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# Technical Note: Cost-efficient approaches to measure carbon dioxide (CO$_2$) fluxes and concentrations in terrestrial and aquatic environments using mini loggers

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# Content

# Manual for adapting and using the CO$_2$ logger for environmental measurements

## Logger adaptions

### Connectors
The CO$_2$ logger used is the ELG module made by Senseair (http://www.senseair.se/products/oem-modules/elg/). It is sold as a sensor mounted on an electrical board which needs the following adaptions for the type of use described in our study:

First, solder connections for calibration, quick start (see below), communication and battery as shown in Figure S1. Dimensions and type of connections are shown in Table S1.
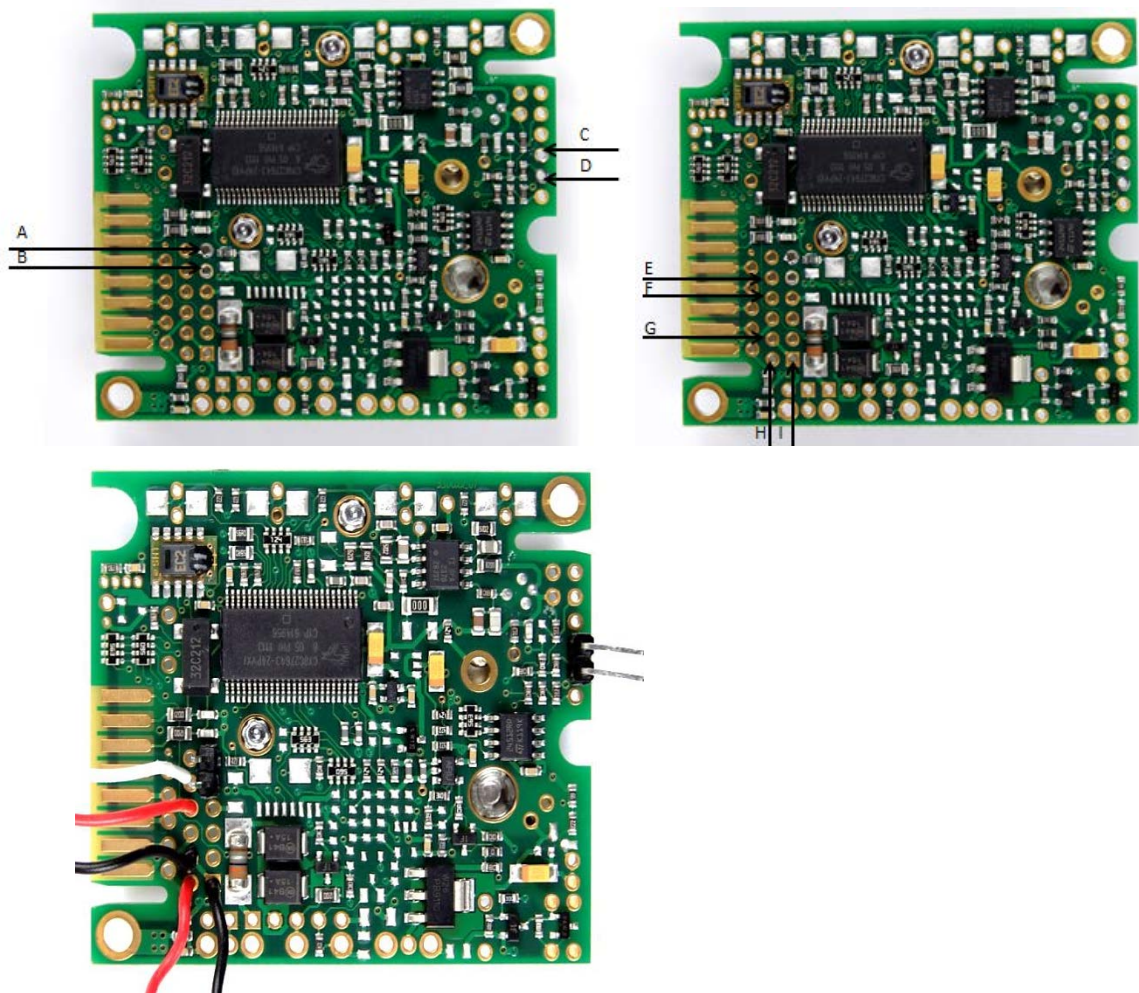


