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Technical note: Facilitating the use of low-cost methane (CH_4) sensors in flux chambers – calibration, data processing, and an open-source make-it-yourself logger

David Bastviken et al.

Correspondence to: David Bastviken (david.bastviken@liu.se)

This supplement contains supplementary tables and figures, and a description of a CH_4/CO_2/RH/T make-it-yourself logger.

Table S1: The best identified relationships between parameters *g* and *S* in Model V4b (Table 1) and parameters *a*, *b*, *c*, and *K* (Model 10a in Table 2). R^2 is the adjusted coefficient of determination, and SD denote standard deviation. Please note that the relationships are examples derived for the specific sensors used only, and the verification of their application to other sensors requires more tests.

Response variable (*y*)	**Best predictor (*x*)**	**Relationship**	**R^2 or SD**
a	*S*	$y = 6.98 \cdot 10^{-2} \cdot x - 3.55$	R^2 0.90
b	-	Constant value for all sensors: -2.36	SD 0.24
c	*(g/S)*	$y = 1.37 \cdot 10^{4} \cdot x^2 - 8.94 \cdot 10^{-2} \cdot x - 1.02 \cdot 10^{-5}$	R^2 0.96
K	*S*	$y = -7.15 \cdot 10^{-2} \cdot x + 0.95$	R^2 0.85

Table S2: Examples of previous studies addressing calibration and performance of the Figaro TGS 2600-type sensors for CH_4. All studies included consideration of humidity and temperature influence on the sensor response. Please see Reference list in main text for full references.

Source	**Sensor model**	**Range (ppm)**	**Notes**	**R^2**
Eugster and Kling, 2012	Figaro TGS 2600	1.8 - 2	Ambient air. Linear models in focus.	0.19[a]
Casey et al., 2019	Figaro TGS 2600	1.8 - 4.5	Linear, inverted linear, and artificial neural network models based on two Month training data tried.	0.66[a]
Collier-Oxandale et al., 2018	Figaro TGS 2600	1.8 - 5	Linear and inverted linear models.	0.6 to 0.8[a]
van den Bossche et al., 2017	Figaro TGS 2611-E00	2 - 9	Linear models. Accuracy of 0.8-2.7 ppm.	No R^2 reported.
This study	NGM 2611-E13	2 - 719	Multiple models tested (see Table 1 and 2).	0.51-1.00 all models considered

[a] The highest reported R^2 values selected.

