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Stephen L. Young
University of Nebraska - Lincoln, steve.young@usu.edu

Francis J. Pierce
Washington State University, fran.pierce@gmail.com

Jason D. Streubel
USDA-ARS, Prosser, WA

Harold D. Collins
USDA-ARS, Prosser, WA

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Performance of Solid-State Sensors for Continuous, Real-Time Measurement of Soil CO_2 Concentrations

Stephen L. Young,* Francis J. Pierce, Jason D. Streubel, and Harold P. Collins

ABSTRACT

Recent advances in sensor technology provide a robust capability for continuous measurement of soil gases. The performance of solid-state CO_2 sensors (Model GMM220 series, Vaisala, Inc., Helsinki, Finland) was evaluated in laboratory, greenhouse, and irrigated winter wheat (*Triticum aestivum* L.). In ambient CO_2 concentration, the GMM222 sensor averaged 427 ± 8.3 $\mu L\ L^{-1}$. Under variable CO_2 concentrations, the sensor was slightly lower than concentrations measured with an infrared gas analyzer (IRGA). In greenhouse pots planted with triticale (*Triticale hexaploide* Lart.) and an agricultural field of irrigated winter wheat, soil CO_2 concentration exceeded the 10,000 $\mu L\ L^{-1}$ limit of the GMM222. Alternatively, the GMM221 sensor, designed to measure between 0 and 20,000 $\mu L\ L^{-1}$, showed soil CO_2 concentrations were between 14,000 and 16,000 $\mu L\ L^{-1}$. The GMM222 accurately measures real-time soil CO_2 concentrations under field conditions that were within the sensor detection limit. However, periods of high biological soil activity require the GMM221 sensor with a higher detection limit.

Soil is a major component in the ecosystem carbon balance. The primary source of soil CO_2 is derived from plants (i.e., rhizosphere respiration) and organisms (i.e., heterotrophic free-living microbes), with a combined contribution to soil carbon stores close to 2 Gt (Tang et al., 2005a; Grace, 2001). Furthermore, belowground soil and plant respiration accounts for the annual processing of one-sixth of the total atmospheric CO_2–pool (Paterson et al., 2008).

Various methods have been used to measure soil CO_2. The spatial-temporal CO_2 flux from soil can be measured with portable (Tang and Baldocchi, 2005) and semipermanent (King and Harrison, 2002) chambers. Soil air samples at different depths and laboratory analyses of soil core samples are two less-automated methods for determining soil CO_2 concentrations (Jassal et al., 2004; Turcu et al., 2005). However, chambers can cause air disturbances, which may alter CO_2 concentration in the soil (Tang et al., 2005b), and the long-term continuous measurement with any of these methods is limited by the need for human labor.

The availability of small, solid-state sensors (i.e., GMM220 series) has allowed for the continuous measurement of soil CO_2 in field settings, including a Douglas-fir forest [*Pseudotsuga menziesii* (Mirb.) Franco; Jassal et al., 2004], an oak–grass savanna (*Quercus* spp.; Tang et al., 2003), a ponderosa pine forest (*Pinus ponderosa* P. Lawson & C. Lawson; Tang et al., 2005b), and a temperate deciduous forest (Hirano et al., 2003). Using only advanced sensor technologies, soil CO_2 concentrations measured from periods of 1 mo to 1 yr ranged from 2 to 12 $\mu L\ L^{-1}$ in the ponderosa pine forest, 386 to 1,044 $\mu L\ L^{-1}$ in the oak-grass savanna, and 6,000 to 10,000 $\mu L\ L^{-1}$ in the Douglas-fir forest.

Soil CO_2 concentrations in irrigated cropping systems have yet to be quantified using continuous measurement instrumentation such as the GMM222. Seasonal fluctuation in soil CO_2 is of importance in these systems, which continually undergo wetting and drying cycles. Irrigation events in semiarid climates of eastern Washington could mimic rain shower events that Tang et al. (2005b) reported increased soil CO_2 concentration six-fold from 1000 $\mu mol\ mol^{-1}$ to nearly 6000 $\mu mol\ mol^{-1}$. Our objectives were to determine the operating parameters and season-long performance of GMM222 sensors in lab and greenhouse testing and field experiments with irrigated winter wheat. While measuring differences in the diurnal patterns of soil CO_2 concentrations are important, we were most interested in checking the performance of the GMM220 series sensors under a range of environmental conditions. Therefore, lab, greenhouse, and field data were used to determine accuracy and responsiveness of the sensors with basic statistics (e.g., mean, standard deviation).