**Figure S1.** Positions where connectors should be soldered onto the logger board. The two upper panels show positions with labels. The use of the connectors is as follows: shorten A+B for zero calibration and C+D for quick start (see text below for explanations). E (UART TxD), F (UART RxD) and G (G0) are used for the communication cable (see below) and H (G+) and I (G0) for battery connection. The lower panel show the board after making the adjustments.

## Extension and power supply cables

An extension cable from positions E, F, and G in Figure S1 to a connector is practical for easy connection to the board in the field. To make such an extension cable, use three differently coloured wire, each about 25 cm long and solder them to the male pin header as shown in Figure S2 and secure with crimp cables. The other end is soldered onto the board (Figure S1).

Solder battery connection on to the board as shown in Figures S1 and S3. A practical length of both the extension cable for communication and the power supply cable is 25 cm for the applications described in this study.
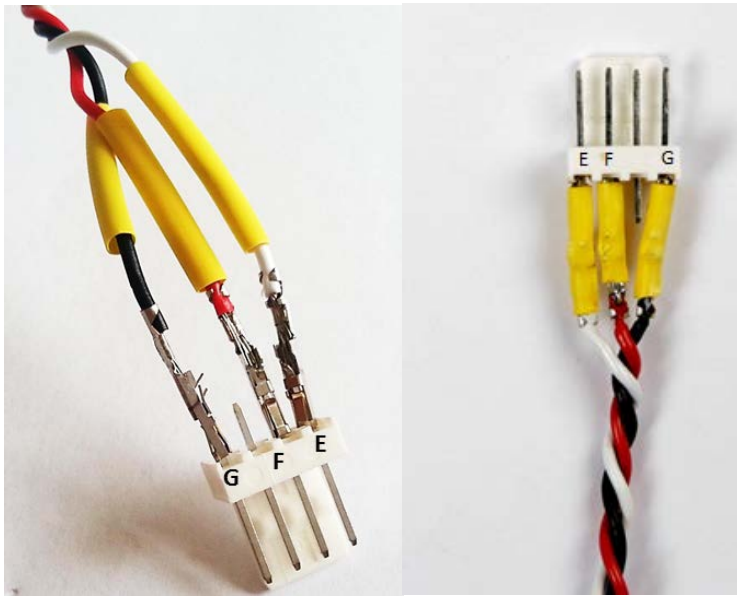


**Figure S2.** Wiring of the connector from the extension cable from the logger board. The position of E, F, and G on the board is indicated in Figure S1.

## Protective coating

The sensor should be painted with anti-tracking varnish (Ultimeg 2000/372) to protect it from condensation and water. Before painting, clean the circuit board (but not the sensor membrane) with ethanol and dry clean with compressed air. Apply a layer of varnish at least three times (additional varnish layers is better for improved corrosion protection). Areas marked in Figure S3 should not be covered with varnish.

