



Ultra-low-cost manual soil respiration chamber

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Abstract. Soil respiration measurement is important to assess natural carbon dioxide production. The closed chamber technique allows relatively easy soil respiration monitoring. A planned spatially large-scale campaign incites us to implement our ultra-low-cost portable chamber. The chamber itself is entirely built from commercial parts with little, easy-to-make, quick machining work. The resulting setup is an easy-to-operate, standalone, robust device. The used sensors are cost-effective yet accurate digital sensors that were successfully checked against some reference sensors. All these characteristics made the described chamber accessible to build and use for a wide scientific and educational community. The wide interest aroused by this construction among our colleagues pushes us to share our achievements. In this short note, we describe this simple device along with its sensors and apparent respiration quotient tip.

15 **1 Background**

On average, the soil has nearly double the amount of carbon dioxide (CO₂) than in the terrestrial atmosphere (Smith 2012). Furthermore, it is one of the biggest generators of CO₂, and the frost-free soil generates nearly ten times as much CO₂ as the whole amount of fossil fuels burned by humanity. Due to the increased microbial activity brought on by the increased soil temperature, this natural CO₂ production is increasing by around 0.1 percent per year (Bond-Lamberty and Thomson 2010).

20 In the context of global warming due to the increase in atmospheric greenhouse gas concentrations, such as CO₂, particular attention is given to soil respiration. There are several techniques and sub-techniques to achieve this goal. One of the most widespread techniques is the closed-chamber technique. This technique is about a century old (Bornemann, 1920), but it has been continuously improved and allows us to monitor more GHG. Among closed chambers, we can distinguish automatic chambers and manual chambers. Each technique has its pros and cons (Savage et al., 2003; Yao et al., 2008; Lee, 2018).

The automatic chambers allow it to operate automatically, which is a salvatory relief, allowing a relatively high operation rate, even during the night. However, the cost and complexity of these chambers prevent their large spread, leading to a relatively high uncertainty when spatial variability is important.

Manually operated chambers rely on the same principle except that the chamber operations (closure and opening) are manual and require a human presence. This kind of chamber can hardly be used during the night, in rain, or in any meteorological



condition that could make human presence exhausting. However, a punctual measurement can be done on a large spatial scale without any external power supply. Not only are these chambers portable, allowing the use of only one chamber in several locations, but the cost of the manually operated chambers is much less important compared to the automatic chambers. The lower this cost, the more important its duplication possibility, allowing a quick and large measurement campaign by a scientific group or for educational purposes.

This short note describes an ultra-low-cost (200 USD for the basic configuration) and fast construction (1-2 weeks) chamber using ultra-low-cost, yet accurate, sensors (20 to 100 USD for the basic sensors excluding oxygen sensors). The described chamber is built using only some commercially available parts requiring only a little machining work, which is so-called MacGyver science. (Hut et al., 2020). Also, to complete our knowledge about soil respiration, oxygen sensors were implemented, and their functioning will be described.

2 Materials and Method

For the needs of large-scale spatial soil respiration measurements, a portable chamber with detachable stainless-steel collars to be placed in the soil was built. Cost-effective construction was sought but did not impair the quality of the measurements. As mentioned by numerous authors, the chamber needs to have its internal air mixed by a fan; proper sealing between the chamber and the soil is essential, along with a pressure equilibration device (Koskinen and Mosie, 1981; Parkin and Venterea, 2010; Christiansen et al., 2011; Clough et al., 2013).

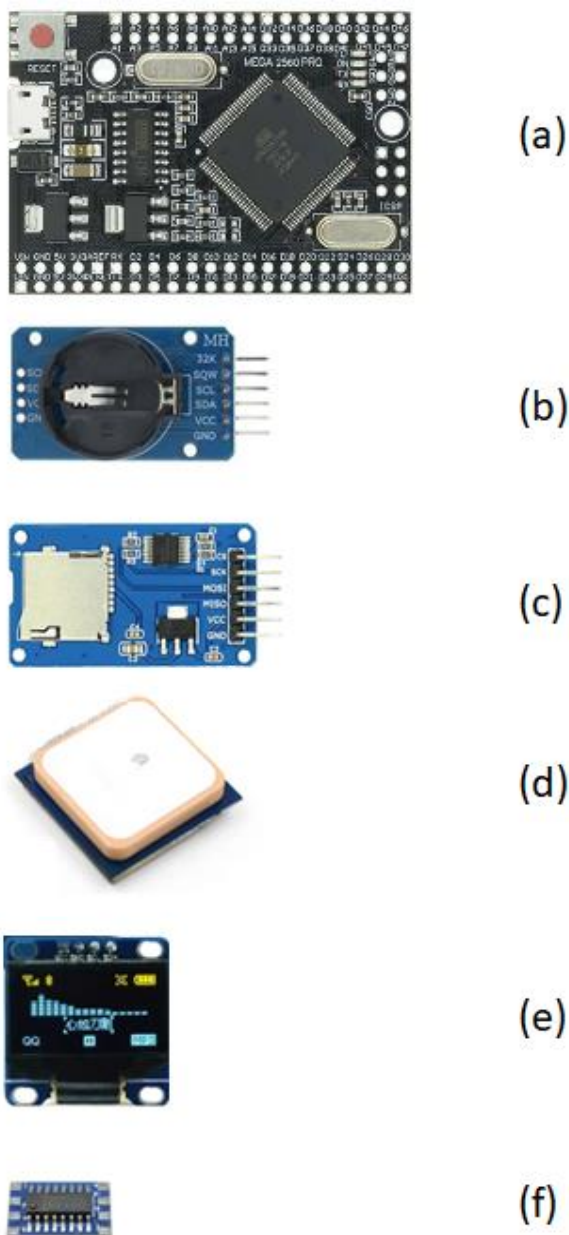
2.1 Electronic modules composing the data logger

The manual soil respiration chamber described here employs a datalogger made of commercial electronics modules for querying and logging information gathered by several sensors. The entire set of modules is housed in a handheld enclosure along with a GPS antenna. A basic UART TTL bus-attached GPS antenna was also incorporated because the same chamber is utilized in multiple locations to help track the precise location of the measurement (Fig. 1).

To read and log data from sensors, a data logger was built with a generic clone of an Arduino Mega Pro for its multiple digital buses (I²C, SPI, and UART), its multiple hardware UART serial ports, and its compactness. The real-time is provided by a generic Real Time Clock module (RTC) powered by a precise DS3231 chip on an I²C bus from Dallas Semiconductor (Dallas, Texas, USA), owned nowadays by Analog Devices (Wilmington, Massachusetts, USA). A generic μ SD card reader on the SPI bus ensures data-saving ability. In the case of RS-232 bus use, a generic module based on an MAX3232 chip from Maxim Integrated (San Jose, California, USA), also owned by Analog Devices, converts the RS-232 level to the TTL level. A small fan (MC20100V3-Q01U-G99, 5V, 0.33W, 20x20x10mm, MagLev from Sunon Electric Machine Industry Company Limited, Qianzhen, District Kaohsiung, Taiwan) fixed on a light and holed stainless-steel plate inside the cloche is gently mixing internal



60 air during the measurement cycle. MagLev (magnetic levitation) life span is very long: 100000 h; the rotating speed is relatively slow (11000 RPM); the rated air flow is 1.2 CFM; and the static pressure is less than 45 Pa.



65 **Figure 1.** Data logger built with a) Arduino Mega Pro, b) RTC, c) µSD card reader, d) GPS, e) OLED display, f) RS232 to TTL module.



A generic 0.96", two-color I²C OLED display allows to indicate all useful information, such as the μ SD card state, GPS position reading, logger state, or battery charge level, along with current sensor readings and acquisition time (Fig. 2).