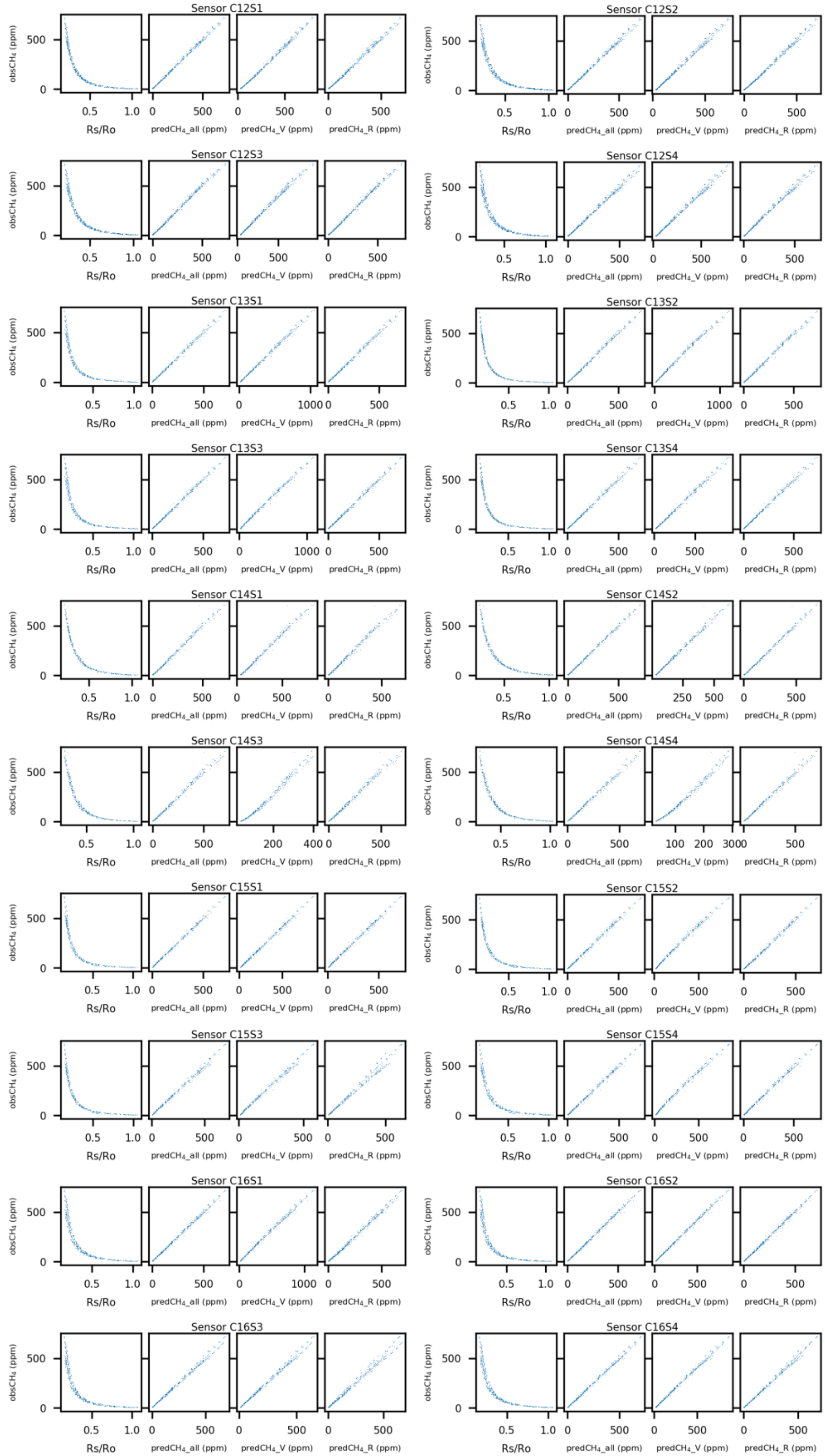
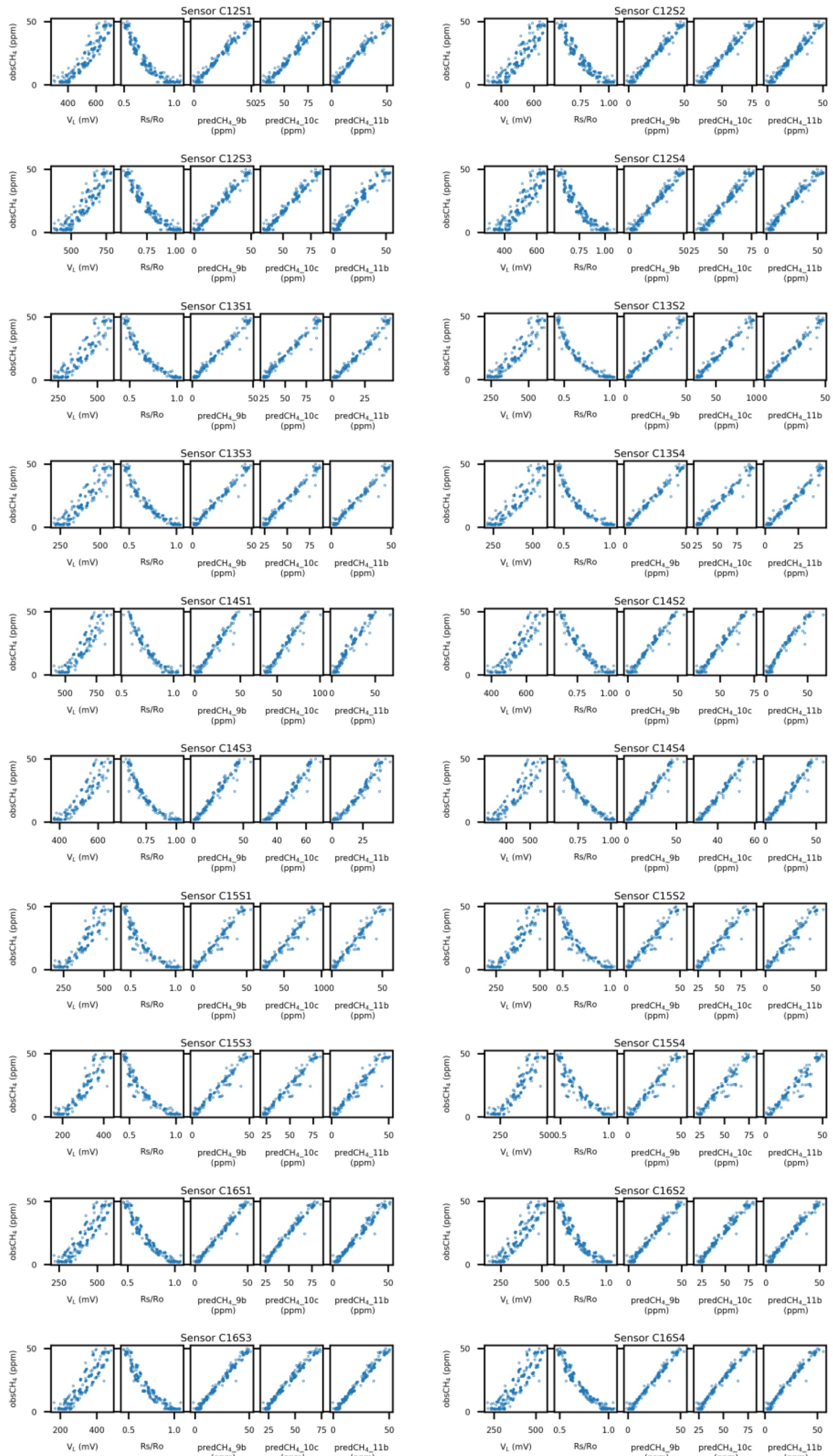


