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Calibrating soil respiration measures with a dynamic flux apparatus using artificial soil media of varying porosity

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Summary

Measurement of soil respiration to quantify ecosystem carbon cycling requires absolute, not relative, estimates of soil CO_2 efflux. We describe a novel, automated efflux apparatus that can be used to test the accuracy of chamber-based soil respiration measurements by generating known CO_2 fluxes. Artificial soil is supported above an air-filled footspace wherein the CO_2 concentration is manipulated by mass flow controllers. The footspace is not pressurized so that the diffusion gradient between it and the air at the soil surface drives CO_2 efflux. Chamber designs or measurement techniques can be affected by soil air volume, hence properties of the soil medium are critical. We characterized and utilized three artificial soils with diffusion coefficients ranging from 2.7×10^{-7} to $11.9 \times 10^{-7}\,m^2\,s^{-1}$ and porosities of 0.26 to 0.46. Soil CO_2 efflux rates were measured using a commercial dynamic closed-chamber system (Li-Cor 6400 photosynthesis system equipped with a 6400-09 soil CO_2 flux chamber). On the least porous soil, small underestimates (< 5%) of CO_2 effluxes were observed, which increased as soil diffusivity and soil porosity increased, leading to underestimates as high as 25%. Differential measurement bias across media types illustrates the need for testing systems on several types of soil media.

Introduction

Soil respiration is often measured in an effort to better understand and quantify carbon cycling in natural and managed ecosystems. Commercially produced measurement systems are readily available and use a variety of measurement techniques, and most researchers depend on these to assure that systems estimate CO_2 efflux accurately and precisely. Numerous studies have compared soil respiration techniques using field-based measurements (e.g. Rochette *et al.*, 1992, 1997; Norman *et al.*, 1997; Pongracic *et al.*, 1997; Le Dantec *et al.*, 1999; Janssens *et al.*, 2000, 2001; Nay & Bormann, 2000), but surprisingly, there have been few attempts to calibrate soil CO_2 efflux systems against known efflux rates (Nay *et al.*, 1994; Widen & Lindroth, 2003). Without knowing the true respiration rate, differences between measurement systems are relative and the process by which the methods differ cannot be fully understood. Consequently, normalization across measurement techniques may not hold under different soil conditions. There is no clear standard for calibrating soil respiration across measurement techniques or means to test the accuracy of these methods (Norman *et al.*, 1997; Rayment & Jarvis, 1997; Janssens *et al.*, 2001). However, without accurate calibration, using measured soil CO_2 efflux rates to compare C budgets of different sites is problematic.

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Nay *et al.* (1994) used a rigorous technique to create known effluxes from the surface of a simulated soil to elucidate measurement bias between dynamic and static (soda lime trap) methods. The most commonly used chamber methods employ either an open or a closed gas exchange principle. Previous studies have shown that closed systems can underestimate soil CO_2 efflux by as much as 34% (Hutchinson & Mosier, 1981; Nay *et al.*, 1994; Healy *et al.*, 1996; Conen & Smith, 2000; Rayment, 2000). The cause of the phenomenon is the subject of lively debate. Rayment (2000) reasoned that closed chambers underestimate soil CO_2 efflux because the effective chamber volume being measured is not only the volume of the chamber but also includes the volume of the air-filled spaces near the soil surface. The magnitude of the underestimation is largely determined by microsite factors that affect soil air volume, and variation in diffusivity can alter the relationship between measured and actual CO_2 efflux rates. An alternative approach is that placement of a closed chamber on the soil surface rapidly induces changes in gas concentration in the soil, thereby changing the diffusive gradient and altering surface flux, assuming constant gas concentration at some level in the profile (Hutchinson & Mosier, 1981; Healy *et al.*, 1996). Conen & Smith (2000) add the caveat of assuming constant gas production within the soil profile and that head-space accumulation of CO_2 in the chamber is linear. Both schools of thought agree that air-filled porosity will affect the degree of underestimation. Therefore, to create a laboratory apparatus that can generate CO_2 fluxes with the intent to calibrate or compare systems, it is necessary to employ a variety of soils or media with porosities and diffusivities typical of the soils to be measured *in situ*. Nay *et al.* (1994) employed a porous foam material that had 60% of the diffusivity of free air, while natural soils exhibit much greater resistance to gas diffusion (Lai *et al.*, 1976; Gliński & Stępniewski, 1985).

Native soils, or soils reconstructed in microcosms that have been allowed to settle, are difficult to use in a laboratory apparatus for physical and biological reasons. The interplay and variation of soil moisture, shrink–swell properties, cracks, voids, soil temperature, microbial activity and organic matter introduce too much physical heterogeneity in the system to create repeatable fluxes that are uniform across the soil surface. Despite these difficulties, Kabwe *et al.* (2002) succeeded in getting repeatable measurements with a dynamic closed chamber system by injecting concentrated CO_2 into a soil microcosm (0.58 m diameter × 1.2 m thick) of sandy soil. However, uncertainty was introduced because they had to subtract initial measurements of respiration to account for microbes and substrate native to the soil and it took 300 and 500 hours to achieve equilibrium at CO_2 injection rates of 400 and 800 mg $CO_2\,m^{-2}\,hour^{-1}$, respectively. Widen & Lindroth (2003) also constructed a system that advanced chamber-based soil respiration measurement calibration and demonstrated important differences between an open and a closed measurement system using artificial soils of varying porosity through which CO_2-enriched air was allowed to diffuse.