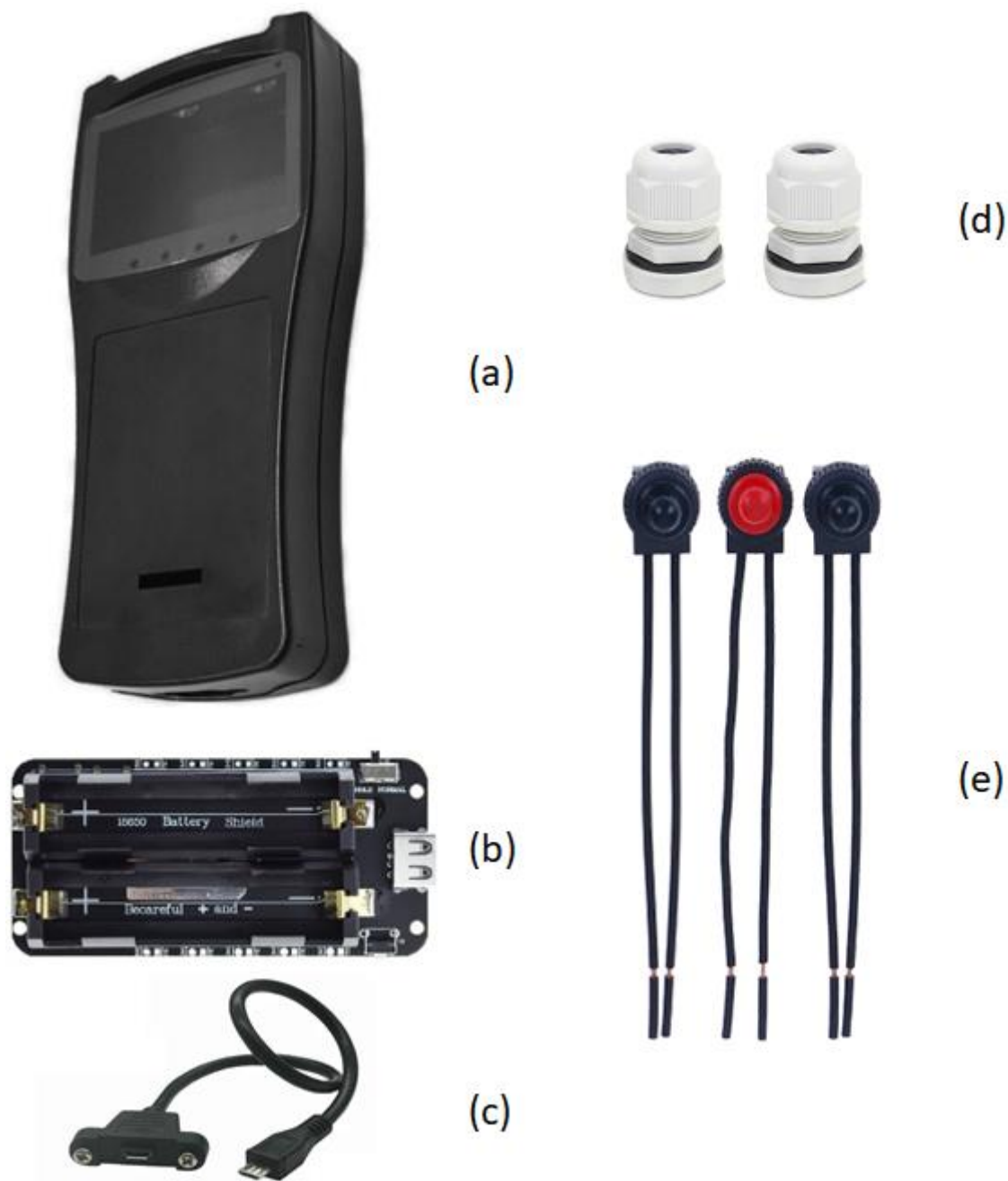
- 70 All electronics modules are housed inside a handheld enclosure (Fig. 3) that also contains a generic power bank module using two 18650 lithium-ion rechargeable batteries. The power bank filled with two generic batteries allows 12 hours of uninterrupted operation. A USB socket and short cable allow charging the batteries using a generic USB charger but also to establish a link with the Arduino to program it or to withdraw the μ SD stored data without having to dismount the μ SD card. Three waterproof push buttons allow the operation of all electronics modules (power On/Off, GPS coordinate memorization, 75 internal fan operation, and launch/stop a measuring cycle). Two waterproof cable glands allow for safe passage of the sensors and fan cables.



Figure 2. small 0.96", yet very readable, OLED display permuting screens with different useful information.

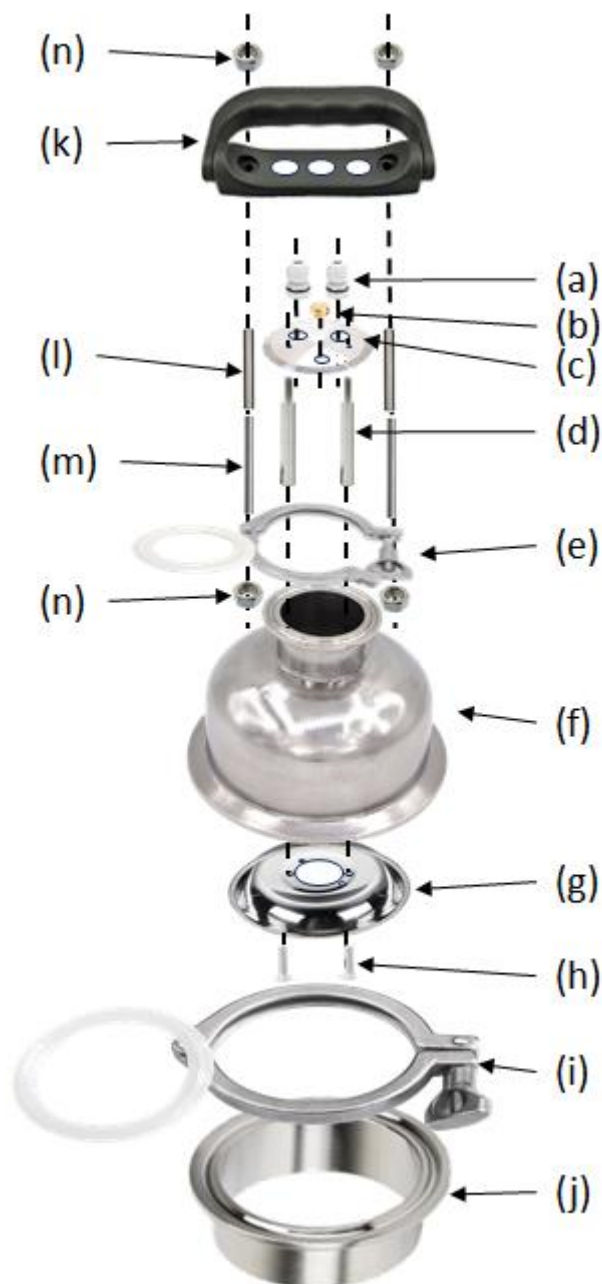
80 2.2 Body of the chamber

- The body of the device (Fig. 4) is built around a sanitary stainless-steel Triclover (also called Triclamp) dome reducer (6"-2"). The 2" opening is end-cap obturated and clamped with a 2" Triclover bracket and its Polytetrafluoroethylene (PTFE) joint. The 2" end-cap is pierced for one waterproof cable gland with 5V power cable, I²C bus, and, eventually, UART bus cable. A second hole may be drilled for another cable gland that may be needed for an optional OXYBase oxygen sensor, and the third 85 hole is for a small exhaust porous silencer used for the equilibration of internal air pressure with external air pressure during the measurement cycle. Two other small holes, tapered for M3 screws, are destined to hold two spacers on which the internal plateau is screwed. The second 6" opening is clamped during the operation on a stainless-steel collar previously placed into the soil at the chosen location. Again, a Triclover bracket and its PTFE joint, but 6" this time, ensure a correct sealing between the chamber body and the collar. The collar itself is made from a 6" Triclover lathe-sharpened ferrule.