Figure S1: Observed CH_4 levels (measured by a Los Gatos instrument) versus Rs/R_0 ratio, and predicted CH_4 levels from each tested sensor. “all”, “V” and “R” for predicted CH_4 denote that parameters were estimated in different ways (Approach I, II and III, and Model 9a, 10a and 11a in Table 2, respectively; see main text for details.)

Figure S2: Observed CH_4 levels (measured by a Los Gatos instrument) versus sensor output (V_L), *Rs*/*R₀* ratio, and predicted CH_4 levels from each tested sensor at CH_4 mole fractions < 50 ppm. Results from three calibration models representing Approach I, II and III (model 9b, 10c, and 11b in Table 2, respectively) are shown.



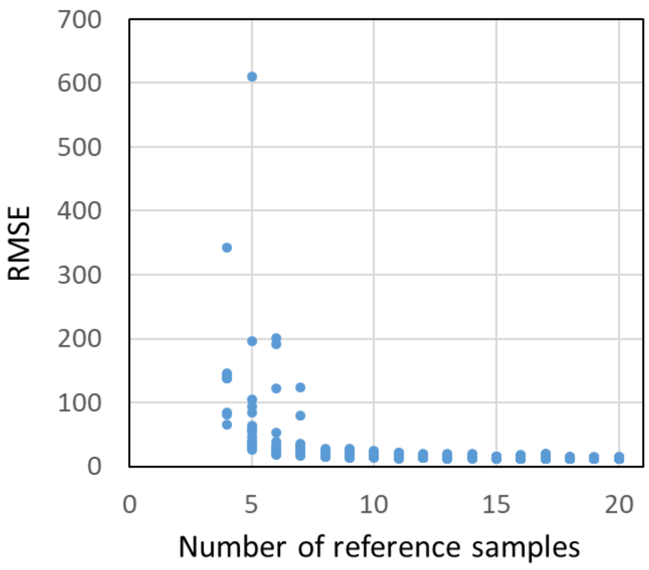


Figure S3: Root mean square error (RMSE) obtained during Monte Carlo simulations in the simplified calibration Approach III, using 4-20 reference samples above the atmospheric background level. See text for details.

