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Supplement of

Assessing the spatial and temporal variability of greenhouse gas emissions from different configurations of on-site wastewater treatment system using discrete and continuous gas flux measurement

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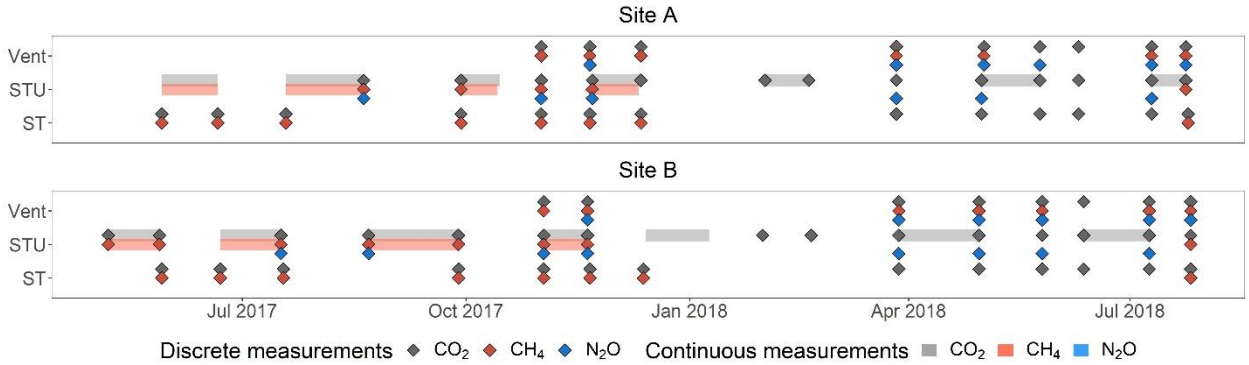


Figure S1. Overview of sampling strategy used in this study. Diamonds mark days where discrete spot measurements were performed and lines mark periods of time where continuous measuring setups were deployed for CO_2 (grey), CH_4 (red) and N_2O (blue).