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Figure 3. The enclosure is made from a) a handheld enclosure, c) μ -USB socket with a short cable, b) a power bank, d) two waterproof cable glands, e) three waterproof push buttons (one black self-locking On-Off and two momentary (On)-Off: one red, one black).



95 **Figure 4.** The body of the chamber is built with a) two waterproof cable glands, b) a small porous pneumatic silencer, c) 2” stainless-steel end-cap, d) two M3 spacers, e) 2” Triclover bracket with a PTFE joint, f) 6” to 2” Triclover reducer, g) small stainless-steel plate, h) two M3 screws, i) 6” Triclover bracket with PTFE joint, j) 6” stainless-steel bottom-sharpened fitting, k) Pierced plastic handle, l) stainless-steel tube partially covering the: m) M4 threaded stainless-steel rod, n) stainless-steel M4 nuts.



100 The 2” Triclover bracket studs were removed and replaced with a piece of stainless-steel M4 threaded rods partially covered with matching tube. On each end, the rods are bolted, at the bottom to the bracket and on the top to the handle.
The handle was drilled to hold three push buttons on the upper side and the handheld enclosure on the bottom.
Figure 5 shows the overall finished setup.



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Figure 5. Side-view of the assembled chamber positioned on the collar and Top-view of the chamber.

This chamber has an internal cloche volume ($V = 1.65 \text{ dm}^3$) to internal collar surface ($S = 2.01 \text{ dm}^2$) ratio of $R = 0.82 \text{ dm}$. Of course, when measurements are computed, the volume of air comprised between the soil surface and the top of the collar has
110 to be added to the cloche volume.

2.3 Embedded sensors and fan

The embedded sensors are the heart of the device. Nowadays, some miniaturized devices allow precise sensing of numerous physical quantities. The air pressure, temperature, and humidity can be precisely monitored by a minuscule BME280 sensor
115 (Bosch Sensortec GmbH, Reutlingen, Germany).



Gas concentration monitoring can be achieved with any small and accurate enough sensor. Several techniques are available, such as semiconductor, electrochemical, or optical. We do not embed a methane (CH₄) sensor, but this is a possibility using a semiconductor sensor (Riddick et al., 2020; Bastviken et al., 2020; Furst et al., 2021).

For CO₂ concentration monitoring, non-dispersive infrared (NDIR) sensors are currently used (Hodgkinson et al., 2013; Dinh et al., 2016). They are relatively cost-effective, small, and accurate enough. Not only CO₂ can be monitored with the NDIR sensors, but also some other gases, such as carbon monoxide (Diharja et al., 2012). Other miniaturized sensors can be used for CO₂, but we found the NDIR sensors have the best quality-to-cost ratio for CO₂ measurement.

Precise oxygen depletion measurement is challenging as the main atmospheric oxygen concentration (20.9%) is relatively high compared to the concentration variations in the closed chamber. When the CO₂ concentration can be multiplied by 5 after a few minutes inside a closed chamber, the oxygen concentration decreases only by barely a few percent of the initial concentration. Then, the sensor dedicated to the oxygen concentration measurement should be particularly accurate and stable. For this reason, we chose to work with optical sensors such as LuminOx and OXYBase. Both are optical, and their functioning is close to each other. The LuminOx (SST Sensing Ltd., 5 Hagmill Crescent, Shawhead Industrial Estate, Coatbridge, UK) is based on non-depleting luminescence technology, and the OXYBase (PreSens-Precision Sensing GmbH, Regensburg, Germany) is based on quenching luminescence. The absolute accuracy, resolution, and response time of the OXYbase sensor is better than that of the LuminOx sensor. The OXYbase sensor costs over six times as much as LumiOx as the cost is substantially non-linear with accuracy. We then have to choose based on our goal. The oxygen sensors are, by far, the most expensive sensors on this device (100 USD–650 USD). Oxygen depletion measurement is interesting and brings new insights into soil respiration (Turcu et al., 2005; Helm et al., 2021); however, their use is still optional.

used, and some of the existing sensor's specifications are summarized in Table 1. Notice that the provided specifications apply to room temperature and pressure ranges. Some of the sensors have several possible configurations, providing different measurement units, and so on. However, in Table 1, for the sake of clarity, only one of the possible configurations is given.



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Sensor model	Brand	Main measure - unit	Bus	Range	Accuracy	Resolution	Response Time	Remarks
BME280	Bosch	P hPa	I ² C and	300 to 1100 hPa	± 0.12 hPa	0.18 Pa	Faster than RH	Offset ±1.5 Pa/K
		T °C	SPI	-40 to+85 °C	± 0.5 °C	0.01 °C	Faster than RH	
		RH %		0 to 100 %	± 3 %	0.008 %	$\tau_{63} = 1$ s	
MH-Z16	Winsen	CO ₂ ppm	UART	0 to 2000 ppm	50 ppm +5% of reading	1 ppm	$\tau_{90} < 60$ s	Self-calibrated
CozIR	SST	CO ₂ ppm	I ² C and UART	0 to 2000 ppm	30 ppm + 3% of reading	1 ppm	$\tau_{90} < 30$ s	Offset 0.14% of reading per 1 mbar barometric pressure change from 1013 mbar
SCD30	Sensirion	CO ₂ ppm	I ² C and UART	400 to 10000 ppm	30 ppm + 3% of reading	1 ppm	$\tau_{63} < 20$ s	Measures also RH and T. Self-calibrated
LuminOx	SST	O ₂ %	UART	0 to 25% of O ₂	2% FS (0.5% of O ₂)	0.01% of O ₂	$\tau_{90} < 30$ s	Measures also P
OXYbase	PreSens	O ₂ hPa	RS-232 RS-485 4-20mA	0 to 500 hPa	4 hPa at 200 hPa	0.3 hPa at 200 hPa	$\tau_{90} < 10$ s	Measures also dissolved O ₂

Table 1. The mentioned measured parameters are: Pressure (P), temperature (T), relative air humidity (RH), carbon dioxide concentration (CO₂), oxygen concentration (O₂)



Figure 6 shows the used sensors and Fan embedded under the cloche.



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Figure 6. Used sensors and fan: a) BME280, (P, T, and RH), b) SCD30 (CO₂), LuminOx (O₂), d) OXYBase (O₂), e) Maglev fan.

All gas-analyzing sensors are digital and placed under a cloche on a dedicated prototype PCB held by the fan. The embedded fan is gently mixing the air entrapped under a closed cloche to homogenize it as well as possible without provoking pressure



150 pulsations that may affect measured effluxes (Le Dantec et al., 1999; Koskinen et al., 2014). The semi-spherical shape of the cloche helps to prevent poorly mixed areas (Livingston and Hutchinson, 1995).

BME280 is used to measure air pressure, temperature, and humidity. Air humidity measurements are necessary to deduce the dry molar fraction of the gazes of interest (LI-COR) or to calculate the soil evaporation rate (Zawilski, 2022). SCD30 (Sensirion AG, Stäfa, Switzerland) is a cost-effective NDIR sensor that provides CO₂ concentration along with air temperature and air
155 humidity. However, these two last parameters are already provided by BME280 with better accuracy. Both oxygen sensors, LuminOx and OXYBase, were tested, but only one at a time should be used. LuminOx is also measuring the air pressure. However, once again, BME280 is providing air pressure with very good precision that may be used for both sensors.

3 Sensors test

Embedded sensors such as SCD30, for CO₂, LuminOx, and OXYBase, for O₂, concentration determination was truly checked
160 by cross-measurement with a reference sensor, if available, or using a reference experimental measurement (respiration).