Example of an Arduino controlled CH_4/CO_2/RH/T logger

Read first

Please note that this description is intended as an example to give inspiration and facilitate extended use for greenhouse gas measurements. What is described below has been working for us but small differences in electronic components among brands or even batches, may generate a need of modifications, so we cannot guarantee full functionality based on this description. Users should be prepared for some own development time and trouble shooting. The authors are interested in learning from issues and improvements and would appreciate communication with users to the extent time allows.

Hardware setup

The parts list is given in Table S2 and the wiring is illustrated in Figure S3. The total material cost in Sweden, November 2019, was in the order of 200 Euro. We made a small interface board to which the CH_4 and DHT (measure *RH* and *T*) sensors were soldered (Figure S3). This interface board was on one side attached to the CO_2 sensor via a connection and on the other side to the cable via another connector. The other end of the cable was attached to the Arduino via connectors soldered onto the SD card logger board. This setup provides capacity to measure humidity and temperature both by the DHT sensor and by the humidity sensor on the CO_2 sensor board – a setup described to give the option to exclude the CO_2 sensor if only CH_4 is of interest, and to have backup measurements as humidity is critical to interpret the CH_4 sensor data. Details regarding the Arduino and the logger shield can be found at https://store.arduino.cc/arduino-uno-rev3 and https://learn.adafruit.com/adafruit-data-logger-shield).

