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Low cost soil CO_2 efflux and point concentration sensing systems for terrestrial ecology applications

Running title:

Low cost terrestrial CO_2 sensing systems

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Abstract

Measuring CO_2 concentrations and fluxes is key to the evaluation of terrestrial ecosystem carbon dynamics. Both the high cost and low portability of currently available sensors and field instruments are constraints to achieving adequate spatial and temporal coverage in characterizing ecosystem CO_2 fluxes and point concentrations. In this work, we used commercially available, low-cost and low-power non-dispersive infrared (NDIR) CO_2 sensors to develop: (1) a soil CO_2 efflux system (K-33 ELG sensor, 0 to 1% or 10,000 ppm(v)) and (2) a point CO_2 concentration system (K-33 BLG sensor, 0 to 30% or 300,000 ppm(v)). We first calibrated the sensors in the laboratory and then tested the systems in the field against benchmark instruments (LI-COR LI-6400 efflux system and Vaisala GMP343 probe). In the laboratory, the K-33 ELG sensor tracked the LI-6400 well during a steady reduction from ~4000 ppm to background CO_2 levels (RMSE = 176 ppm). Lab results of the K-33 BLG point sensor were less favorable (RMSE = 424 ppm) because of its broad range of detection, but were still deemed suitable for proof-of-concept testing at elevated CO_2 levels (> 1500 ppm). In field tests of soil CO_2 efflux on locations with and without leaf litter, the K-33 efflux system yielded surface efflux rate values proportionately lower (13 to 33% of mean value) than those obtained with a LI-COR LI-6400; differences between the two systems were not significant for two of the four sample plots. In a test on leaf cutter ant nest vent, the K-33 BLG point system yielded comparable spatial and temporal patterns and slightly higher (~10-15%) CO_2 concentrations in comparison with a Vaisala GMP343 probe. Overall, the results provide proof-of-concept for the use of two low-

cost, portable CO_2 sensing systems to enable terrestrial ecologists to substantially improve the characterization of CO_2 fluxes and concentrations in heterogeneous environments.

Introduction

CO_2 concentration and flux measurements are critical to the evaluation of terrestrial ecosystem carbon balance and turnover. Research applications commonly deploy high sampling frequency CO_2 sensors (>10 Hz) for eddy covariance measurements (Baldocchi 2003) and slower response sensors for point concentration and flux measurements, such as for photosynthesis and respiratory chamber-based studies (Davidson et al. 2002, Risk et al. 2011) and soil diffusion analysis (e.g., Tang et al. 2003). The sensors involved are typically relatively heavy, power-intensive instruments that cost thousands of dollars. As a result, studies are often limited in their spatiotemporal measurement coverage. Soil respiration, for example, is a result of complex interactions among the biotic, chemical, and physical constituents that can vary greatly over small spatial and temporal scales (Stoyan et al. 2000; Schwendenmann et al. 2003; Davidson et al. 2006; Allen et al. 2007; Vargas and Allen 2008). Unfortunately, investigators rarely (if ever) have access to observations encompassing these scales. New tools and technologies are needed to provide a cost-effective means of quantifying CO_2 concentrations and fluxes over fine spatial and temporal scales.

We developed two CO_2 gas sensing systems for application in terrestrial ecosystems (Figure 1). Using available commercial CO_2 gas sensors, we designed sensor systems supportive of (1) soil efflux and (2) point concentration measurements. Our designs were driven by soil gas and efflux characterization questions. We validated the sensors in the lab and the two sensing systems under field conditions by comparing measurements with commercial systems.

Methods

We designed a soil CO_2 efflux (hereafter K-33 efflux) system to measure surface effluxes associated with soil respiration and CO_2 diffusion. We designed a CO_2 point-concentration (K-33 point) system to measure CO_2 concentration in subsurface vents or chambers in the nests of *Atta cephalotes*, a neo-tropical species of leaf cutter ant. Both of these CO_2 sensing systems employ inexpensive ($200 to $300 including data access interface) integrated circuit non-dispersive infrared (NDIR) CO_2 sensors (K-33 Development Kit, CO2meter.com, Florida, USA). Yasuda et al. (2012) examined the earlier K-30 sensor from this manufacturer and concluded that the sensor was highly accurate and amenable to packaging into sampling kits. The K-33 is similar to the K-30, but also outputs temperature (-40 to 60 ± 0.4 ˚C) and relatively humidity (0 to 100% ± 3%). The K-33 sensor's power consumption is modest (about 60 mA at 6V during its 12-sec measurement cycle; 50 µA during rest).