3.1 SCD30 cross test

Before using the SCD30 sensor for CO₂ monitoring, it was tested by comparison with the high-precision optical feedback-cavity enhanced absorption spectroscopy (OF-CEAS) Li-7810 from Li-Cor (LI-COR Biosciences, Nebraska, USA) for three
165 months using six chambers. To avoid any difference between measurements due to the air-leading pipes, we installed SCD30 and Li-840A (LI-COR Biosciences, Nebraska, USA) close to the Li-7810 in the same external circuit. Figure 7 shows all the measurements of Li-7810 versus SCD30. A linear regression of these measurements shows a good correspondence with a 1.08 slope and a small offset of less than 27 ppm with a rather high correlation coefficient ($R^2=0.98$). It is worth noting that SCD30 exhibits much better correspondence with Li-7810 than our flow-through LI-840A Infra-Red Gas Analyzer (IRGA), which is
170 not self-calibrated and, probably, quickly deserves a deep cleaning despite the air filter presence (Fig. 8).

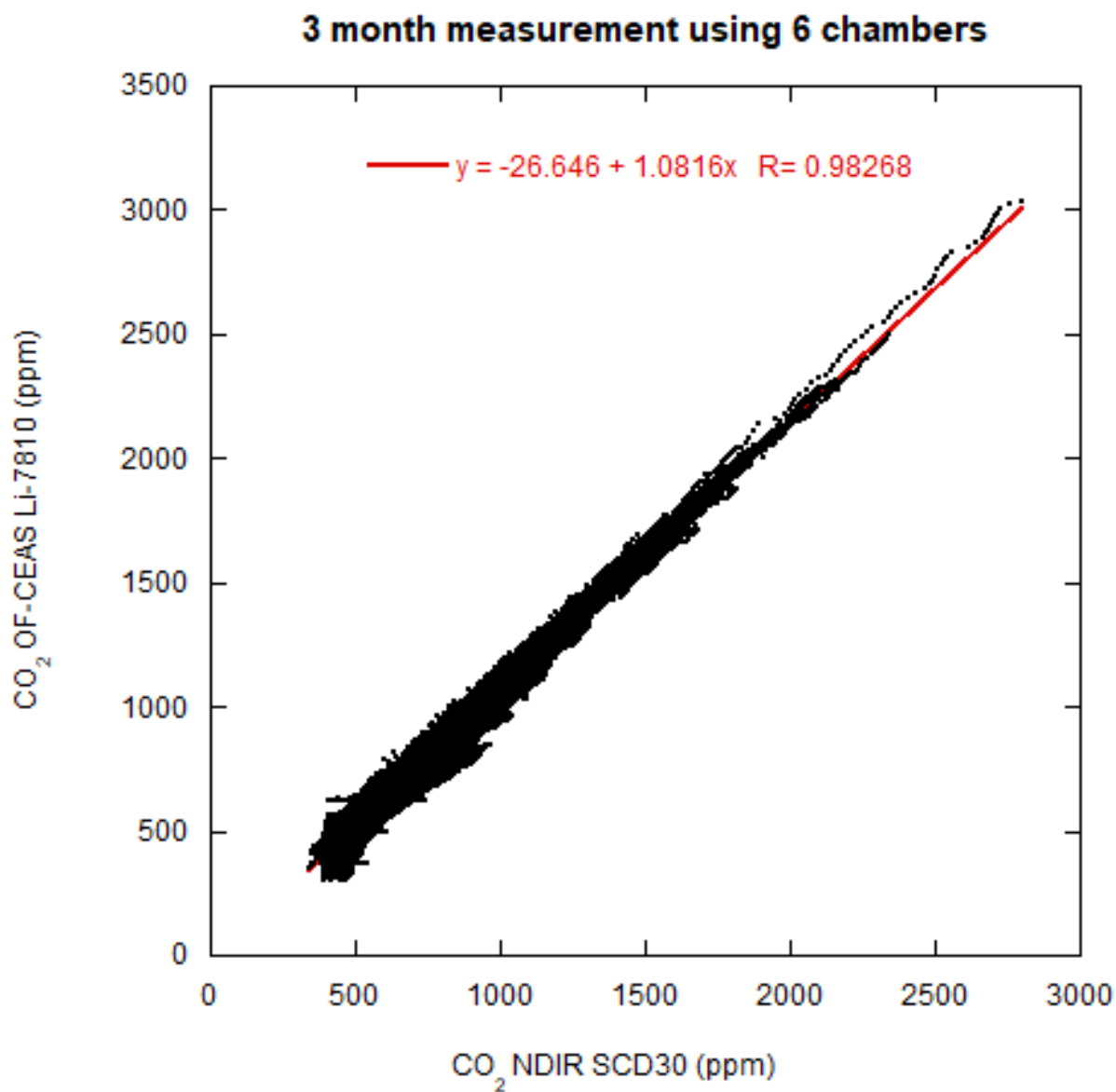
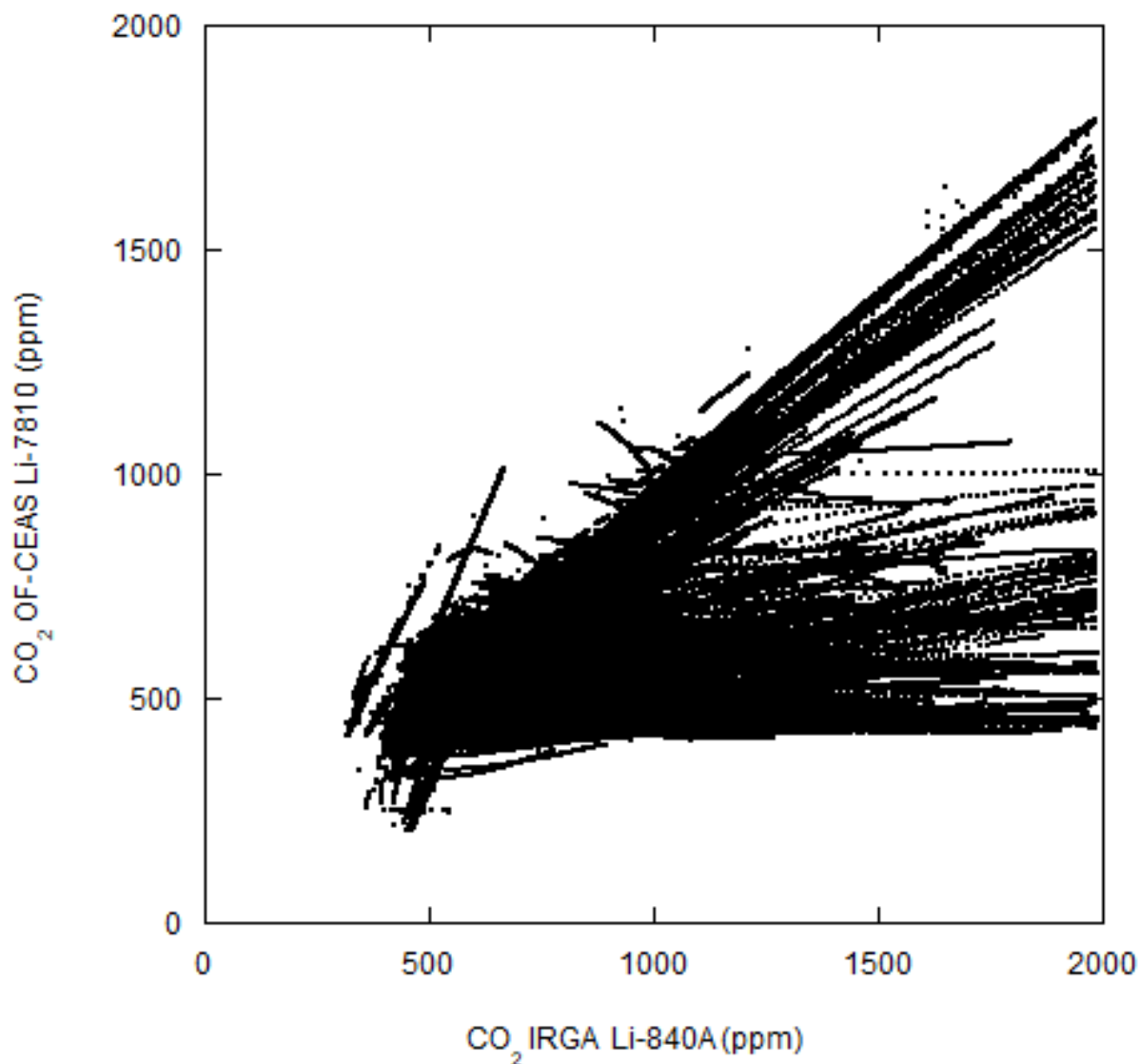


Figure 7. OF-CEAS Li-7810 measurements versus NDIR SCD30 measurements during a three-month campaign conducted with six chambers. The red solid line represents a linear regression.