METHODS AND MATERIALS

Site

All experiments were conducted in lab, greenhouse, and field sites located at the Irrigated Agriculture Research & Extension Center, Washington State University, Prosser, WA (46°15′10″ N, 119°44′14″ W; 203 m). For field testing, the 30-yr (1961–1990) weather record shows an average annual rainfall at this location of 294 mm, of which, 78% falls between November and May, and average annual maximum and minimum temperatures of 18.8 and 5.1°C, respectively, ranging from an

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S.L. Young and F.J. Pierce, Washington State Univ., Center for Precision Agricultural Systems, 24106 N. Bunn Rd., Prosser, WA 99350; J.D. Streubel and H.P. Collins, USDA-ARS, 24106 N. Bunn Rd., Prosser, WA 99350.
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*Corresponding author (steve_young@wsu.edu).

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Abbreviations: IRGA, infrared gas analyzer; PVC polyvinyl chloride.

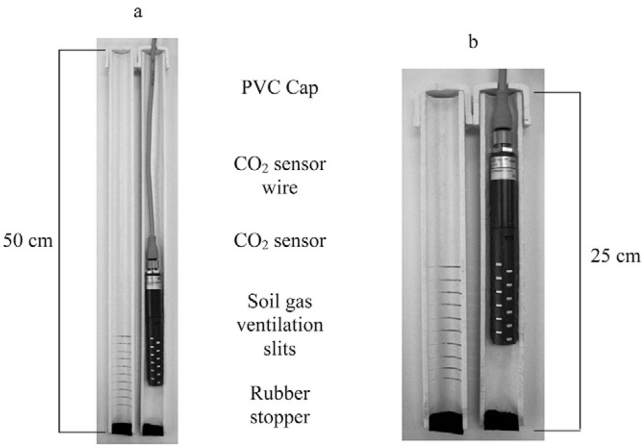

Fig. 1. Cut-away view of CO_2 sensors inside PVC tubing. The tubing was inserted vertically into the soil, putting the CO_2 sensors at (a) 38 cm and (b) 15 cm deep.

average maximum of 32.4°C in July to an average minimum of −2.3°C in December (WRCC, 2009). The soil is a Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids) (Rasmussen, 1971). Full irrigation is required for crop production.

Soil CO_2 Measurement System

A real-time CO_2 measurement system was developed to interface to the GMM220 series CO_2 sensors. Each CO_2 sensor was connected to a data logger wired to a multidrop bus consisting of a single RS-485 cable. The high power requirements of the CO_2 sensors required a single power supply wire connected to a 110-V AC power outlet regulated to 12A. In the lab, the multidrop bus was connected via RS-485 to a modbus (a serial communications protocol)-to-Ethernet gateway connected directly to the Internet. In the greenhouse and field, the multidrop bus was connected via RS-485 to a wireless modbus bridge consisting of two 900 MHz frequency-hopping spread spectrum radios; one connected on-site to the multidrop bus, and the other connected via a modus-to-Ethernet gateway at a remote location to the Internet. Each sensor was set to record samples every 10 s, and 1 min averages were automatically transmitted through the RS-485 bus either directly or via the wireless modbus bridge to the modbus-to-Ethernet gateway and automatically stored on a remote database. A Java web-based software application was developed to display real-time data for each pair of sensors in each treatment and to facilitate downloading of raw data for more detailed analysis and interpretation.

Laboratory

To check for stability over time, a single GMM222 with a range of 0–5000 $\mu L\ L^{-1}$ was inserted into a 19-L airtight container and sealed for 2 wk. Following the stability test, the accuracy of the GMM222 was measured by comparison with an IRGA (Model ADC-225 MK3, The Analytical Development Company, Hoddeson, UK). The GMM222 was placed in a 420-mL airtight container with known CO_2 concentrations beginning at 0, 400, 800, 1200, and 2000 $\mu L\ L^{-1}$. For each concentration, 1-mL samples were manually evacuated using a gastight syringe and immediately analyzed with the IRGA. Time of sampling was recorded for each manual evacuation to correlate with readings from the GMM222.

Greenhouse

After lab testing, the GMM222 was subjected to more severe conditions using pots of soil in an environmentally controlled greenhouse. Before installing in soil, a housing unit was fabricated to prevent direct contact of the GMM222 sensor with the soil. Protective units were constructed of 2.5-cm polyvinyl chloride (PVC) tubing and followed a modified design by Tang et al. (2003) and Turcu et al. (2005). Housing units were built for shallow (15 cm) and deep (38 cm) insertion of GMM222 sensors into the soil (Fig. 1). Starting 3 cm from the soil end of the PVC pipe, eleven slits 1 mm wide and spaced 1 cm apart were cut halfway through the PVC pipe to allow soil gas to diffuse into the sensors. A rubber stopper was used to plug the open end inserted into the soil. A PVC cap was put over the end extending above the soil surface and protective shrink wrap was applied with a heat gun to secure electric cables that extended to the data logger.