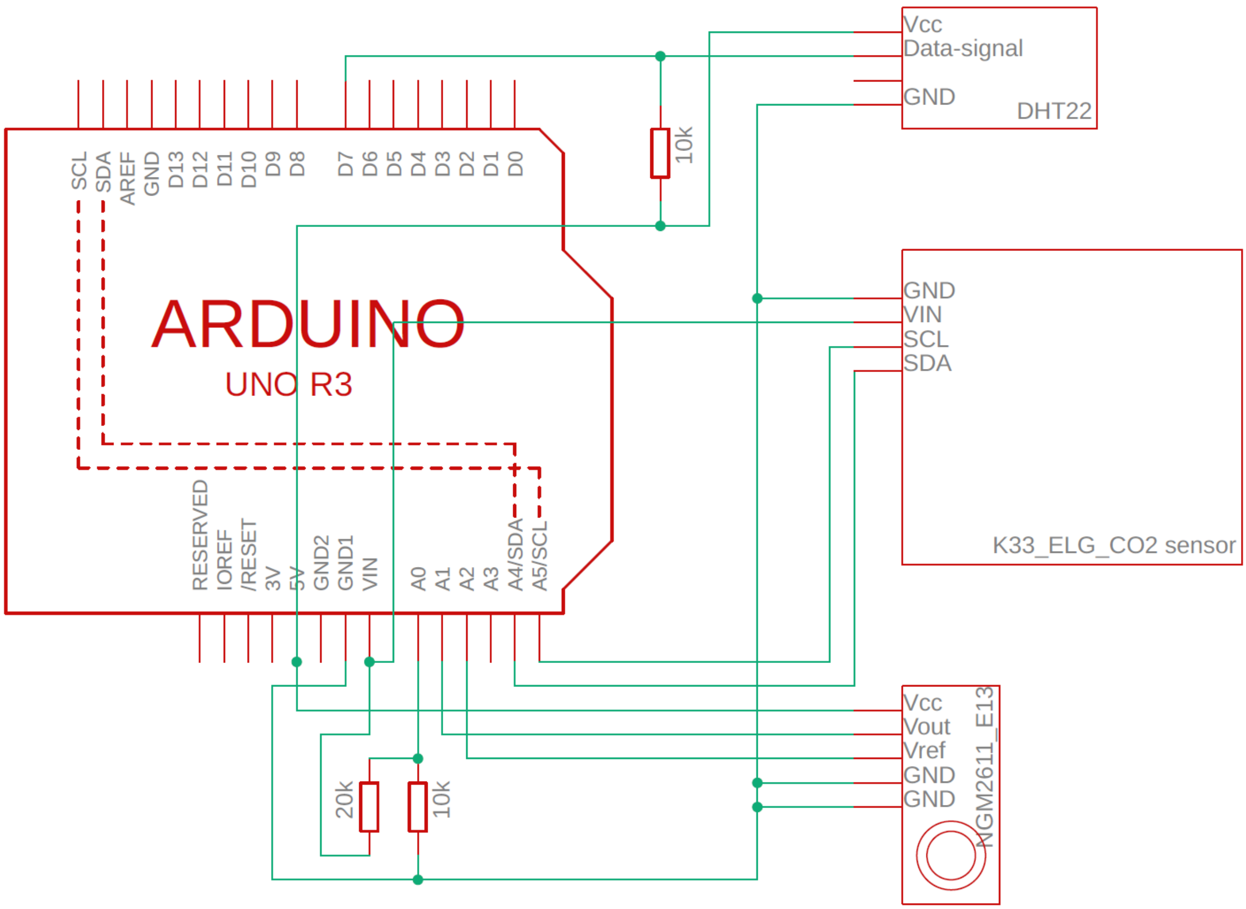


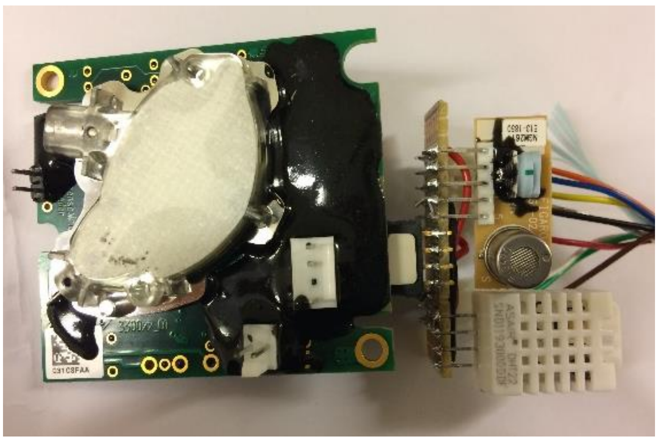
Figure S5. Wiring diagram for the CH_4/CO_2/RH/T logger described here. See detailed information about the CO_2 sensor board at www.senseair.com.

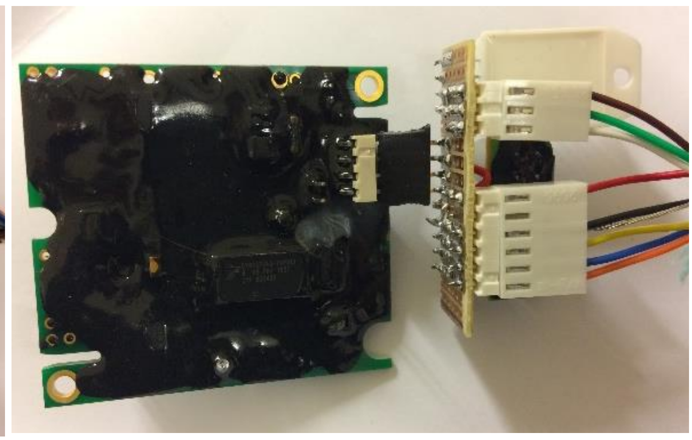
Table S3. Parts used to make the CH_4/CO_2/RH/T logger described here.

