methods again yielded very similar results. If only a seasonal estimate of soil respiration is required from a location, then a weekly manual sampling system with spatially well distributed flux measurements may be the best approach.

The automated system afforded greater opportunity to model short-term responses of soil respiration to diel

variation and to wetting events. This temporal resolution may be important if soil respiration rates are being compared to eddy covariance estimates of total ecosystem respiration. The high temporal frequency of sampling allowed the effective capture and modelling of the effects of rapidly varying water content on soil respiration, accounting for an additional 30% of the observed variation in soil respiration over the study period compared to a temperature function alone. The high temporal frequency of the automated system also demonstrated that diel and seasonal responses to soil temperature were not significantly different during the study period. However, this finding needs to be substantiated in other seasons at this site and at other sites.

The balance of these trade-offs depends upon the objectives of the research and the relative importance of characterizing spatial or temporal variability. Both are important for soil respiration. Ideally, a combination of numerous, spatially extensive, infrequent manual measurements and spatially fewer, high frequency automated measurements would provide important cross-checks for characterizing both sources of variation.

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