The ideal medium for generating artificial fluxes is inert to the gas being studied, is non-compressible, is composed of particles of uniform size and shape, and has air-filled spaces similar to those of natural soils. Complexities arising from microbe metabolism, soil chemistry, carbon substrate quality and fluctuating water content are avoided when an inorganic medium is utilized. In this study, we describe a dynamic flux apparatus that uses mass flow controllers, real-time feedback from CO_2 analysers, and logical routines to create virtually any soil CO_2 efflux rate. The apparatus is based on the principles of Nay *et al.* (1994), but uses soil media of greater complexity and air volumes that are representative of dry field soils. It differs from that of Widen & Lindroth (2003) in that a stable CO_2 concentration is maintained in the footspace below the soil, akin to variation present in natural soil profiles. We describe the diffusive properties of the three artificial soils and how we utilized each to assess flux estimates using a commercial dynamic closed chamber system across a range of known CO_2 efflux rates.

Methods

Apparatus

The design of the dynamic soil efflux apparatus was based on that of Nay *et al.* (1994) and involves supporting an artificial soil above an air-filled footspace wherein the concentration of CO_2 in air can be manipulated. Our intent was not to pressurize the footspace in any way, so that only the diffusion gradient between the air in the footspace and the air at the soil surface drives the CO_2 efflux. The major changes, relative to Nay *et al.* (1994), include: controlled CO_2 injection via mass flow controllers, real-time monitoring of CO_2 concentration in the footspace and outside the apparatus, automated efflux generation and monitoring by a data logger, creation of a rugged frame to support more than 150 kg of soil medium, and use of media with similar CO_2 diffusivity and porosity as dry field soils.

The efflux tank was constructed using a rectangular Nalgene container (91 cm long × 51 cm wide × 51 cm high). To support the soil medium and create a footspace, an aluminium frame was constructed. On top of the frame, fibreglass netting was supported by thin wires and glued to the walls of the tank for extra support. A porous nylon air cleaner element was laid over the fibreglass mesh to prevent the medium from falling through. This construction (Figure 1) allowed the lower 31 cm of the tank to be a footspace (0.144 m^3) and the upper 20 cm to be filled with a soil medium (0.093 m^3). The footspace was equipped with: five small electric fans to mix the air (two shown), two windows constructed of Lexan^{TM} (DuPont Corp., Wilmington, DE), two ports to monitor CO_2 concentration, one port to inject concentrated CO_2, and six 1/4 inch (6.4 mm) ports (three shown) and four 3/8 inch (9.5 mm) ports (two shown) for pressure equilibration. During normal operation, two or three fans were used to achieve optimum mixing. Pressure in the footspace was monitored with a digital manometer (model MA2-005P, Modus Instruments Inc., Northboro, MA). All pressure equilibration ports were closed and then sequentially opened until the pressure differential with the atmosphere fell below detectable limits (+0.1 Pa), in order to select the minimum number of open ports needed to achieve equilibrium with atmospheric pressure. The CO_2 concentration in the footspace was monitored with an environmental gas monitor-2 (EGM-2) infrared gas analyser (IRGA) (PP Systems, Haverhill, MA) scaled 0 to 10 000 $\mu mol\,CO_2\,mol^{-1}$, configured to sample footspace air in a closed loop. The CO_2 concentration at the soil surface was monitored with an EGM-2 scaled 0 to 2000 $\mu mol\,mol^{-1}$. A Campbell data logger Model 21 X (Campbell Scientific Inc., Logan, UT) was programmed to collect data from the two IRGAs, calculate real-time CO_2 efflux from the soil medium surface and maintain a preselected