For the K-33 efflux system, we selected model K-33 ELG (0 to 10,000 ppm range) in anticipation of chamber concentrations typical of soil efflux measurements. For the K-33 point system, we selected model K-33 BLG (0 to 300,000 ppm linear range) in anticipation of elevated local CO_2 levels in a test application involving leaf cutter ant nest characterization (e.g., Kleineidam and Roces 2000). The manufacturer-reported accuracy and repeatability of the K-33 sensors are 3% and 1% of the measured value, respectively. Both models may be used to sample diffusively or with a directed tube focused on the NDIR transducer.

In the K-33 efflux system, we installed a passive sampling K-33 ELG sensor inside a rectangular plastic chamber (15.4 x 8.9 x 4.2 cm depth) equipped with sharpened edges along the bottom to facilitate formation of a seal with the underlying soil surface. We introduced a small pump (0.5 L/min, Model CM011, CO2meter.com) in the top of the chamber to act as a fan

(Figure 1b). We calculated soil CO_2 efflux rates from the linear portion of the observed time series, using the following expression for efflux (*F*) into a closed chamber (e.g., Jones, 1992):

$$F = \left(\frac{PV}{RTA}\right)\frac{dC}{dt}$$

where the resulting *F* is in µmol m^{-2} s^{-1}, *P* is the barometric pressure (Pa), *V* is the volume of the flux chamber (m^3), *R* is the universal gas constant (8.205 atm m^3 mol^{-1} K^{-1}), *T* is the air temperature (K), *A* is the soil interfacial area (m^2), and *dC/dt* is the slope of the linear portion of the observed CO_2 chamber concentration time series (ppm(v) sec^{-1}). It is worth noting that our fan had no effect on K-33 efflux rate estimates, probably due to the shallow geometry of our chamber. Therefore, we did not use the mixing fan for the efflux measurements reported below, but do recommend it for deeper chambers.

For the K-33 point system, we attached inlet and outlet tubing to the sensor couplings and placed a pump (same as above) inline to deliver gas to the sensor. We collected gas samples by simultaneously activating the sensor and pump. For a 2.5 m length of flexible plastic tubing (3.1 mm i.d.), purging the tube between samples required ~ 2 sec. The pump required 90 mA (at 6 V), sufficient for ~ 24 h of continuous operation on a fresh battery pack (4 AA). We equipped the inlet tubing with an inline particle filter (0.22 mm PVDF, Sterlitech Corp., Kent, WA, USA) at the tip to prevent contamination of the inlet while sampling.

The K-33 sensor board has memory for 5400 sampling events (e.g., 45 h continuous sampling at 30 sec intervals). The K-33 has a 12-sec measurement cycle that allows for a maximum sampling rate of about 1/15 Hz (or 15-sec sampling intervals). It is worth noting that the similar K-30 model is capable of more frequent sampling (0.5 Hz), but requires the user to develop the sensor interface and data management modules and does not measure temperature or relative humidity.

Prior to testing the sensor systems, we validated both K-33 sensors using laboratory gas dilution tests, comparing their output to that from a benchmark gas analyzer (LI-6400, LI-COR Inc., Lincoln, NE; range 0 to ~3100 ppm). To do so, we introduced a CO_2 rich mix (>4000 ppm) into an enclosure containing the two K-33 sensors and the LI-6400 benchmark gas analyzer. A small amount of soda lime placed in the enclosure slowly scrubbed CO_2 levels down to below atmospheric levels (~ 400 ppm) over the course of several hours. The result was a calibration curve ranging from background CO_2 levels to 3,500 ppm. Sampling intervals were 15-sec for the K-33 sensors, and 2-sec for the LI-6400.

Lastly, we validated the efflux and point sensing systems under field conditions. To validate the K-33 efflux system, we compared it to the LI-6400 system equipped with a 6400-09 soil CO_2 flux chamber in side-by-side soil efflux measurements on lowland tropical Oxisol soils at La Selva Biological Station in Costa Rica. We carried out two paired tests, one on a compacted bare soil and the other on leaf litter-covered forest soil, in order to expose the systems to a range of soil efflux rates. During the tests, we monitored soil temperature and volumetric moisture content using an uncalibrated sensor (EC5, Decagon Devices, Pullman, WA, USA). For each plot, we performed six measurements with both the K-33 efflux and LI-6400 system, alternating flux chamber positions after each event to control for local variation of soil respiration rates. We statistically compared the K-33 and LI 6400 measures of soil CO_2 flux rates from bare ground and leaf litter using separate ANOVAs, with location of measurement included in the model as a random effect.