3 month measurement using 6 chambers



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Figure 8. OF-CEAS Li-7810 measurements versus IRGA Li-840A measurements during three months. Li-840A derived during the test and presents measured CO₂ saturation for 2000 ppm due to the analog output configuration.

A good air analyzer is always preferable to a small (or even minuscule) analyzer. However, small analyzers can be embedded
180 under the cloche when big analyzers can only function outside of the chamber, which induces some other problems such as
air-leading tube disturbances, external condensation, and so on. Also, the price difference between a Li-840A and an SCD30
is about 160-fold, and between a Li-7820 and an SCD30 is about 1300-fold.



185 However, for some GHG gases, such as N_2O , a miniaturized, precise-enough analyzer does not exist. A variant of the described chamber, designed for an external multi-gas Fourier-transform Infrared Spectroscopy (FTIR) GT5000 Terra analyzer (Gaset Technologies Oy, Vantaa, Finland), was built. In this case, only the BMP280 and the fan were embedded under the cloche, and the data was transferred to a laptop PC via Bluetooth. Two fittings on the top of the chamber were added for air-leading tubes (In and Out). A detailed discussion about the problems with external analyzers will be presented elsewhere. Arduino programming is relatively simple. All I²C bus-attached devices have available libraries and programming assistance widely available on the web. UART-bus-based sensor communication is relatively easy to establish. The GPS also has
190 numerous libraries that can be used, as they generally use the NMEA 0183 protocol.

3.2 LuminOx and OXYBase cross tests

195 To test the oxygen sensors, we performed a comparison between LuminOx and OXYBase sensors performing an apparent respiration quotient (*ARQ*) measurement test with both sensors at the same time. To test *ARQ* measurement, an animal contained in a closed space would be very helpful. However, any experimentation including an animal is strictly regulated by law. These restrictions do not concern volunteer humans and one of us accepts to be briefly closed in a winery, clean, pressurized tank of 22 hl volume (2.2 m³). The CO₂ and O₂ evolution was monitored by a battery-powered data logger reading all available sensors at the same time.

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As expected, the CO₂ evolution with time is nearly linear:

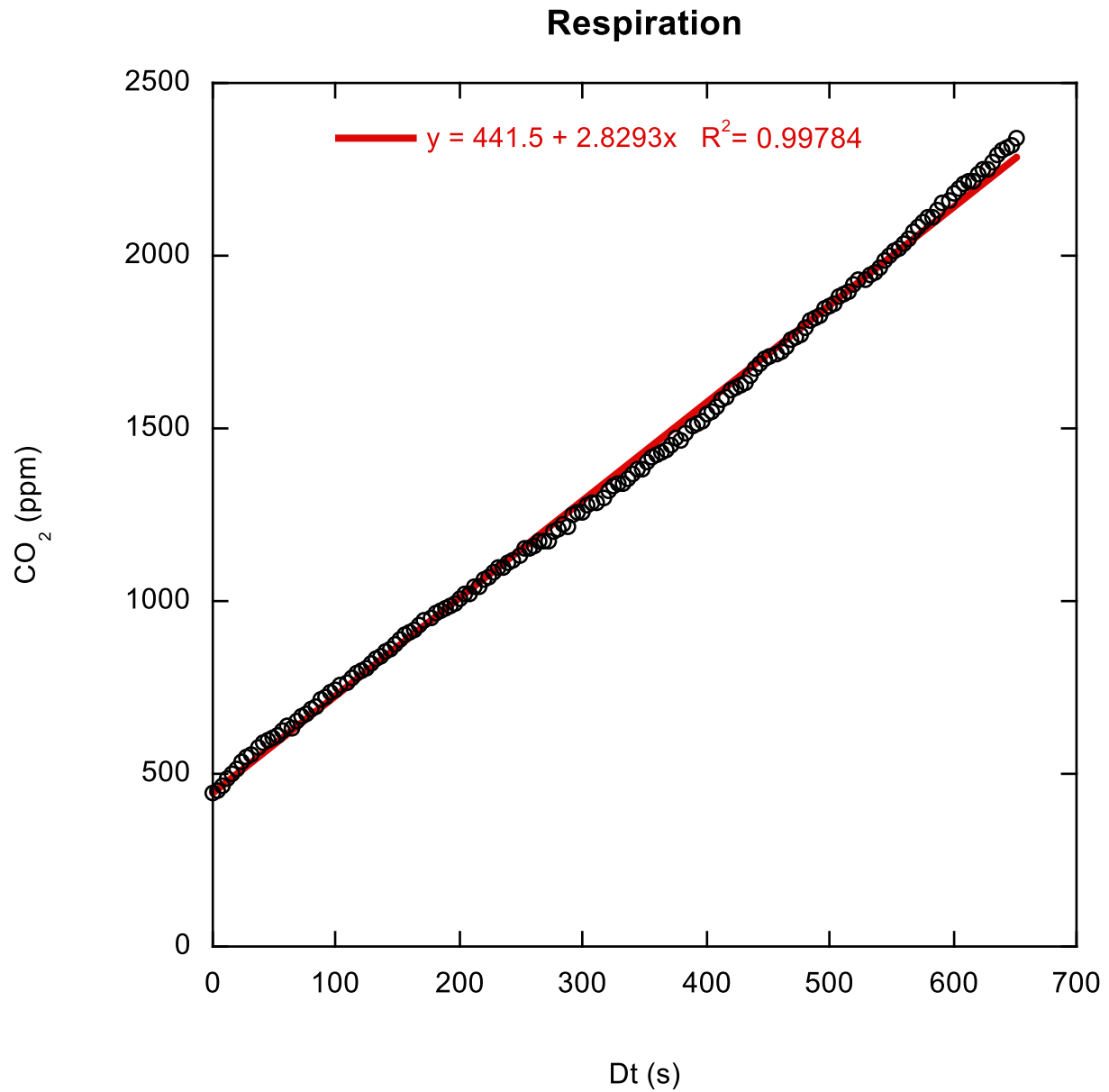


Figure 9. Measured CO₂ evolution in a tank with a breathing human inside. The red solid line represents a linear regression.