The PVC-housed GMM222 sensors were inserted into 30-cm-diam. pots filled with soil. Six pots were planted with triticale (115 kg seed ha^{-1}) and six remained bare soil. A soil probe was used to remove soil just slightly larger than the PVC housing to assure a tight fit by the GMM222 sensors. After installation, continuous measurements were collected for soil CO_2 concentration at each sensor for 2 wk. The environmental parameters (i.e., temperature, soil moisture) were altered periodically to monitor response of each of the GMM222 sensors. To simulate irrigation, 10 to 1000 mL of water were applied to each pot using a 60-mL syringe. Diurnal fluctuations in temperature were controlled manually through forced air heat (53°C) followed by exhaust fans and bags of ice placed on the pots to cool the sensors (25°C). Similar to lab testing, data was recorded onto a data logger for each GMM222 and later downloaded for analysis and interpretation.

Field

Following greenhouse testing, eight GMM222 sensors were installed into a field plot of bare soil for 2 wk. The sensors were inserted to a depth of 15 cm and spaced uniformly in a 1-m^2 grid. Data was recorded with a data logger, similar to lab and greenhouse tests, but transfer of the data was through radio communication, as previously described.

On 22 April, GMM222 sensors were moved from the 1-m^2 grid and placed in 100 m^2 field plots of irrigated winter wheat. Sensors were located close to the center of each plot in the interrows. Shallow and deep sensors were inserted in each plot to depths of 15 and 38 cm, respectively. Power and communication wires connected each sensor to a data logger, which was supplied with power from an alternating current power source that had a 12-A converter. Data acquisition was via radio transmission and Ethernet connection for real-time viewing and downloading.

Field verification of GMM222 sensors was conducted late in the season using soil gas probes. Similar to Jassal et al. (2004), 1 cm^3 soil air samples were drawn out of probes buried at the same depths as the GMM222 sensors. The probes were made of thin steel tubing (1.2-cm o.d.) coupled to a fine-mesh screen

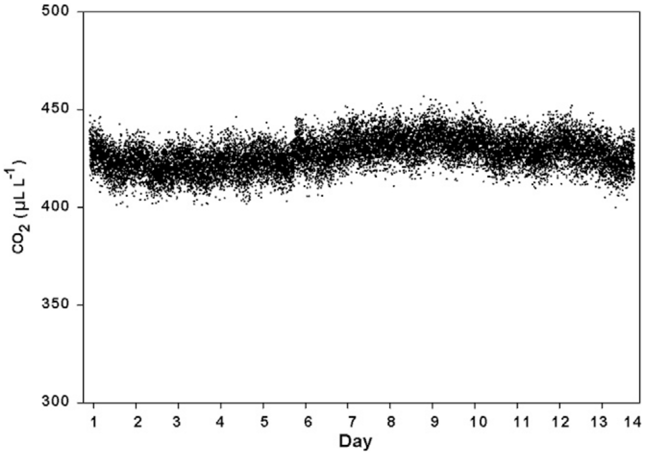

Fig. 2. CO$_2$ measurements recorded every 1 min over a 2-wk period using a CO$_2$ sensor (Model GMM222, Vaisala, Finland) enclosed in a 19-L airtight container. Average CO$_2$ concentration was 427 ± 8.3 µL L^{-1}.

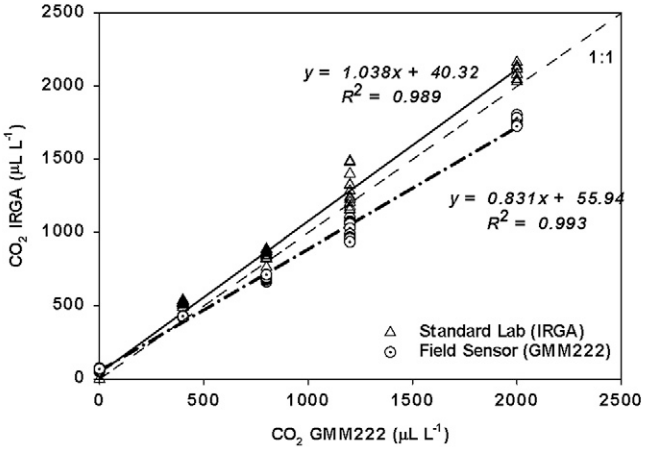

Fig. 3. Measurements from an infrared gas analyzer (IRGA; Model ADC-225 MK3, Analytical Development Company, Hoddeson, UK) and a single CO$_2$ sensor (Model GMM222, Vaisala, Finland) in five known atmospheric concentrations of CO$_2$ (0, 400, 800, 1200, and 2000 µL L^{-1}). The dashed line is a 1:1 concentration.