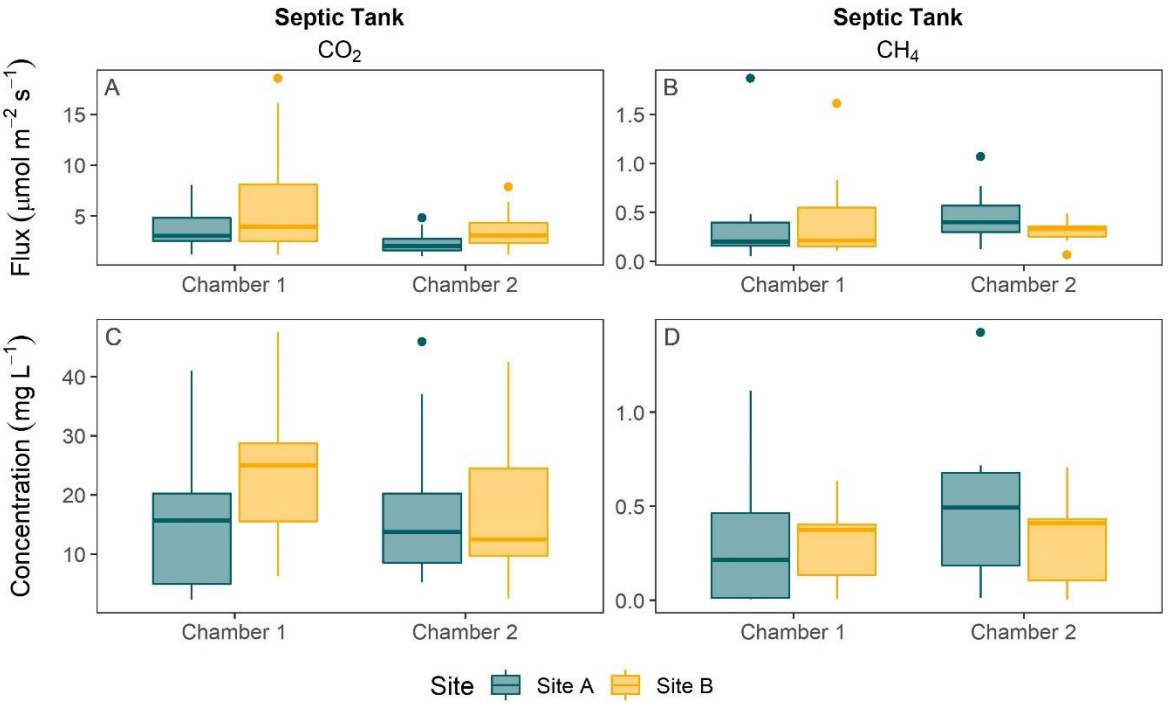


Figure S2. Boxplot of the distribution of observed CO_2 and CH_4 fluxes (panel A and B) and dissolved CO_2 and CH_4 concentrations (panel C and D) from the septic tank chambers for both sites.

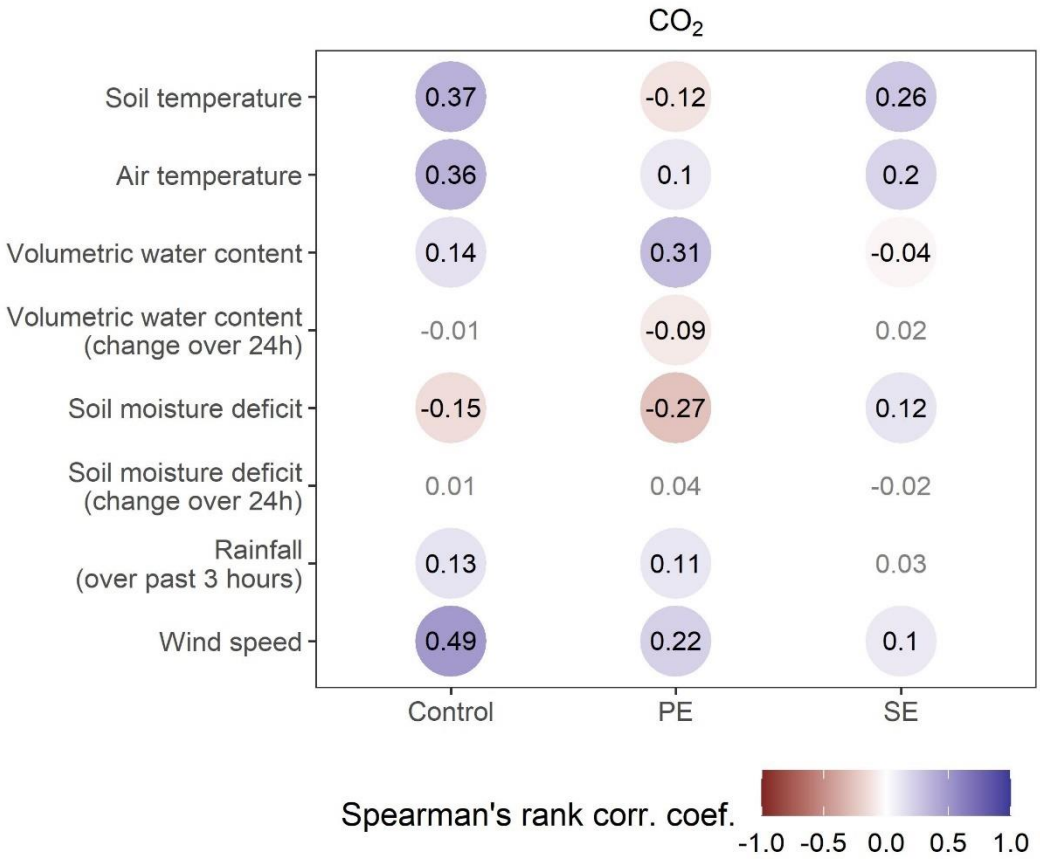


Figure S3. Correlograms of observed fluxes over the STU for CO_2 to selected environmental parameters during drought conditions in the summer 2018. The numerical value and fill color correspond to Spearman's rank correlation coefficient where the correlation was significant (i.e., $p \leq .05$). Grey numerical values without colored circles represent correlations that were not significantly different from zero (i.e. $p > .05$).