205 The O₂ evolution measured by LuminOx and OXYBase was close with a small offset and relatively matching slope:

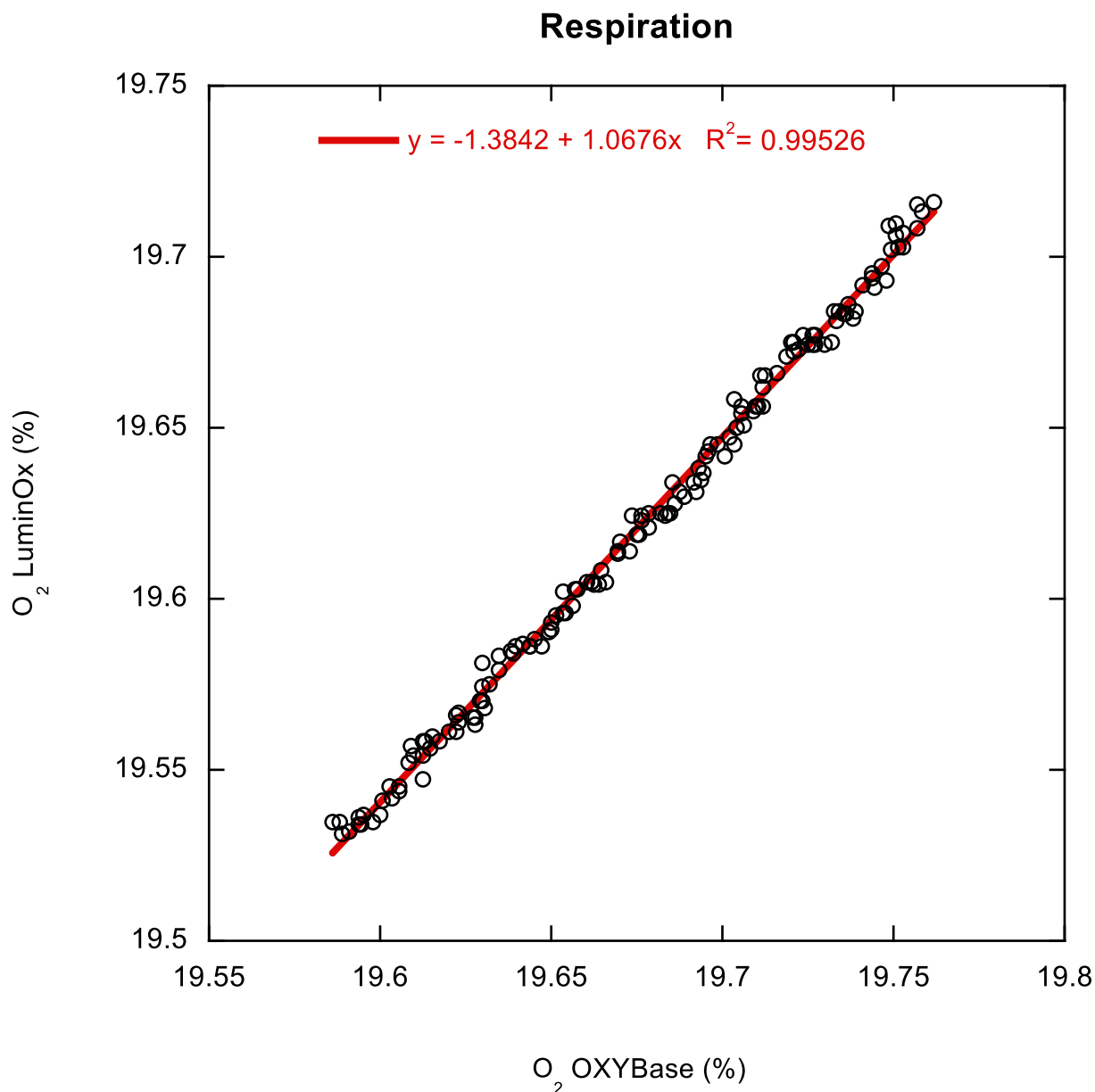


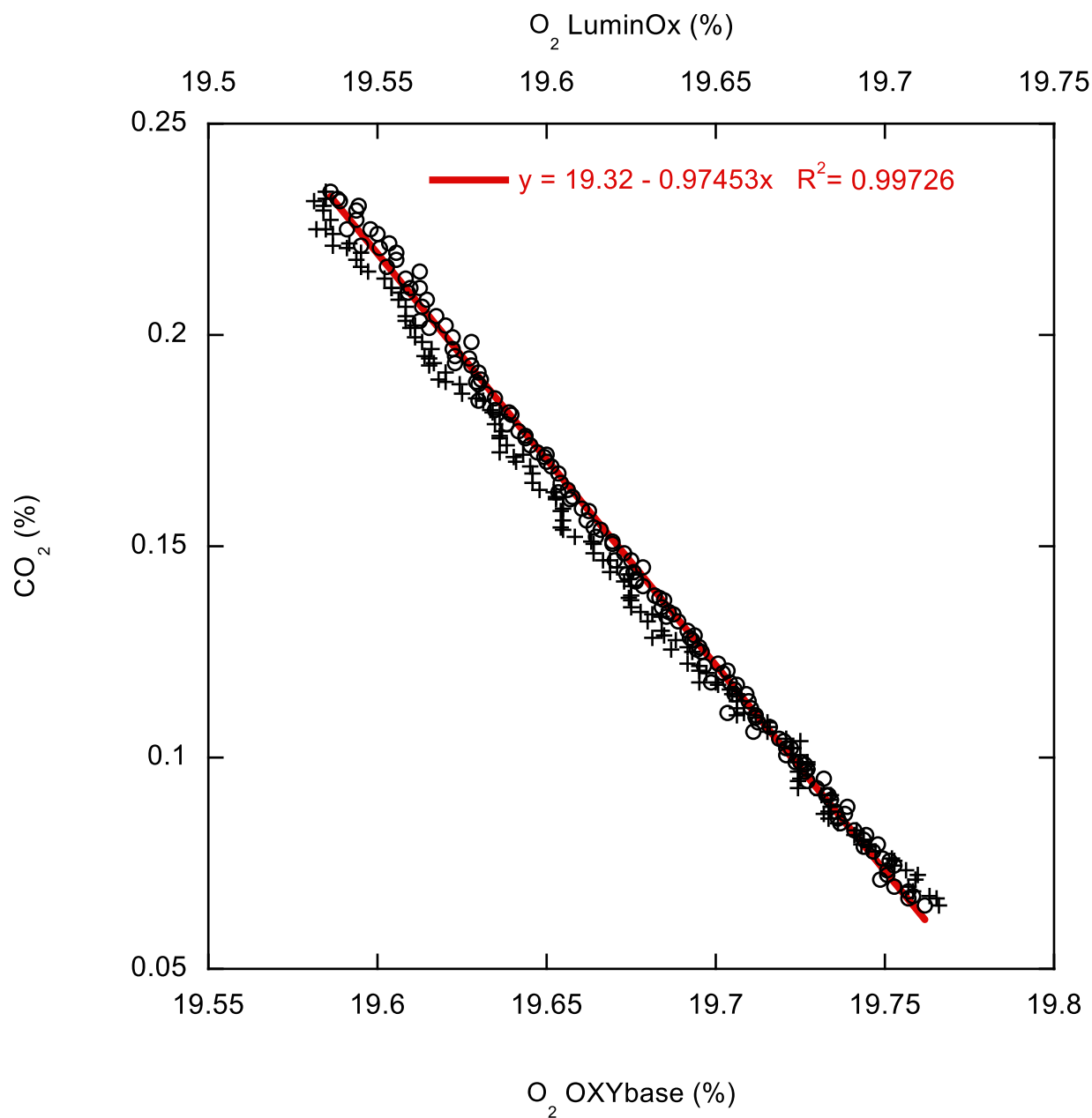
Figure 10. Measured O₂ part with LuminOx versus O₂ measured with OXYBase during the respiration experience. The red solid line represents a linear regression.

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The *ARQ* calculation, using a linear regression explained in paragraph 5, determined with OXYBase's measurements is 0.97 when the *ARQ* determined with LuminOx's measurements is 0.90. Both sensors allow then a relatively correct *ARQ* calculation.