**Figure S3.** A board after applying protective varnish (in this case the varnish had a grey colour – other colours or transparent varnish is also available). The temperature, relative humidity, and $CO_2$ sensors and connector areas (encircled) should be protected from varnish.
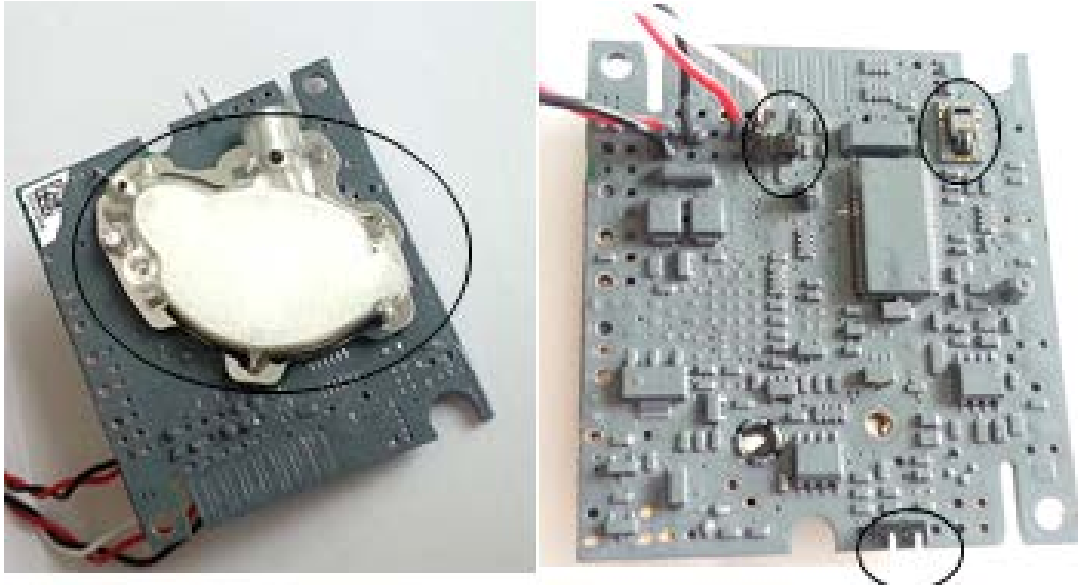
## Data communication cable

To communicate with the sensor a modified TTL-232R-3V3-cable is needed (TTL-232R-3V3; FTDI chip; Glasgow, United Kingdom). One part is composed of three differently colored wires (the same type as for the extension cable described above). One end of this is attached to a connector, matching the connector in the extension cable and the other end is soldered to a straight pin header (1x5) that is then connected with the TTL cable (Figure S4). For details of pins and housing see Table S1.

**Table S1.** Connections for the sensor.

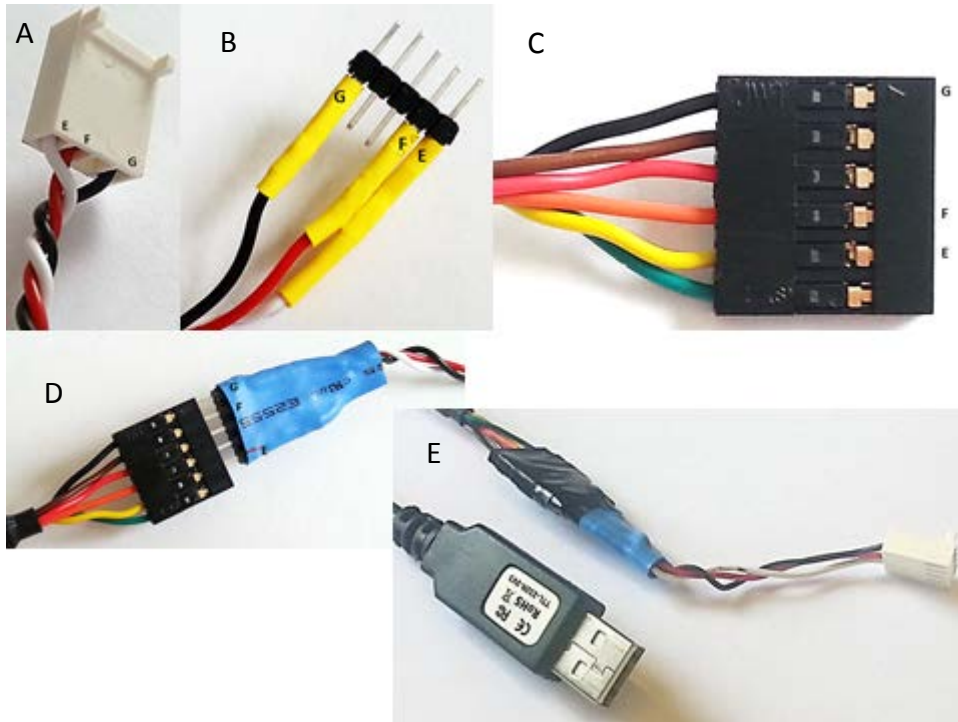| Component | Dimensions | Function |
|---|---|---|
| Straight pin header | Pole no. 1x2, pitch 2.54 mm | Calibration (A+B), quick start(C+D) and modification of TTL-cable |
| Pin header | Pole no. 1x4, pitch 2.54 mm | Connection cable from sensor |
| Cable socket | Pole no. 1x4, pitch 2.54 mm? | TTL- cable |
| Battery holder | 9V, 100 mm | Battery connection |
| Jumper | Pitch 2 mm | Calibration and quick start |