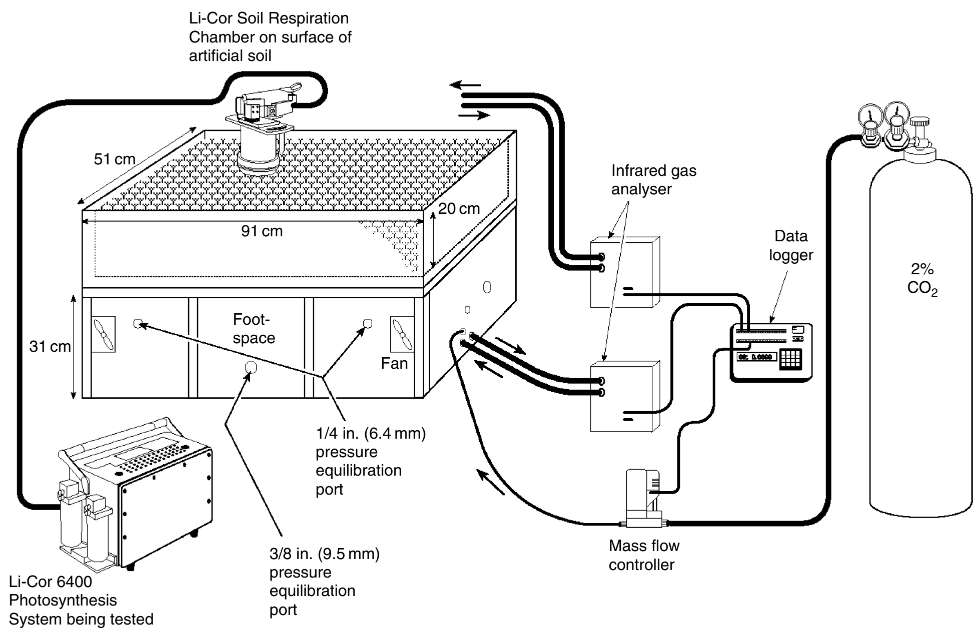

Figure 1 Diagram of the dynamic flux apparatus.

or pre-programmed rate of efflux by injecting 2% by volume CO_2 in air into the footspace via a Sierra 'sidetrak' mass flow controller Model 840 L (Sierra Instruments, Inc., Monterey, CA) as needed.

Efflux theory and application

The concept of the dynamic flux apparatus requires the footspace to be maintained at a specific CO_2 concentration, allowing CO_2 to move through the soil medium via gas diffusion. The CO_2 efflux can be calculated using Fick's law:

$$F/At = f = -D_p(\mathrm{d}c/\mathrm{d}x), \tag{1}$$

where F is grams of gas, A is area (m^2), t is time (s), f is gas flux density (g gas m^{-2} soil s^{-1}), D_p is soil gas diffusivity (m^3 soil air m^{-1} soil s^{-1}), c is the concentration of CO_2 in the gaseous phase (g gas m^{-3} soil air), and x is the thickness of the medium (m).

To create a known CO_2 efflux using artificial soil, it is necessary to understand the diffusive properties of the material. Soil gas diffusivity (D_p) and soil aeration are the major physical factors controlling the diffusion of gas through soil (Kruse *et al.*, 1996; Moldrup *et al.*, 2000). Under native soil conditions, soil air content varies through displacement by soil water. For the purposes of this work, we focus on the diffusion of CO_2 through non-organic, dry soils to eliminate any confounding processes. The most difficult part of creating a steady-state flux apparatus is the accurate determination of D_p, which we calculate empirically. A laboratory diffusion apparatus was built and operated according to the design originally described for argon and nitrogen gas movement in soil (Evans, 1965; Rolston, 1986). Diffusivity was calculated using Rolston (1986):

$$\ln[(C - C_s)/(C_o - C_s)] = -D_p(At/Vl), \tag{2}$$

where C_s is the ambient CO_2 concentration (μmol mol^{-1}), C_o is the initial CO_2 concentration (μmol mol^{-1}), C is the observed CO_2 concentration (μmol mol^{-1}), V is volume of the diffusion chamber (m^3) and l is the length of the chamber (m).

These calculations of D_p did not account for the additional resistance to diffusion created by the rugged materials that support the medium in the dynamic flux apparatus (Figure 1), or for the settling of medium particles over time. Therefore efflux tanks themselves were also used to derive empirically $\ln[(C - C_s)/(C_o - C_s)]$. This allowed the additional resistance to diffusion of the materials supporting the medium in the efflux tank to be accounted for in the calculation of D_p. The ratio of chamber air to soil air in the Evans (1965) type apparatus was sufficiently large to minimize dilution errors, which are similar to closed chamber errors described by Rayment (2000), but the footspace volume in our apparatus was not large enough to avoid these errors and could result in detectable error. Rolston (1986) provides a correction equation, which we applied to our values of D_p. The two methods compared favourably, but as expected the D_p values of the dynamic flux apparatus remained somewhat smaller (6–14%). For the purposes of the experiment, corrected values, determined from the efflux apparatus, were used since these data accounted for structural material supporting the medium and any potential leaks in the tanks, fittings or tubes. The value of D_p was determined for three different artificial soils: coarse landscaping pebbles, fine sand and a 50:50 mixture of fine sand and landscaping pebbles (mixed soil). Once D_p was determined for each artificial soil, efflux was calculated by measuring the CO_2 concentration within the footspace and at the soil surface (Equation (1)).

Measurement of surface fluxes

To demonstrate the utility of this technique, a Li-Cor 6400 photosynthesis system (Li-Cor Inc., Lincoln, NE) equipped with a 6400-09 soil CO_2 flux chamber was used to measure surface fluxes generated by the apparatus. This measurement device utilizes a dynamic closed-chamber system (DCCS) that uses a non-steady state gas-exchange principle across a soil surface area of 0.00716 m^2. The 6400-09 allows the user to determine the insertion depth, thus varying the system volume, which at zero insertion depth is 0.000991 m^3. We used an insertion depth of 0.02 m resulting in a volume of 0.000848 m^3. The 6400-09 operates by drawing down the head-space CO_2 concentration within the chamber (near-ambient concentration) and then shifts into measurement mode whereby CO_2 accumulates to a preselected concentration at which point the rate of increase is closely monitored and flux is calculated. A series of flux rates was generated through each of the artificial media to test the DCCS. The maximum flux rate obtainable was limited by the range limit of the IRGA and the value of D_p. It usually took 60–120 minutes to ensure system equilibrium after a 1 μmol m^{-2} s^{-1} change in efflux. The CO_2 concentration in the footspace was held constant during each measurement interval. We measured as many rates as possible in a 2–3-day period for each medium.