To validate the K-33 point system, we compared its output with that of a commercial NDIR probe (Model GMP343, Vaisala Oyj, Helsinki, Finland). To do so, we connected the outlet from the K-33 point system to a tube leading to the GMP343, which was enclosed in a small chamber equipped with inlet and outlet ports. We used the pump on the K-33 system to deliver the sampled gas sequentially to the K-33 and GMP343. The test was carried out by continuously drawing gas from five large vents within a leaf cutter ant (*Atta cephalotes*) nest at La Selva Biological Station, where preliminary tests had revealed CO_2 concentrations in excess of 10,000 ppm.

Results

During the laboratory sensor validation tests (Figure 2a), the K-33 ELG sensor output matched that from the LI-6400 precisely (RMSE = 176 ppm). Lab results for the K-33 BLG point sensor (Figure 2b) were less favorable (RMSE = 424 ppm). However, most of the BLG error was associated with lower concentrations (< 1500 ppm) which are at the extreme low end of the BLG's relatively wide range of detection. Thus, BLG was deemed suitable for proof-of-concept testing at elevated CO_2 levels (> 1500 ppm). For applications requiring precision at lower concentrations, lower range sensors (e.g, K-33 ELG) could be substituted into the K-33 point system.

The K-33 efflux sampling system exhibited a linear CO_2 accumulation ($R^2 > 0.99$) over the 5-minute intervals (15 to 18 points). The value of dC/dt (equation 1) relates directly to the efflux estimate and produced standard errors less than that associated with inter-sample variability for the same location. The mean K-33 efflux rate estimates were consistently lower than those from the LI-6400 systems (Figure 3). Specifically, the average K-33 rates for bare and litter-covered soils were about 72% and 74% of the respective LI-6400 rates. The relative patterns for efflux from leaf litter and bare soil surfaces were the same for both sensing systems, meaning that high efflux rates were high both using the LI-6400 and K-33 efflux systems. Preliminary tests with the K-33 system on other soil types with efflux rates as low as 0.5 μmol $m^{-2}s^{-1}$ (e.g., clays in Merced, CA) met with similar success (results not shown), suggesting that these inexpensive systems can function over a wide range of soil conditions.

Observed changes in soil temperature were modest (< 0.4 °C), and changes in soil moisture were not detectable during the measurement periods (results not shown). Eliminating these two potential variables, we identified two possible reasons for the differences between the two efflux systems. First, the two efflux chambers were different, with the LI-6400 soil interface area (72 cm^2) being about half the area of the K-33 system (139 cm^2). In addition, the LI-6400 chamber edge, being metal and slightly deeper than that of the K-33, penetrated more deeply into the surface. This could have afforded the LI-6400 better access to the soil gas, particularly in light of the heavy rains that had soaked the upper soil layers in the days prior to the tests. Second, it is possible that the K-33 edge created an inferior seal relative to the LI-6400. A leaking chamber would produce consistently lower efflux estimates. In several samples, the K-33 efflux system data exhibited a modest slope decrease (~10%) about 2 to 3 min into the 5-min sampling cycle, a finding consistent with the presence of a minor leak. Such a leak would produce a negative bias in the efflux rate estimate. This aspect of the system development merits further investigation.

Results from the K-33 point measurement comparison for five leaf cutter ant vents are summarized in Figure 4; the inset figure details the correlation between GMP343 and K-33 BLG system responses. Overall, the temporal patterns of CO_2 measurements were similar for the two systems, though the K-33 point system yielded slightly greater CO_2 concentrations than the GMP343. For the GMP343, transitions between CO_2 concentration changes were attenuated relative to the K-33. We interpret the attenuated GMP343 sensor reading to be related a signal dampening effect caused by its surrounding chamber. The CO_2 concentrations ranged from about 1000 to nearly 20,000 ppm, varying in magnitude and steadiness of the signal across vents. For example, the first vent (Figure 4) cycled between approximately 1000 and 5000 ppm, whereas the second vent produced a steady concentration of 6000-7000 ppm. These observations highlight the spatial and temporal variability of the ventilation network.

Conclusions

We developed low cost and low power CO_2 point concentration and surface efflux measurement systems. Laboratory tests with the sensor components and field tests with the systems provide proof-of-concept that these systems yield reliable measurements that can help researchers overcome the logistical challenges of capturing soil respiration spatial heterogeneity. As presented, the systems could operate for a day or more on a 6 V AA battery pack (depending on sampling rate), and the total cost of each system was less than US$600 for the user-friendly development kit. Using the more basic model K-30 sensor (requiring user-developed data communications and storage), this cost can be reduced by half.