with a point at the end for insertion into the soil. A silicon rubber septum was placed on the end of the tube located just above the soil surface. Soil air samples were collected using a polyethylene 1-mL medical grade syringe and needle inserted into the septum.

On 15 August, soil gas probes were inserted into irrigated winter wheat plots that contained GMM222 sensors. Two probes were pushed into the soil at a distance of 3 cm from either side of the sensor. In September and October, soil air samples were extracted from each probe. The samples were taken immediately to the lab and injected into a CO$_2$–free air stream passing through the IRGA. Sample CO$_2$ concentration was determined from the ratio of the area under the concentration versus time curve to that obtained from standard concentrations. The date and time were recorded for comparison with data from GMM222 sensors.

RESULTS AND DISCUSSION

Lab and Greenhouse

In the lab tests we conducted, the GMM222 sensor operated according to manufacturer specifications. In the 19-L airtight container, a single GMM222 sensor recorded CO$_2$ concentration slightly higher (400–450 µL L^{-1}) than current atmospheric concentrations (see http://cdiac.ornl.gov/, verified 4 Sept. 2009) over a 2-wk period (Fig. 2). The fluctuations in readings varied by 31 µL L^{-1}, which was consistent with calibrations by the manufacturer. In addition, comparisons of the GMM222 sensor to the IRGA revealed an 18% bias in measuring known concentrations of CO$_2$ (Fig. 3). The nearness of our lab tests to manufacturer specifications was expected under the controlled conditions of the lab.

We were able to simulate soil moisture and temperature extremes that were expected in the field by using controlled conditions of the greenhouse. The GMM222 sensors recorded diurnal patterns in soil CO$_2$ concentration while in close proximity to the soil and the resulting effects from the addition of water and heat. The GMM222 recorded differences in soil CO$_2$ concentrations consistent with other research on soil CO$_2$ concentrations and the effects of diurnal temperature and moisture patterns (see Flechard et al., 2007; Vargas and Allen, 2008). Outlier or extreme measurements by the GMM222 were absent under the imposed conditions, and no external damage to the sensor was observed during irrigation events. In the pots of bare soil, CO$_2$ concentration ranged from 700 to 1200 µL L^{-1}, which was lower than the pots of triticale. By the end of 2 wk, soil CO$_2$ concentrations in triticale were approaching 10,000 µL L^{-1}, which is the upper limit of detection for the GMM222 sensors.

Field

The response of GMM220 series sensors for measuring soil CO$_2$ concentration in field conditions was consistent over a 2-wk period (Fig. 4). The variation in soil CO$_2$ concentration between the eight sensors was attributed to changes in soil characteristics (e.g., texture, structure, microbiology) that are known to occur over very narrow spatial scales. The normalized difference between all eight sensors was found to be ±250 µL L^{-1} (data not shown). The successful lab and greenhouse testing supported measured field variability and not failures in sensor performance.

The maximum CO$_2$ concentration of 10,000 µL L^{-1} that could be recorded by the GMM222 was reached on 16 May and remained at this level until late August for the upper sensor and early September for the lower sensor. The

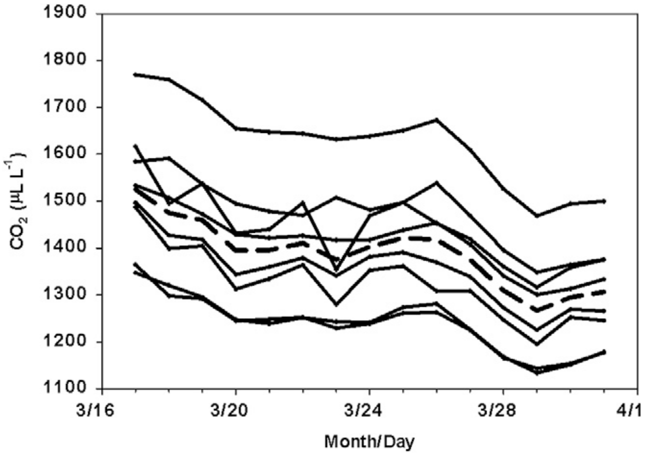

Fig. 4. Comparison of eight CO$_2$ sensors (Model GMM222, Vaisala, Finland) uniformly installed to 15 cm in a 1-m^2 grid of bare soil in the field. The dashed line represents average soil CO$_2$ concentration.