**Figure S4.** Illustrations of the connectors needed on the TTL cable for data communication. Panel A and B shows the three coloured wires attached to a connector on one end and to a straight pin header (1x5) on the other end. Panel C and D shows the connection of this straight pin header to the TTL cable. Panel E shows the finished data communication cable.

## Communication with a sensor

The software UIP5 for communicating with the sensors can be downloaded for free at http://www.senseair.se/products/software/uip-5/. After installing the software, open the program and go to the **Help** menu and **check for updates**.

Connect and install the cable on the computer and open UIP5. Choose the menu **Meter/ Connection configuration.** Choose the right **COM port** and make sure the box **ModBus** is checked and save the settings.

Connect a sensor (with the battery connected) and click on **connection status** in the bottom right corner of the screen (or **Ctrl+d**) to connect/disconnect a sensor.

In the control window (the lower right part of the screen) the "Logger" tab is used for starting and stopping measurements, setting log period, synchronizing logger time with computer time (RTC), read data to the computer (delivered as text files), and managing the logger memory. The tab "$CO_2$" can be used for quick calibration as described below.

Note that the logger should always be battery powered when connected to the computer. Without battery power, connection to the computer will fail. With a bad battery (insufficient power) the sensor may return unrealistic ppm values while connected. If there are connection problems, the first step of problem solving should be to change to a new battery.

## Calibration

The recommended calibration is a "**zero calibration**" i.e. repeated calibration cycles in $CO_2$ free gas (we used $N_2$). To do this, connect the sensor to UIP5 set the **log period** to 300 s and set *RTC*. Disconnect <u>without</u> starting. Connect a jumper to the **quick start** pins and make note of the time. After the light stops flashing, connect another jumper to the zero calibration pins.

It is desirable to calibrate many sensors batch-wise. Place the sensors in a gas tight box, glove box, glove bag or similar and purge with a low but steady flow of nitrogen. If the flow is too high the $CO_2$ concentration will decrease too fast during each calibration cycle which will return an error message and automatically stop the calibration. When the sensors have been calibrating for a minimum of three hours in a zero $CO_2$ atmosphere, remove the jumper from the zero calibration pins before next measurement cycle starts. Remove the quick start jumper and connect to UIP5 to confirm the sensor is calibrated.

An alternative, simplified calibration may be used if conditions do not allow a zero calibration. Via the $CO_2$ window in the UIP5 it is possible to type in the $CO_2$ concentration around the sensors if known, and press "calibrate" while having the logger turned on at, for example, 60 s measurement interval. The sensor will then perform a calibration relative to the typed in value. This option should only be used when the air around the sensor has a stable $CO_2$ concentration. The calibration cycle should be repeated several times for best results.

After calibration, the sensors should be compared with a reference instrument (e.g. a GC). This could be done by starting the sensor and placing it in a closed environment with possibilities to take manual samples. Such a measurement validation procedure should be executed after each calibration, occasionally during and after use whenever possible, and after storage, to check when a new calibration is needed.

## Assembling the chamber and the sensor protection box

The chambers used in this study were produced from polypropylene plastic buckets covered with aluminium tape to minimize light induced heating of the chamber headspace (note that the loggers can be used in any type of flux chamber). Two pieces of Styrofoam were attached around the rim to keep it floating in the water (Figure S5).