Type	Part	Brand	MFG Part No	Qty
Processors	Arduino Uno Rev3 SMD; www.arduino.cc/en/Guide/ArduinoUno	Arduino	A000073	1
Datalogging	Assembled Data Logging shield; www.adafruit.com/product/1141	Adafruit	1141	1
	SD Memory Card 2 GB; www.elfa.se/Web/Downloads/et/_1/Transcend_TS2GSDC_Datasheet_1.pdf?pid=11074864	Transcend	TS2GSDC	1
Sensors	Methane Sensor Module; www.figarosensor.com/product/entry/ngm2611.html	Figaro	NGM2611-E13	1
	DHT22 Temperature Humidity sensor; www.adafruit.com/product/385	Adafruit	385	1
	K33 ELG Carbon dioxide sensor; www.senseair.com/products/flexibility-counts/k33-elg/	Senseair	033-8-0007	1
Cable	Data Cable PVC 8x 0.22mm²; 1.5m used here.	Alpha Wire	6300/8 SL005	1.5m
Connector	KK 254 Through-Hole PCB Header, Straight, 3 Contact, 1 Row, 2.54mm Pitch	Molex	22-23-2031	2
	KK 254 Through-Hole PCB Header, Straight, 6 Contact, 1 Row, 2.54mm Pitch	Molex	22-23-2061	2
	KK 254, Receptacle Housing, 3 Pole, 1 Row, 2.54mm Pitch	Molex	22-01-3037	2
	KK 254, Receptacle Housing, 6 Pole, 1 Row, 2.54mm Pitch	Molex	22-01-3067	2
	Crimp Terminal, Female, Tin, 22-30AWG	Molex	0850-0032	16
Breakboard	Prototyping Board Phenol Hard-Paper FR2	Rade-macher	790-5	1

Software

An Arduino code was developed by combining and adapting publicly available information from sensor producers and the generous open source Arduino community contributions on internet. The code is available at http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-162780. For information on basic Arduino software use, there are many excellent open source tutorials on the internet.





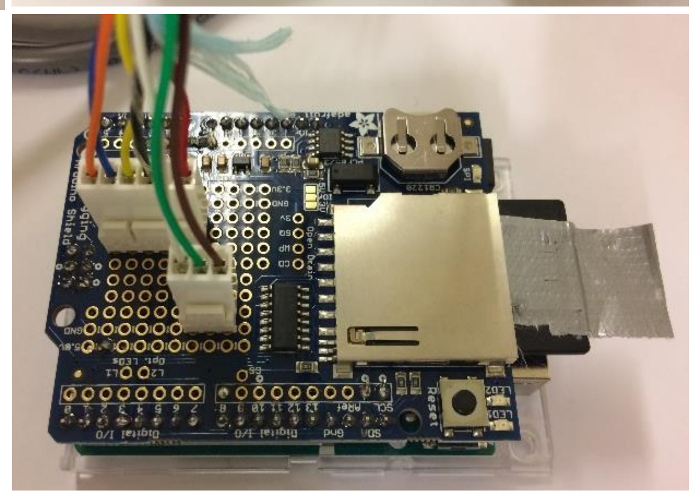


Figure S6. Photos of the prototype CH_4/CO_2/RH/T logger described here. Upper left and right panels show the sensors (front and back, respectively). Lower right panel show the logger shield on top of the Arduino unit.

Power supply

The CH_4/CO_2/RH/T logger described here was primarily tested and calibrated using 12V power supply or acid lead battery of 12V and 7Ah with a solar panel. For about 8h measurement, it is possible to use a set of two 9V batteries (connected in parallel) or 8 AA batteries using battery holder. A risk of using such small sets of battery is that the CH_4 sensor signal may be less stable (more noisy), but the system still works. Note that with our setup, there is no error indication or alarm, when battery is low.

General use

1. Load the software onto the Arduino board.
2. Connect the sensors with the controller and logger boards. The measurement cell of the CO_2 sensor (white part) should be facing the same direction as the methane sensor.
3. Insert the SD card to the SD card holder (logger shield on the Arduino board).
4. Connect the power source via the power cable.
5. Connect the power cable to the main board and **NOTE THE REAL CLOCK TIME**. This is important as the logger real time clock and associated time stamps logged is not always reliable and may be drifting.
6. The main board should now start, and a LEDs should be blinking every 2 seconds (or other selected interval) when data is logged to the SD card.
7. After about one minute, the CO_2 sensor LED in the measurement cell should start blinking (visible through the white membrane).
8. The CO_2 sensor LED will keep blinking once per minute (or at other selected time intervals for CO_2 measurements).
9. To turn off the device, unplug the power cable from the main Arduino board. Again **NOTE THE REAL CLOCK TIME to enable drift correction.**
10. Download the data to computer, and reformat the SD card using SD formatter program before using again to minimize the risk of time stamp recording errors.