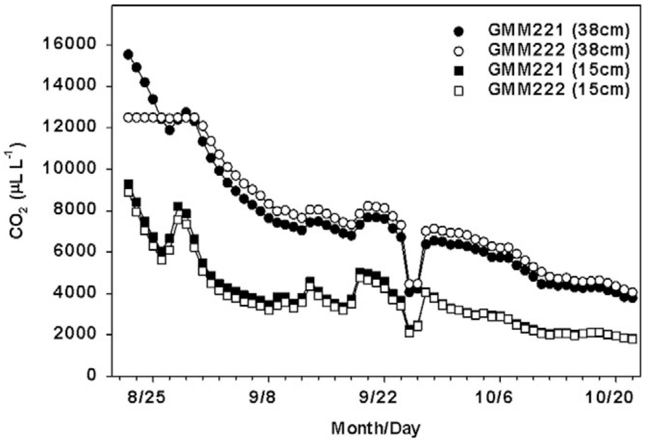

Fig. 5. Late-season soil CO_2 concentrations at shallow and deep depths in a harvested winter wheat field. Two different CO_2 sensors (Model GMM221 and Model GMM222, Vaisala, Finland) were used to measure shallow (15 cm) and deep (38 cm) soil CO_2 concentrations.

installation of the GMM221 sensor with a range of 0 to 20,000 μL L^{-1} provided values for soil CO_2 concentrations > 10,000 μL L^{-1} and matched the GMM222 sensor at concentrations < 10,000 μL L^{-1} (Fig. 5).

While we did not expect to measure soil CO_2 levels > 10,000 μL L^{-1}, the rates above the threshold for the GMM222 sensor confirmed the high soil CO_2 concentration levels recorded in the greenhouse experiment. Our basis for selecting the GMM222 was that a majority of the research by Tang et al. (2003, 2005a, 2005b) and others (Vargas and Allen, 2008) has shown maximum soil CO_2 concentrations to be <1000 μL L^{-1} in semiarid grasslands and forests (but see Jassal et al., 2004; Turcu et al., 2005). The high values in our study could have been due to a design flaw in the sensor PVC housing, thereby allowing soil CO_2 to pool and cause a false reading by the GMM222. We checked this by removing the chamber with the sensor from the soil for 18 h and reinserting back into the same hole. Upon insertion into the soil, the soil CO_2 concentration immediately returned to levels from the previous day. Any pooling of CO_2 in the chamber would have required more than the few minutes that were observed in this case.

Field soil CO_2 concentration measurements from the GMM222 were verified in situ from soil gas samples. On 11 September, soil gas samples from atmosphere probes were 5449 μL L^{-1} and 15,360 μL L^{-1} for shallow and deep depths, respectively. During this same sampling time, CO_2 sensors were reading 5798 μL L^{-1} and 12,431 μL L^{-1} at the same depths. A second sampling on 2 October showed probe readings of 8752 μL L^{-1} (shallow) and 13,866 μL L^{-1} (deep), while sensors read 4,753 μL L^{-1} and 12,264 μL L^{-1} for the same depths. Similar trends between probe and sensor were recorded in nearby plots of warm season grasses (data not shown). Soil probe samples taken from the field and analyzed on the IRGA indicated the GMM222 was underestimating soil CO_2, similar to the lab tests (see Fig. 3). Future studies that incorporate a season-long soil gas sampling regime for comparison purposes will help to solve the some of the inconsistency between the two methods.

For soil CO_2 concentrations > 10,000 μL L^{-1}, the GMM221 recorded a maximum of 16,154 μL L^{-1} on 21 August in harvested irrigated winter wheat. The GMM221 sensors were installed in close proximity to the GMM222, and the high soil CO_2 value indicates high root and microbial respiration (Jassal et al., 2004).

CONCLUSIONS

The performance of GMM220 series CO_2 sensors was adequate for the range of conditions imposed in lab, greenhouse, and field studies. In addition, the CO_2 sensors remained unharmed by wet soil from irrigation and changes in temperature. The GMM222 accurately detected real-time soil CO_2 concentrations in irrigated winter wheat. For cropping systems that produce high biomass, a 0 to 10,000 μL L^{-1} detection rate is inadequate for measuring soil CO_2 concentration during peak periods of root and microbial activity.

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