Two plastic boxes were placed inside the chamber. The bigger box (Lock&Lock, 350 ml, HPL806) contained the $CO_2$ sensor (sensor box) and the smaller one (Lock&Lock, 180 ml, HPL805) was to protect the battery and the data communication connector from water (battery box).

The sensor box has a slanting plastic sheet, used as a condensation trap to reduce the condensation on the sensor in a passive way not consuming power (other ways to reduce condensation by e.g. pumping air through a desiccant or heating the sensor would consume significant amounts of power). Ventilation holes were made on one short side (7 mm diameter, Figure S6). The gap between the plastic sheet and the bottom of the box should be minimum 1 cm to not restrict air flow too much (Figure S6). Attach the sensor box to the lid so the sensor is placed on the same side as the ventilation holes. Some of the condensation will stick on the sheet (instead of the sensor) and drain before reaching the sensor. When closing the boxes, make sure the cables are in a corner of the lid and not directly by a clasp.

**Figure S5.** Inside (left) and outside (right) of the chamber type used. The tube with the 3-way syringe valve to the right is for manual sampling at the end of selected deployments to check sensor performance.



**Figure S6.** Three pictures of the sensor box with ventilation holes and condensation protection sheet.

The sensor is attached to the lid with M3 polyamide (non-corroding) bolts and nuts (Figure S7). The boxes are attached to the chamber with M6 polyamide bolts and nuts. All holes are sealed with rubber sealing. The battery box was made to be as water tight as possible. The parts for the protective boxes are listed in Table S2.

**Table S2.** Chamber parts.

| Part | Dimensions |
|------|------------|
| Sensor box | 350 ml, 8 cm x 11.3 cm |
| Battery box | 180 ml, 6.8 cm x 8.7 cm |
| Styrofoam collar | 2 x 45 cm |
| Chamber | 8 L, inner radius 12.5 cm, height 12 cm |
| Bolts and nuts for sensor | M3 |
| Bolts and nuts for sensor box | M6 |



**Figure S7.** Sensor placed in lid.

## Logger settings

Connect to a sensor and choose the Logger tab (Figure S8). There the Logger Settings, Logger Status and Logger Data are shown. Table S3 describe the sub categories in Logger Settings and Logger Status. In the Logger Data window, data saved in the log can be read.
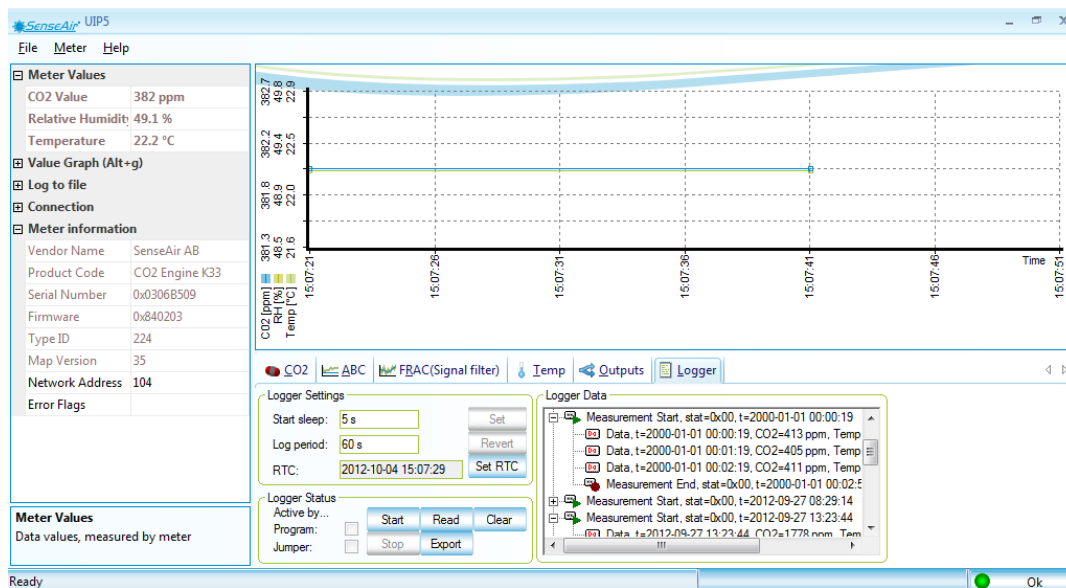