Results

Physical properties affecting gas diffusion were assessed for each of the three dry artificial soils (Table 1). The combination of sand and pebbles (mixed soil; 50:50 by volume) produced a medium that had greater bulk density than its constituent materials (Table 1), the result of the pebble pore volume being packed with sand. Since only dry materials were used, total porosity and air-filled porosity are the same and are referred to as porosity throughout. The porosity of the mixed soil was almost half that of pebbles alone. Using pebbles, sand and the mixed soil, we were able to achieve a range of porosities and D_p values (Tables 1 and 2). The pebbles exhibited a diffusion coefficient more than four times that of the mixed soil. The relationship between air content of soil, bulk density, tortuosity and D_p is illustrated in Figure 2. Bulk density and tortuosity increase, as D_p declines, while greater soil porosity results in larger D_p values. The interaction between D_p and porosity is frequently presented as a non-linear relationship (e.g. Moldrup *et al.*, 2000); however, with only three points fitted, non-linear equations could lead to biased interpretation, therefore a linear model was applied (Figure 2).

The CO_2 concentration of air in the footspace of the flux apparatus could be manipulated from near ambient (370 μmol mol^{-1}) to 10 000 μmol mol^{-1} CO_2 in air (limitation of the gas analyser). Based on the diffusivity of each soil medium, the maximum efflux for mixed, sand and pebble media was approximately 6, 12 and 24 μmol CO_2 m^{-2} s^{-1}, respectively. The relationship between CO_2 efflux generated by the apparatus and the flux measured by the DCCS was linear for all soil types (Figure 3). Observed efflux versus expected efflux was virtually inseparable for the mixed soil, but deviated in sand and pebbles (Figure 3). Since the maximum obtainable CO_2 efflux rate is different for each soil type, direct comparisons between the soils can be made only at the low end of the range (Figure 4). The deviation from expected efflux increased with efflux rate, but stabilized rapidly in the mixed and sand media to a constant level (Figure 5). The generated efflux correlates exceptionally well with the DCCS measures on mixed soil medium (Figure 5) – the difference is less than 5%. Measurements with the DCCS underestimated (10–15%) the generated flux through sand, but were rather consistent across a range of effluxes (Figure 5). Efflux measured on the pebble medium was greater than expected at low efflux rates (< 2 μmol m^{-2} s^{-1}) before stabilizing to a more consistent underestimate that was as high as 25% (Figure 5).

Discussion

The soil characteristics of D_p, porosity, bulk density and tortuosity are clearly co-related and their mutual relationships (Figure 2) illustrate the physical properties that control CO_2

Table 1 Physical properties of three non-organic, dry, artificial soils utilized with the dynamic flux apparatus

Medium	Bulk density /Mg m^{-3}	Porosity (dry)	Particle density /Mg m^{-3}	Diffusion coefficient of CO_2[a] /m^2 s^{-1}	Tortuosity[b]
Mixed (sand and pebbles)	1.87	0.26	2.54	2.72×10^{-7}	2.396
Sand	1.64	0.38	2.66	5.83×10^{-7}	1.997
Pebbles	1.40	0.46	2.61	12.78×10^{-7}	1.805

[a]Data averaged over entire profile.

[b](Dimensionless) ratio of average capillary tube length to the length of the porous medium, along the diffusion axis, in a sinuous capillary tube of uniform diameter (Moldrup *et al.*, 2001).

Table 2 Comparison of gas diffusion coefficients of CO_2 measured with the dynamic soil efflux apparatus with published values

Source	Medium	Depth /cm	Diffusion coefficient of CO_2[a] /$m^2\ s^{-1}$
Our apparatus	Mixed (sand and pebbles)	0–20	2.72×10^{-7}
Our apparatus	Sand	0–20	5.83×10^{-7}
Our apparatus	Aquarium gravel[b]	0–20	1.19×10^{-6}
Our apparatus	Pebbles	0–20	1.28×10^{-6}
Lai *et al.* (1976)	Moist lawn soil[c]	0–23	5.83×10^{-7}
Lai *et al.* (1976)	Dry lawn soil[c]	0–23	1.17×10^{-6}
Lai *et al.* (1976)	Cultivated soil, with dry cracked surface[c]	0–23	9.44×10^{-7}
Lai *et al.* (1976)	Soil irrigated for 7 days, surface water-logged[d]	0–23	3.06×10^{-7}
Lai *et al.* (1976)	Water-logged soil after 5 days of drying[d]	0–23	7.50×10^{-7}
Nay *et al.* (1994)	Polyurethane foam	0–18	9.89×10^{-6}
Gliński & Stępniewski (1985)	Expected range on various dry soils		8.10×10^{-6} to 3.20×10^{-7}
Gliński & Stępniewski (1985)	Expected range on various saturated soils		8.80×10^{-10} to 3.50×10^{-11}
Bakker & Hidding (1970)	Non-puddled topsoils, air-filled porosity 0.04–0.4[e]		2.16×10^{-6} to 2.16×10^{-8}
Gradwell (1961)	Silt loam topsoils, air-filled porosity 0.02–0.4[e]		1.97×10^{-6} to 2.20×10^{-8}
Gliński & Stępniewski (1985)	CO_2 in free air at 20°C		1.59×10^{-5}
Gliński & Stępniewski (1985)	CO_2 in H_2O at 20°C		1.77×10^{-9}