The two examples presented here illustrate only a small portion of the ecological science applications these types of CO_2 sensing systems. For example, in the context of land-atmosphere fluxes they can be configured in vertical arrays to replicate heavier, more expensive eddy covariance system CO_2 sensing components. Given their low-cost and portability, we can afford to replicate the systems in support of tackling research questions requiring higher resolution spatial coverage than is economical with current commercial systems. With the development of simple operating procedures, such sensing systems will become accessible to a broader user community, ranging from less technically savy scientists, to mobilized teams of citizen scientists and school children. In effect, these low-cost analogs to the commercially available CO_2 sensing and surface efflux instruments hold the potential to democratize CO_2 data collection.

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Data Accessibility

CO_2 calibration and experimental data: figshare doi: 10.6084/m9.figshare.1443591 (Harmon et al. 2015)

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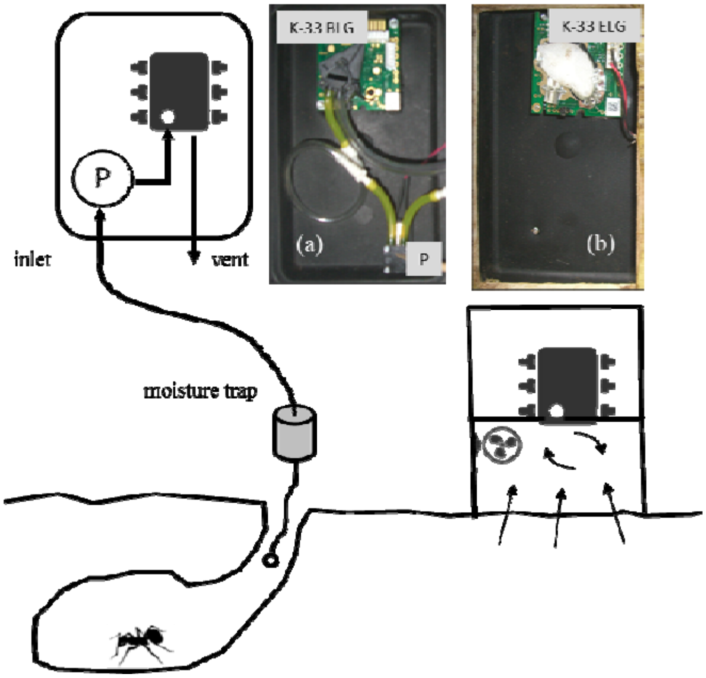


Figure 1. Schematic diagram for low cost sensing systems based on non-dispersive infrared (NDIR) CO_2 sensors packaged (a) CO_2 point (K-33 BLG) and (b) soil CO_2 efflux (K-33 ELG) measurement systems (note: P = gas phase pump).