**Figure S8.** Screenshot of the logger menu in UIP5.

**Table S3.** Explanation of Logger Settings in "Logger" tab in the UIP5 software for logger control.

| Setting | Explanation | Allowed frequencies |
|---------|-------------|---------------------|
| "Start Sleep" | Specifies the delay before start. | 0-255 |
| "Log Period" | Specifies the time interval between measurements | $1-2^{24}$ (1 second to ~6 months) |
| "RTC" | Set Real Time Clock (adjust sensor time to computer time). | - |
| "Set" | Activates new settings | - |
| "Revert" | Undo the last change in settings. | - |

**Log Period** specifies the time between measurements in seconds. For example if measuring $pCO_2$, the Log Period could be set to 3600 s (1 hour) and for flux measurements, 300 s (five minutes).

Note: All data in the log will be erased each time **Log Period** is changed.

A measurement is started by clicking **Start** and stopped by clicking **Stop**. (**Start Sleep** specifies the delay from **Start** and before the first measurement starts.)
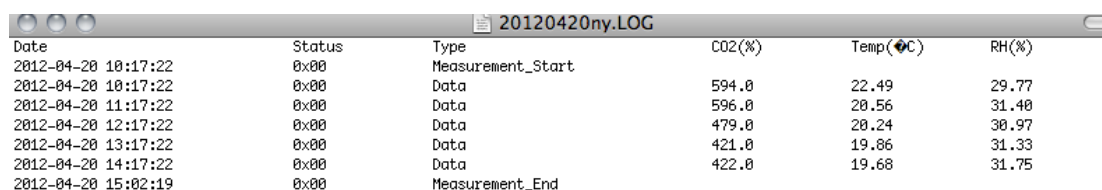
Note: Always set RTC (i.e. the computer clock time) before starting a measurement. In **Logger Settings** choose **set RTC**. If RTC is not set, the time stamps in the log file will be incorrect.


## Download data

Connect a sensor and choose **Logger**. **Stop** ongoing measurement, choose **Read** and then choose **Export** (if **Export** is not activated, try to disconnect and connect the sensor again). To control what data is exported, choose "**save selected part**" and "**save only data records**" in the export log window appearing. The log file is saved in the desired directory on the computer as a text file that is easily opened in e.g. Excel for further analysis.


## Status codes and error values

Figure S9 shows a short log file. The different status codes are explained in Table S4. More than one status code can be shown at the same time. The codes 0x70 means that 0x10, 0x20 and 0x40 are active. The value **32767** is used as an **ErrorValue** for $CO_2$, Temp and RH. If a measurement for any of the parameters fails the value 32767 will be written in the log. In most cases errors indicated by status codes or the error value can be resolved by replacing the battery.

```
○ ○ ○                          📄 20120420ny.LOG                                    ⬯
Date                    Status      Type            CO2(%)      Temp(◆C)     RH(%)
2012-04-20 10:17:22     0x00        Measurement_Start
2012-04-20 10:17:22     0x00        Data            594.0       22.49        29.77
2012-04-20 11:17:22     0x00        Data            596.0       20.56        31.40
2012-04-20 12:17:22     0x00        Data            479.0       20.24        30.97
2012-04-20 13:17:22     0x00        Data            421.0       19.86        31.33
2012-04-20 14:17:22     0x00        Data            422.0       19.68        31.75
2012-04-20 15:02:19     0x00        Measurement_End
```