[a]Data averaged over entire profile.
[b]Tested with diffusion apparatus (Evans, 1965), but not used with our flux apparatus.
[c]Sandy loam measured *in situ*.
[d]Loamy sand measured *in situ*.
[e]Calculated from model describing the relationship of D_p soil/D_p air as a function of air-filled porosity at 20°C (Gliński & Stępniewski, 1985).

efflux across soil media in our apparatus. As bulk density and tortuosity increase, D_p decreases. Conversely, as porosity increases, D_p increases. Our values of D_p are at the low end of the range expected for dry soils (Table 2; Gliński & Stępniewski, 1985). It seems likely that the structure of the efflux tank induced some additional resistance to diffusion, possibly from the compaction of the air-cleaner element. The diffusivities we created were still one tenth that of the polyurethane used by Nay *et al.* (1994). The value of D_p in water is 10^{-4} that of D_p in free air, hence wet or saturated soils exhibit substantially lower D_p than the media used in our study (Table 2). Our D_p values were similar to those measured by Lai *et al.* (1976) in a variety of soils under field conditions, but when compared with Bakker & Hidding (1970) and Gradwell (1961) these values would be at the high end of the range encountered in the field (Table 2). Porosities achieved with the media (0.26 to 0.46) used in the study fall within the range commonly observed in the field (0.15 to 0.60), but do not get as small as those found in very wet soils (Gliński & Stępniewski, 1985).

Our results demonstrate that soil physical properties can affect how accurately a dynamic closed-chamber system (DCCS) estimates soil respiration. On the soil medium with the lowest porosity (mixed), there was minimal deviation between observed and expected flux rates (Figure 5). On the other soil media with higher porosities, the DCCS markedly underestimated calculated flux (Figures 3 and 4). Underestimation by DCCS has been reported by others (Hutchinson & Mosier, 1981; Healy *et al.*, 1996; Conen & Smith, 2000; Rayment, 2000; Widen & Lindroth, 2003). Conen & Smith (2000) presented a model that predicts the underestimation of fluxes from closed chambers using total soil air volume and chamber volume. Our results are in close agreement on the sand and pebble substrates, though the flux underestimate was lower than predicted on the mixed soil (Figure 6). Conen & Smith's (2000) model could be used to convert results for particular soils; however, fluctuations in soil moisture confound the determination of soil air volume and make retrospective analysis or corrections difficult. The best means of preventing or reducing underestimation of gas flux by closed chambers is increasing chamber height (Matthias *et al.*, 1978; Healy *et al.*, 1996; Conen & Smith, 2000).

Using a laboratory apparatus to create CO_2 fluxes, Nay *et al.* (1994) found a near-constant 15% underestimate of CO_2 flux with a DCCS. We generally observed constant underestimation except at the lowest flux rates (Figures 4 and 5). At rates less than 2 μmol $CO_2\ m^{-2}\ s^{-1}$ our DCCS overestimated flux on the pebble and mixed media. This deviation is relatively small when compared with the complete range of fluxes that were created (Figure 3). It could be that the gas mixing or circulation in the measurement chamber may be dislodging or disturbing soil air and this was detectable only at low flux rates. Widen & Lindroth (2003) demonstrated a linear relationship between measured and reference CO_2 fluxes using a Li-Cor