Respiration

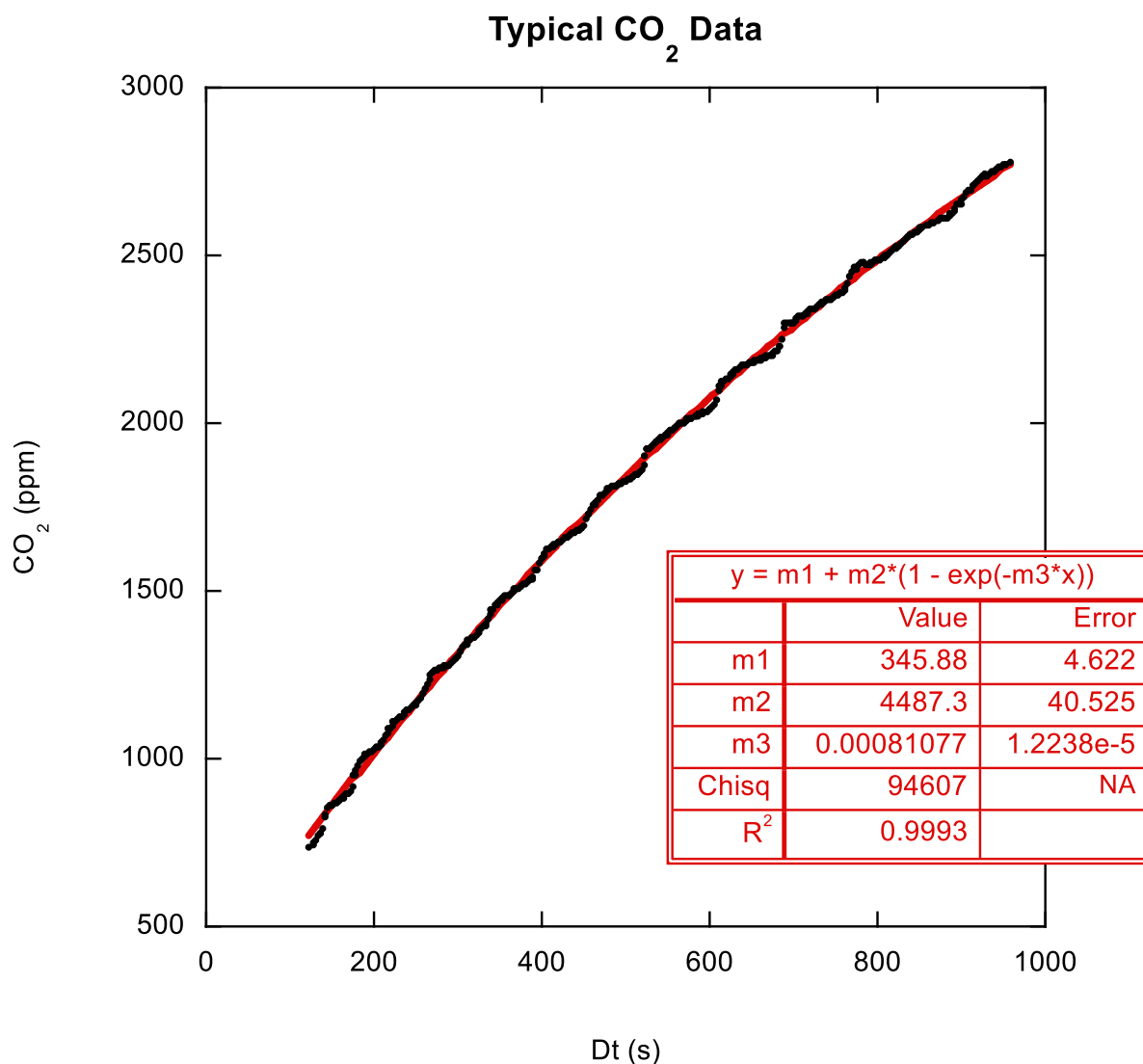


215 **Figure 11.** CO₂ part measurements versus O₂ part measured by OXYBase (lower abscissa) and O₂ part measured by LulminOx (upper abscissa). The red solid line represents a linear regression of CO₂ versus O₂ measured by OXYBase.



4 Typical results

220 A typical measurement with a closed chamber technique displays CO₂ rising and O₂ decaying with time. Historically, the effluxes or influxes were calculated using a linear regression on the initial data. However, several authors have shown that linear regression can lead to a severely biased calculation (Kutzbach et al., 2007; Silva et al., 2015), but it is beyond the scope of this note to discuss it here. As an illustration, we use the “exponential rise” regression, also called “asymptotic regression”. Figure 9 displays a typical carbon dioxide accumulation measured with a chamber positioned on its collar pressed into the soil.



225 **Figure 12. Typical CO₂ measures in the chamber. The solid red line represents an asymptotic regression (fit).**

The calculated CO₂ efflux F_{CO_2} would be then:



$$F_{CO_2} = m_2 * m_3 * R$$

230

(1)

With m_2 and m_3 being the curve regression constants calculated using a plot of CO_2 concentration versus closing time (Fig. 12) and R being the actual volume-to-surface ratio. The measured asymptotic concentration is given by the sum m_1+m_2 and represents the CO_2 concentration in the superior soil layer (0.5% here).

A similar calculation could be conducted on the O_2 concentration to determine the oxygen influx.

235 Figure 13 displays a typical O_2 measurement taken at the same time as the CO_2 concentration in Fig. 12.

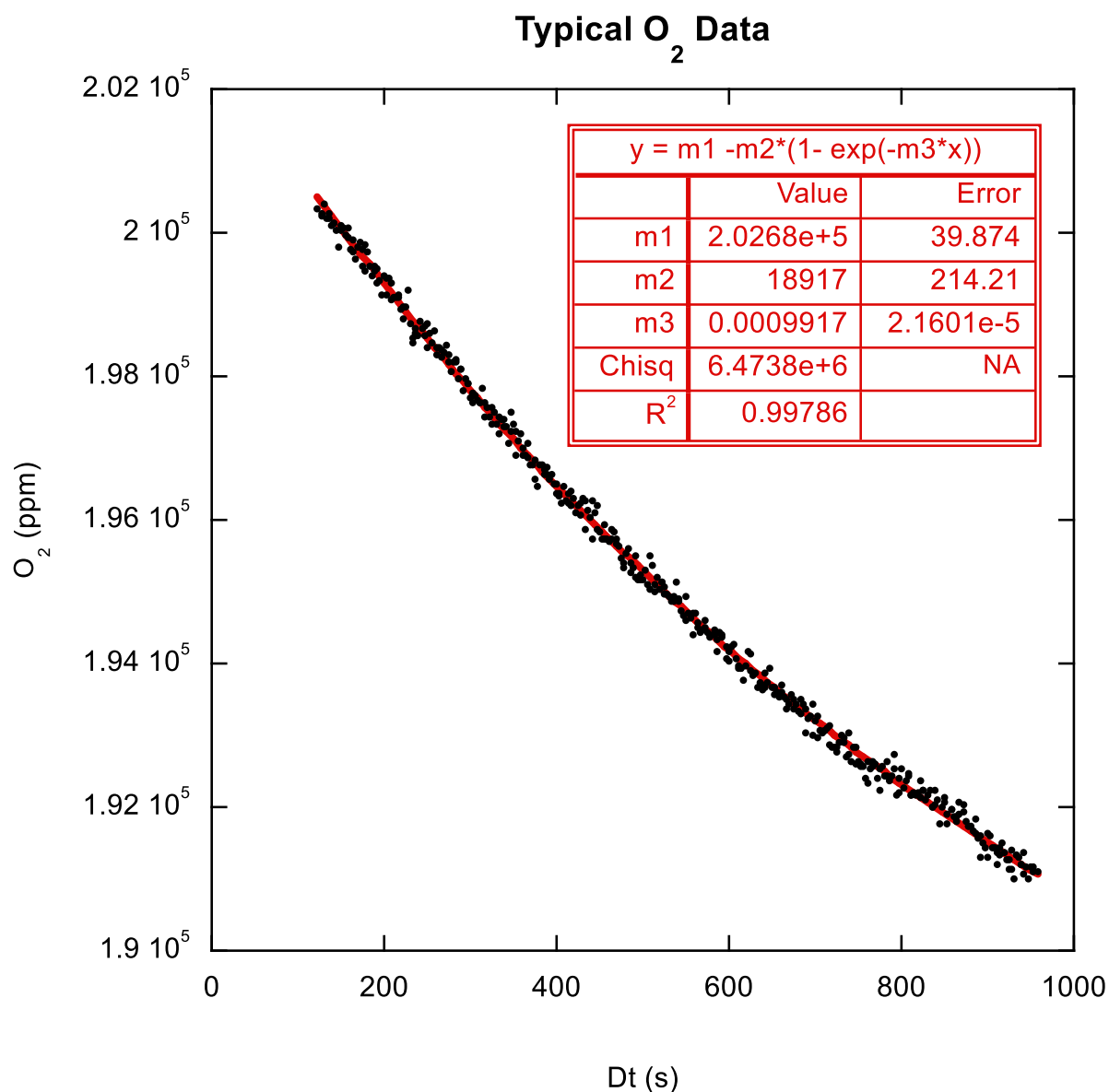


Figure 13. Oxygen concentration measurement versus time. The solid red line represents an asymptotic regression.