**Figure S93.** Example of a short log file.

**Table S4.** Sensor status codes

| Status code | Meaning | Plausible explanation |
|---|---|---|
| 0x00 | No warning | |
| 0x10 | Low battery warning | Indicating battery voltage < 5.25V. Change battery. |
| 0x20 | Low battery alarm | Indicating battery voltage < 4.75V. Change battery. |
| 0x40 | Error Status | Indicating failed measurement or internal errors. Can relate to error measuring $CO_2$, temperature, RH or other internal errors. Read log file for details. |

# Recommendations of routine for reliable field measurements

As a routine for measurements the following steps are recommended:

1. Check, and if necessary make a sensor calibration before use. Test the calibration by comparison with reference gas analyzer (e.g. GC). This can be done with batches of loggers for increased efficiency.

3. Start the logger and set suitable measurement interval. For flux measurements a shorter interval is needed (e.g. 1-10 min depending on the system). For $p$CO2$_{aq}$ measurements the response time of the system, decided by the headspace equilibration time (in turn regulated by $k$ and volume to area ratio of the chamber), makes longer measurement intervals (15-60 min) more adequate to save power and memory space.

4. If using small 9 V batteries – ensure that battery voltage is kept above 7.5 V throughout the whole measurement period to prevent repeated shutdowns that can result in data loss. This can be done by adapting the measurement frequency or the interval between battery replacements.

5. Withdraw occasional manual samples from the chambers by syringe to validate logger measurements by comparison with a reference gas analyzer and for drift correction. In cases of long term deployments it is highly recommended to collect parallel manual samples whenever visiting the chamber (at least when starting and ending the deployment).

6. After use for as long as 1- 2 weeks in the field – bring the chambers indoor for proper drying to minimize moisture accumulation in the measurement cell leading to frequent condensation events. It is recommended to let the loggers dry after all field use and to store them under dry conditions to avoid corrosion.

Step 1-2 should be performed immediately before field use. We recommend building a database for the measurements in which each logger is given a unique permanent name that is linked to all data from the logger to record the history for each individual unit.

# Tests in addition to those described in the main text

## Influence of temperature and relative humidity on $CO_2$ measurements

In an initial test of temperature effects only, data from five replicate loggers were compared with syringe samples for analyses by gas chromatography at -17, 5, 8, 20, 27, 37, and 46 °C in well temperature equilibrated environments taking advantage of Swedish winter outdoor temperatures (-17 °C) and various temperatures available in our laboratory. The difference between GC and logger data averaged 1 % and never exceeded 5 % for any of the temperatures, indicating that the logger response was not biased by temperature. However, after some of the field tests described in the main text, concerns of possible interaction effects between temperature and humidity on $CO_2$ values were raised. We performed an additional sensor performance test as follows: Three replicate and recently calibrated sensors were mounted together with a weather station (WXT520, Vaisala) logging both temperature and humidity, and our LGR greenhouse gas analyzer for $CO_2$ measurements (DLT-100), in a climate room where temperature and humidity was varied. The temperatures used were 5, 10, 15, 20, 25, 30, 35, and 40 °C. At each of these temperatures the relative humidity (RH) was allowed to increase continuously over 30-60 minutes, from 8 – 95 % while all instruments logged data with a minimum measurement frequency of 1 minute. To compensate for differences in sensor response times moving 5 minute averages were compared.

The temperature from the sensors showed a linear correspondence with the weather station as described by

$T_{WXT} = 0.988 \cdot T_{ELG} - 1.03$   *(n = 297, $R^2$ = 0.999)*                     Equation S1

where $T_{WXT}$ and $T_{ELG}$ denote temperature measurements in °C from the Vaisala weather station and the Senseair sensor, respectively. Data from all the three Senseair sensors were included in Equation S1.