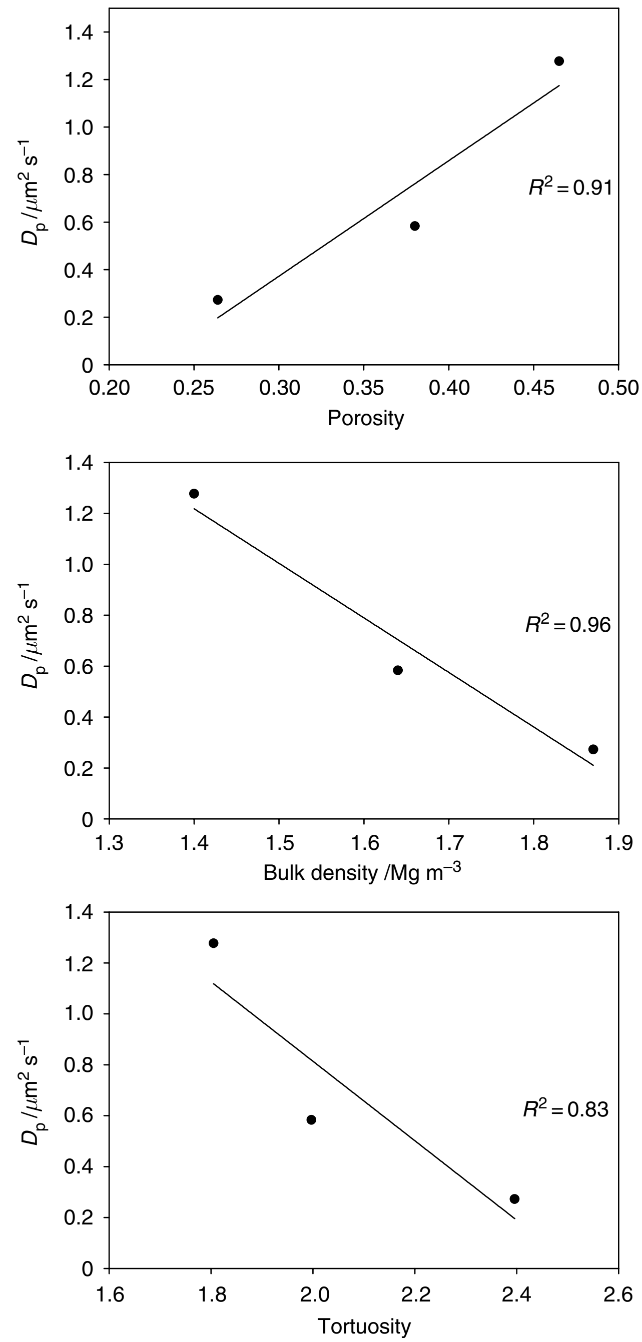

Figure 2 Effects of soil physical properties on the diffusion coefficient of CO_2 (D_p) in soil air. Curves are fitted with linear equations.

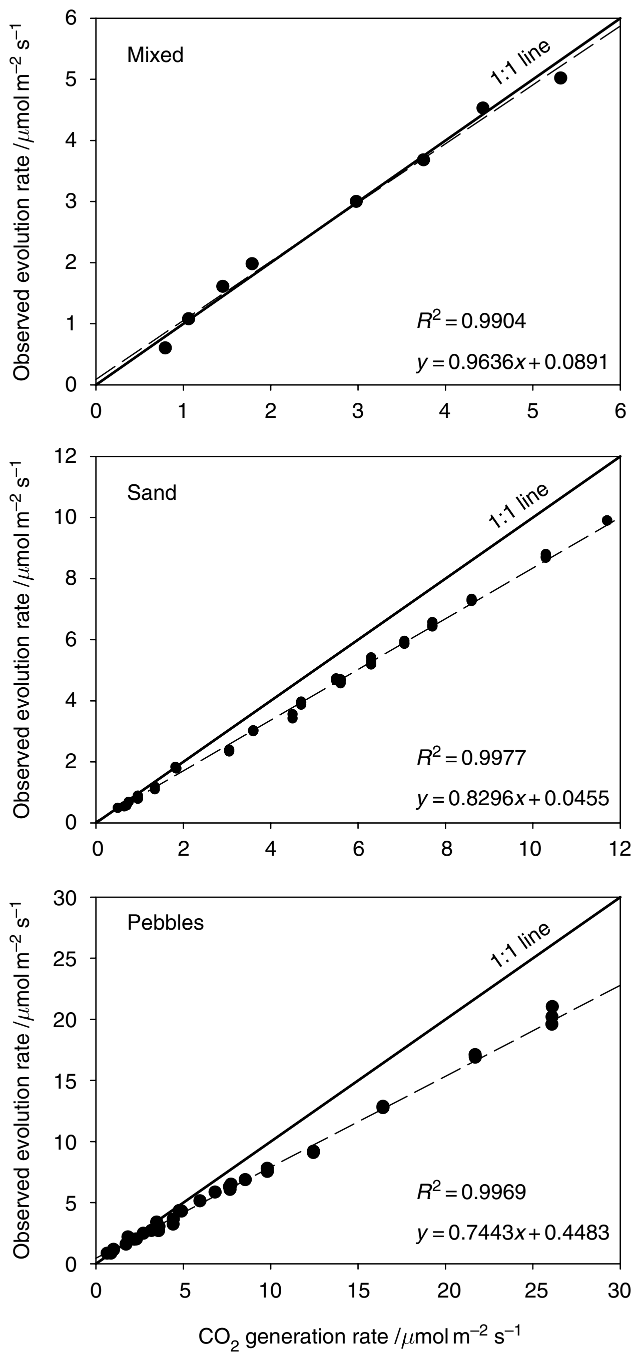

Figure 3 Comparison of CO_2 evolution generated by the dynamic flux apparatus and CO_2 evolution measured by the DCCS. Data are presented across the full range of fluxes generated on each medium.

6200-09 soil respiration system. They generated fluxes through three sandy soils of varying porosity (0.60, 0.34 and 0.34 with water added) and found that the DCCS underestimated on the most porous sand (0.60), was in agreement with generated flux on the dry sand (0.34) and overestimated generated flux on the wetted sand (< 0.34). While differences exist between our results and those of Widen & Lindroth (2003), the trend with respect to the effect of porosity on measured flux is similar.