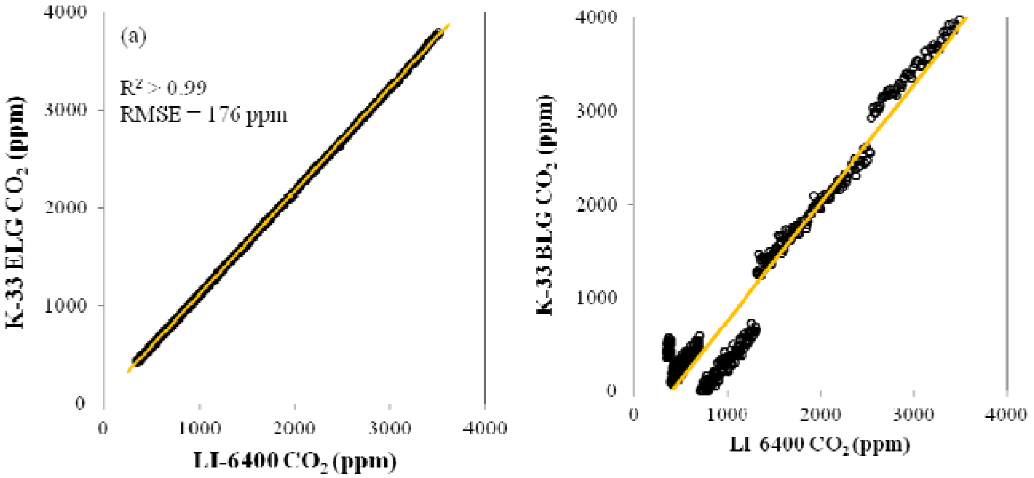
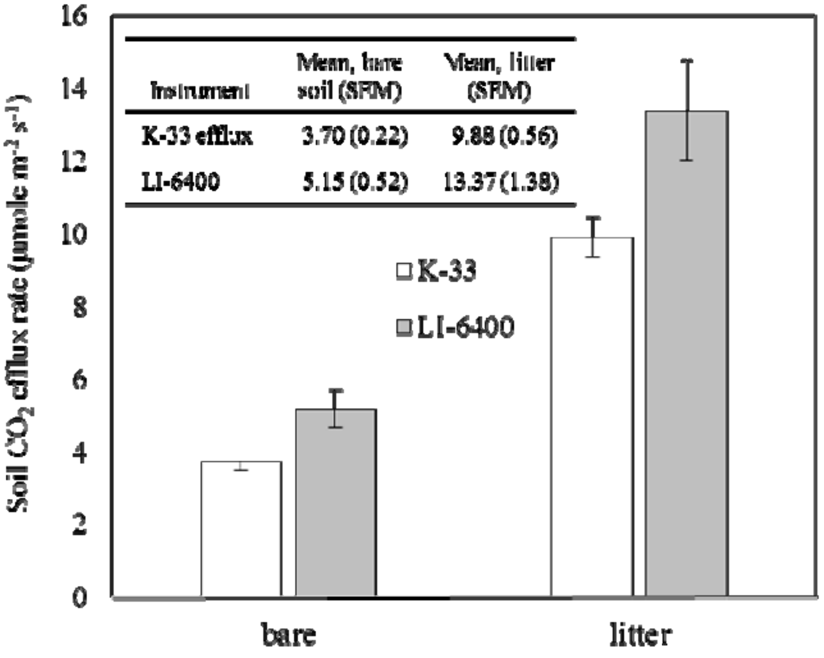


Figure 2. Comparisons of (a) K-33 ELG and (b) K-33 BLG sensors with the benchmark LI-6400 instrument response (LI-6400 symbols in orange).



Instrument	Mean, bare soil (SEM)	Mean, litter (SEM)
K-33 efflux	3.70 (0.22)	9.88 (0.56)
LI-6400	5.15 (0.52)	13.37 (1.38)

Figure 3. Soil CO_2 efflux measurements using the K-33 efflux and the LI-6400 systems on bare tropical Oxisol soil and forest soil with leaf litter (error bars ± standard error); CO_2 efflux significantly differed between the two systems (ANOVA) for both the bare ($p = 0.006$) and litter ($p = 0.002$) plots.

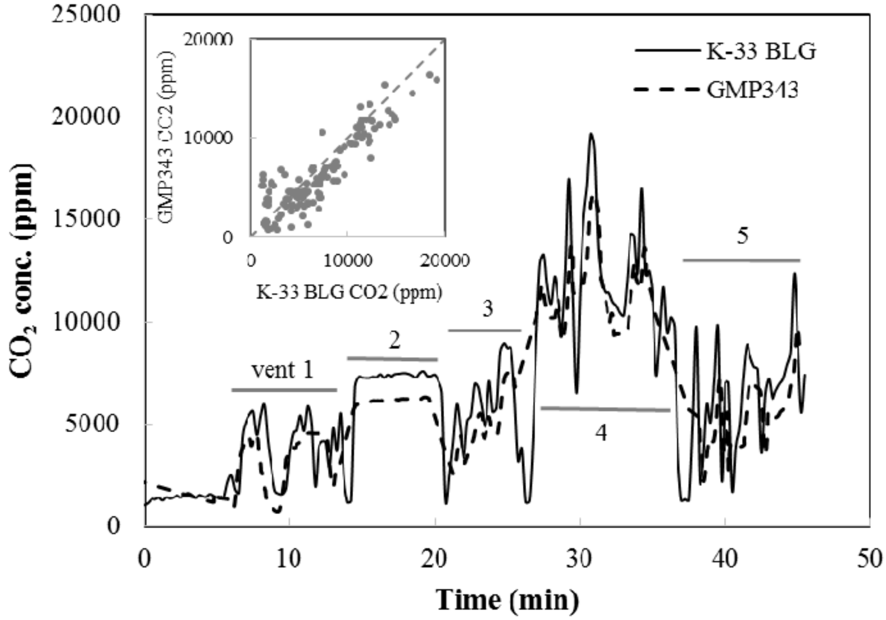


Figure 4. CO$_2$ concentrations detected in five leaf cutter ant nest vents by the K-33 point system and Vaisala GMP343 probe connected in series; inset plot compares the same data on 15-sec intervals over the 45-min sampling duration.