Similar to F_{CO_2} calculations, the corresponding oxygen influx F_{O_2} calculation would be:

$$240 \quad F_{O_2} = m_2 * m_3 * R$$

(2)

With m_2 and m_3 being the constants deduced from an asymptotic regression of the plot of O₂ concentration versus time and R being the same volume-to-surface ratio as for the F_{CO_2} calculation in Formula 1. Always similar to the asymptotic CO₂



concentration, the measured asymptotic O_2 concentration is given by the difference $m1-m2$ and represents the O_2 concentration
245 in the superior soil layer (18.4% here).

5 Apparent respiration quotient circulation

To determine the apparent respiration quotient (ARQ), by its definition, we can proceed with a quotient of F_{CO_2} and F_{O_2} formation.

$$250 \quad ARQ = \frac{F_{CO_2}}{F_{O_2}} \quad (3)$$

This quotient comes from the definition of the ARQ (CO_2 flux divided by O_2 influx).

In the reported typical measurements, using this quotient, $ARQ = 0.194$

255 However, this calculation accumulates uncertainties in both non-linear regressions used for F_{CO_2} and F_{O_2} determinations. Another simple way to calculate ARQ would be to use CO_2 concentration versus O_2 concentration, then a linear regression to give direct ARQ . Indeed, if we suppose that ARQ is constant during the time of the chamber closure, we can write:

$$ARQ = \frac{\frac{dCO_2}{dt}}{-\frac{dO_2}{dt}} \quad (4)$$

260 Then:

$$\frac{dCO_2}{dt} = -ARQ * \frac{dO_2}{dt} \quad (5)$$

By integration

$$265 \quad CO_2(t) = -ARQ * O_2(t) + C_0 \quad (6)$$

With C_0 being a constant:

$$C_0 = ARQ * O_2(t = 0) + CO_2(t = 0) \quad (7)$$

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Figure 14 displays the typical CO_2 and O_2 measurements already shown in the previous figures, but this time the CO_2 concentration is plotted versus the O_2 concentration. A linear regression provides simple ARQ determination.

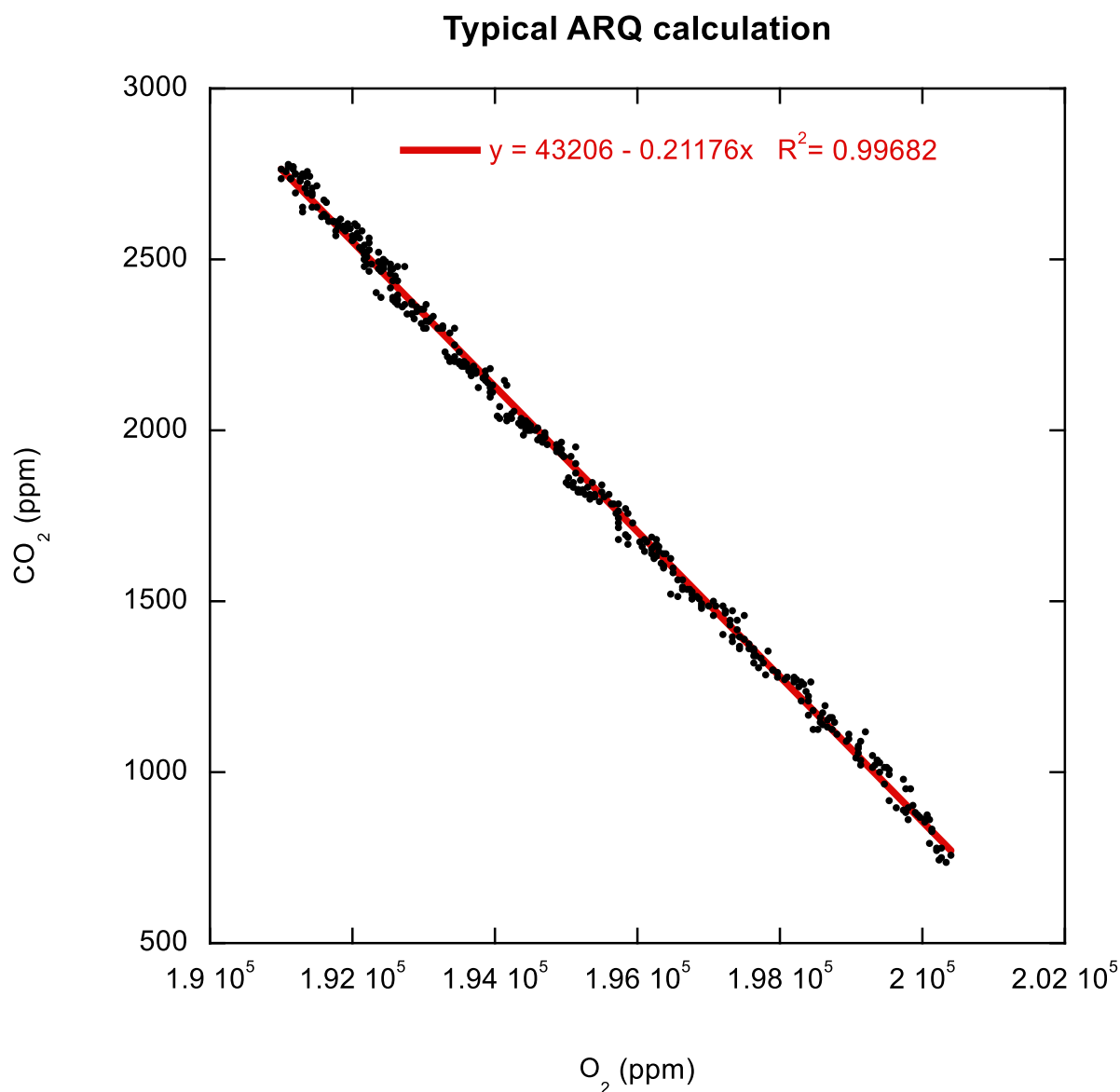


Figure 14. CO₂ concentrations versus O₂ concentrations. The solid red line represents a linear regression.

275 We can note that the ARQ provided by the linear regression of CO₂ concentrations versus O₂ concentrations ($ARQ = 0.212$) is slightly different from the ARQ calculated using the F_{CO_2} and F_{O_2} quotients (8.5% difference). For ARQ determination, we suggest using a CO₂ concentration versus O₂ concentration plot and a linear regression, as it does not accumulate successive non-linear regression uncertainties. We may also note that the measurements done with this chamber using low-cost sensors provide an excellent confidence level R^2 matching the theoretical linear and asymptotic regression.



280 We can also note that the expected ARQ would be close to 1, as for respiration, the same amount of O_2 is absorbed as the
quantity of CO_2 released. However, this does not account for the fact that the soil may capture and store a consequent amount
of the produced CO_2 (Sánchez-Cañete et al., 2018).

6 Conclusion

285 The importance of the soil's most significant natural CO_2 production measurement does not have to be proved. For this purpose,
an ultra-low-cost portable chamber was built and is described in this note with the hope of helping our scientific community
develop their own devices. The described chamber uses only commercial parts with little mechanical work. All used sensors
are digital and cost-effective yet accurate enough to allow measurements with excellent confidence level R^2 when regressed to
adequate linear and non-linear laws. The described chamber is easy to build and easy to operate, allowing a wide range of
290 users to work with it.

Disclaimer

No human was harmed during these studies.

295 *Authors contributions*

BZ conceived the portative chamber, found and tested the sensors, and wrote the first draft.

VB defined the specifications, found the necessary budget, and reviewed the draft.

Competing interests

300 The contact author has declared that none of the authors has any competing interests.

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310 the INC.



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