We believe that the dynamic flux apparatus presented here, when used with a variety of soil media, represents an improvement over other means of generating precisely known CO_2 gas

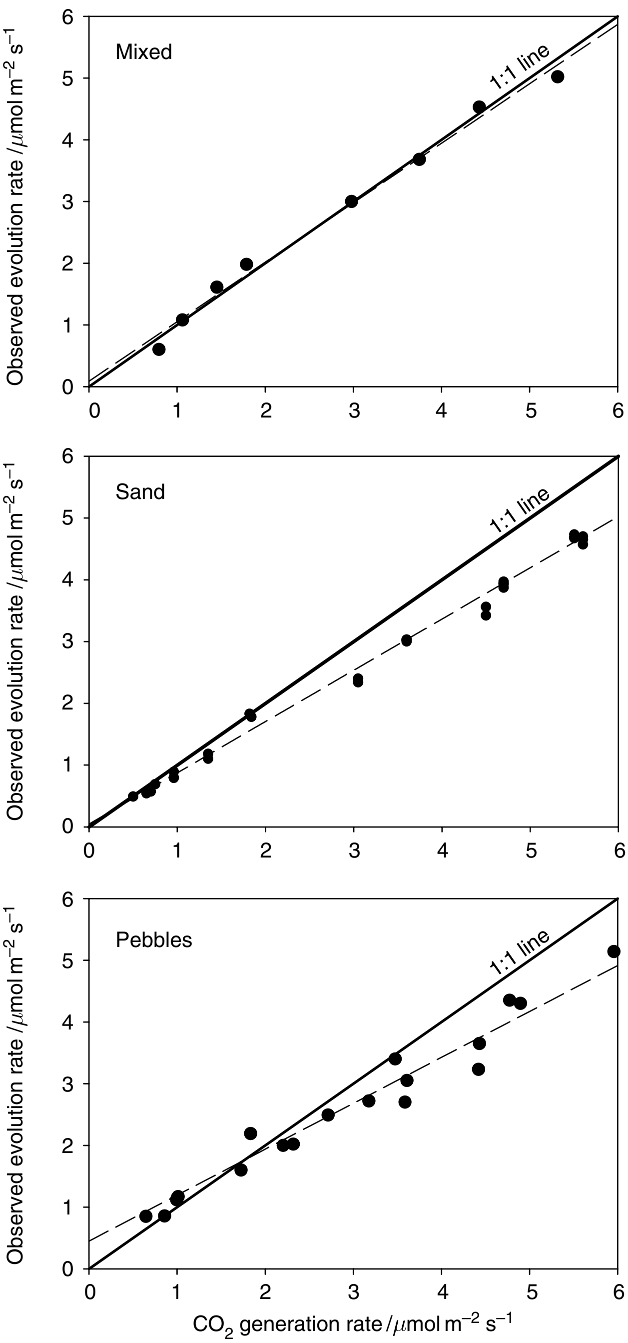

Figure 4 Comparison of CO_2 evolution generated by the dynamic flux apparatus and CO_2 evolution measured by the DCCS. Data are scaled from 0 to 6 $\mu mol\, CO_2\, m^{-2}\, s^{-1}$ to facilitate direct comparison across soil medium.

fluxes from porous, soil-like material (Nay *et al.*, 1994; Bekku *et al.*, 1997; Kabwe *et al.*, 2002; Widen & Lindroth, 2003). Natural soils will probably have several layers or regions of varying porosity and lower values of D_p. The potential for leaf litter to induce air volume based errors may be even more dramatic and complex. Respiration chambers are often placed on litter and organic material on forested sites. Not only are these materials potential sources of CO_2, but their complex aeration can be difficult to account for and may pose problems for closed chambers. Newly fallen litter may exhibit much greater air volume than the soils below or in some cases become a barrier to diffusion (Maier & Kress, 2000). This could be problematic on sites with deep litter layers. Our dynamic flux apparatus allows chamber systems to be tested with soils of varying porosity under ideal circumstances, which will identify areas of concern with the chamber technique. This experiment did not consider the effects of soil water, changes in barometric pressure, air turbulence or mass flow, which can alter soil respiration via processes other than diffusion. In contrast to systems described by Nay *et al.* (1994) and Bekku *et al.* (1997), we used soil media that exhibited porosity and D_p values similar to dry field soils and demonstrated the impact of varying soil properties on flux determination by a DCCS. By using artificial media it was not necessary to consider the effects of soil microbes and moisture, as done by previous workers (e.g. Bekku *et al.*, 1997; Kabwe *et al.*, 2002). Kabwe *et al.* (2002) used microcosms, which afforded great stability of the media, but required weeks to come into equilibrium; thus, sufficient sampling across a range in efflux rates would take a prohibitively long time. The system described by Widen & Lindroth (2003) is an excellent means of testing or calibrating respiration chambers, but there are some notable differences with our dynamic or steady-state calibration system. Our dynamic flux apparatus uses deeper soil (20 cm versus 5 cm) providing more resistance to surface eddies that could dislodge air parcels from deep within the apparatus. The dynamic flux apparatus creates a steady-state condition allowing a constant flux of CO_2 from the medium, much like CO_2 efflux from natural soil. Since steady flux rates can be generated, the apparatus can be used to test static measurement techniques (soda lime or alkali trap). This system is also programmable, so that it can perform automated tests (on open design systems) that can run without disturbing the measurement chamber.