For relative humidity there was a significant interaction effect with temperature. Therefore the best calibration between RH values from the weather station ($RH_{WXT}$) and the sensors ($RH_{ELG}$) was obtained with the multiple regression

$RH_{WXT} = 0.934135 \cdot RH_{ELG} + 0.29414 \cdot T_{ELG} + 0.912959$

*(n = 297, $R^2$ = 0.990)*        Equation S2

The combined effect of temperature and humidity on $CO_2$ measured by the ELG sensor ($CO_{2ELG}$) resulted in a systematic bias with lower values relative to the LGR at low humidity and higher values at high humidity with this effect being modulated by temperatures. The maximum difference of $CO_2$ measured with the LGR ($CO_{2LGR}$) and $CO_{2ELG}$ ($CO_{2LGR} - CO_{2ELG}$) was between -6.6 and +7.6 % of $CO_{2ELG}$. To correct for this we made the following multiple regression

$CO_{2corr} = 153.165 + 0.797236\ CO_{2ELG} - 0.799018 \cdot T_{ELG} - 0.45636 \cdot RH_{ELG}$

*(n = 297, $R^2$ = 0.87)*        Equation S3

where $CO_{2corr}$ denote corrected $CO_2$ values. Please note that Equation S3 is valid under non-condensing conditions and $CO_2$ levels in the range of 400-550 ppm only. The residual

difference $CO_{2LGR}$ - $CO_{2corr}$ was unbiased relative to humidity and temperature and ranged from -1.6 to 2.3 % of $CO_{2corr}$.

## Test of chamber response time effects from the sensor protection box

The plastic box with holes, protecting the sensor from condensation and splashing water (Figure S6) could potentially delay the response time. To test this we took advantage of the logger capacity to control one peripheral device and used six chambers with loggers, two of which were equipped with a computer fan. Two others units were connected to a small membrane pump that pumped air from inside the protective box right near the sensor to a sintered aquarium bubble stone right under the water surface within the chamber. This pump setup were believed to both mix the air in the headspace and also speed up the equilibration between the chamber headspace and the water which would be beneficial when $pCO_2aq$ measurements are in focus (but obviously not suitable when using chambers for flux measurements). The two remaining chambers represented reference chambers with no device for mixing the headspace. $CO_2$ concentrations were measured in all chambers every $2^{nd}$ hour for 20 hours. The fan or the pump was run for 3 minutes before each measurement.

The comparison between mixed (by fan or pump) and reference chambers without electrical mixing of the headspace is shown in Figure S10. No significant difference was seen, which indicates that the time delay due to the protective box was negligible. A longer delay without mixing cannot be excluded during calmer conditions (see Fig. 4 and 6). For the fastest response it is recommended to remove the protective cover whenever possible without risking sensor integrity.
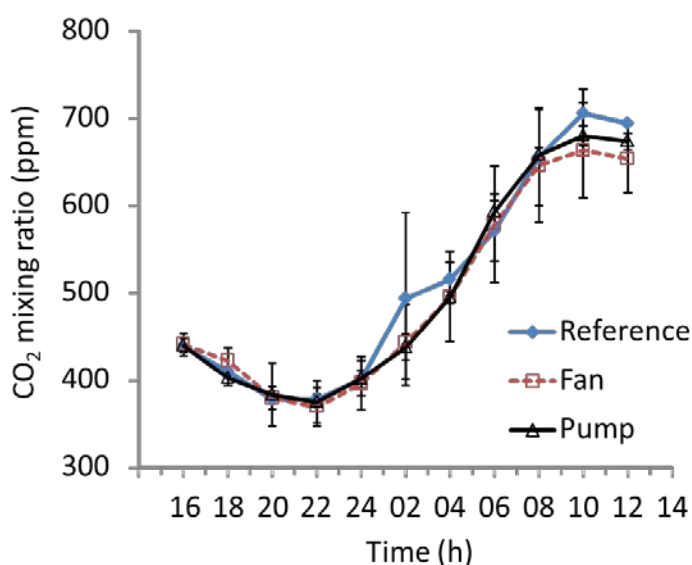


**Figure S10**. Comparison of different ways to mix the headspace of floating chambers on a small pond. Reference chambers had no powered mixing in addition to the natural mixing by chamber and water movements. "Fan" and "Pump" denote chambers equipped with a fan or a pump, respectively) to mix the chamber headspace. Two unites of each type was used in this test. See text for details.