A drawback of our method is the need to measure D_p precisely through the soil medium (including the apparatus structure), which can be time-consuming. In addition, the apparatus needs to be checked for leaks and whether its components have the capacity to adsorb or desorb CO_2 during the empirical determination of D_p. The parameters must be verified before a calibration exercise because any settling or layering of particles has the potential to alter D_p over time.

Chamber-less methods of measuring or calculating CO_2 efflux from soils are becoming more prevalent, yet chamber measurements remain essential to the study of carbon cycling in a multitude of ecosystems. Chambers are applied to check assumptions used to estimate soil fluxes from net ecosystem exchange values and test forest carbon exchange models (Lai

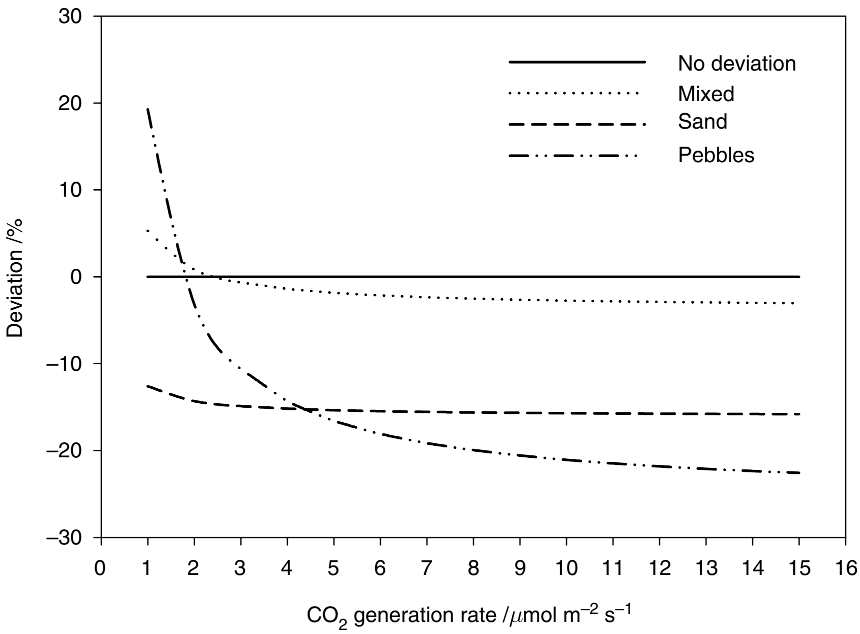

Figure 5 Deviation of CO_2 efflux measured with the DCCS compared with the CO_2 generated through soil medium.

et al., 2002a,b). Chamber-based soil respiration sampling also allows analysis of microsite variability and closely spaced treatments or plots. Rigorous testing and calibration are necessary to ensure the accuracy of chamber-based soil respiration measurements so that their use in quantifying absolute C fluxes is tenable.

The purpose of this study was not to examine the functionality of a popular commercial respiration system, but to illustrate the need for a calibration system that uses media of varying porosities. In fact, our work demonstrates that although measurement bias differed among the soil media used, the relationship between generated and measured flux rates was always linear. In addition, although the DCCS used may not always be accurate under all soil porosities, it was precise on a given soil medium. Such qualities greatly simplify the construction of calibration curves.

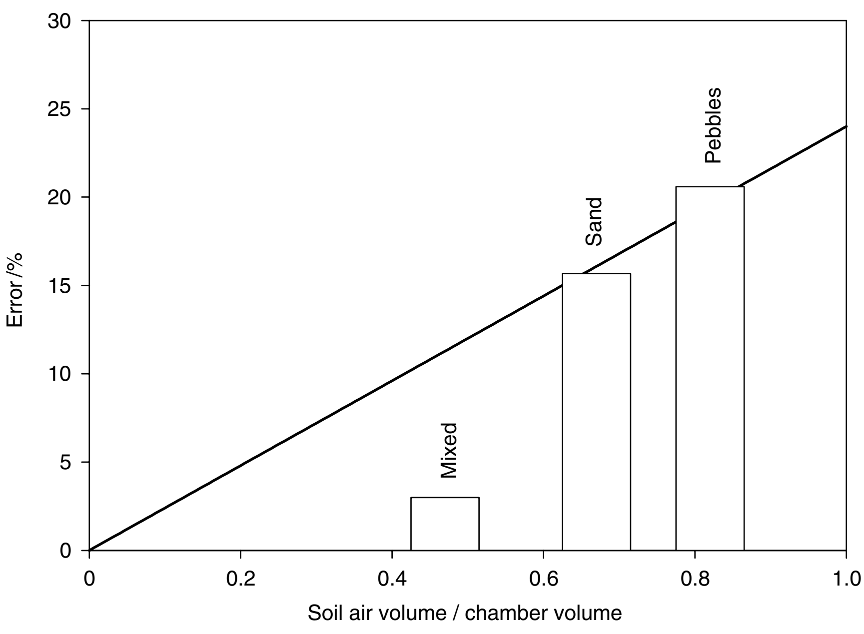

Figure 6 Comparison of flux underestimation (% error) by the DCCS technique and the ratio of soil air to chamber volume at the point where the error becomes stable (see Figure 5). The solid line represents the relationship predicted by Conen & Smith (2000).

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