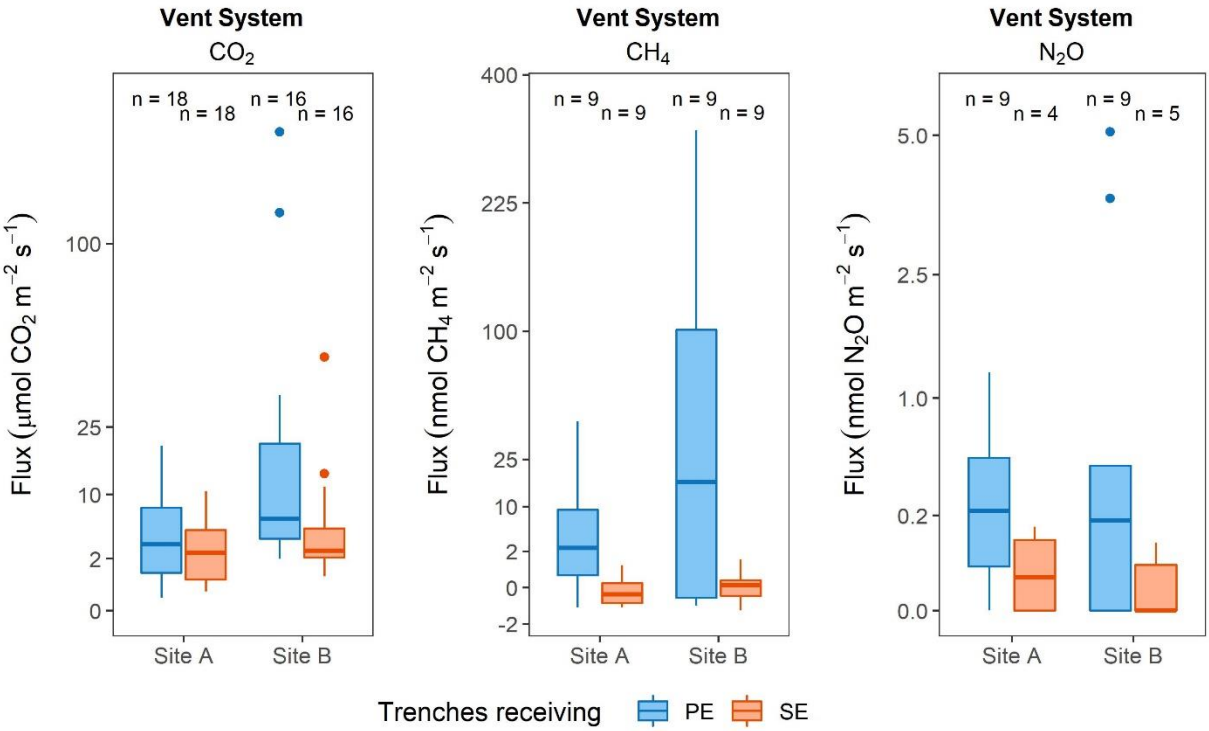


Figure S4. Boxplots of observed gas fluxes from the STU vent system for CO_2, CH_4 and N_2O over trenches receiving primary (PE) and secondary (SE) effluent for both sites. Statistical results are presented as p-value of Wilcoxon signed rank tests with estimated effect size r and corresponding boot-strapped 95% confidence intervals; n denotes the number of observations per group. Note that the y-scale for CO_2 is given in units different from units used for CH_4 and N_2O and that the y-axis has been square-root transformed to improve data visualisation.

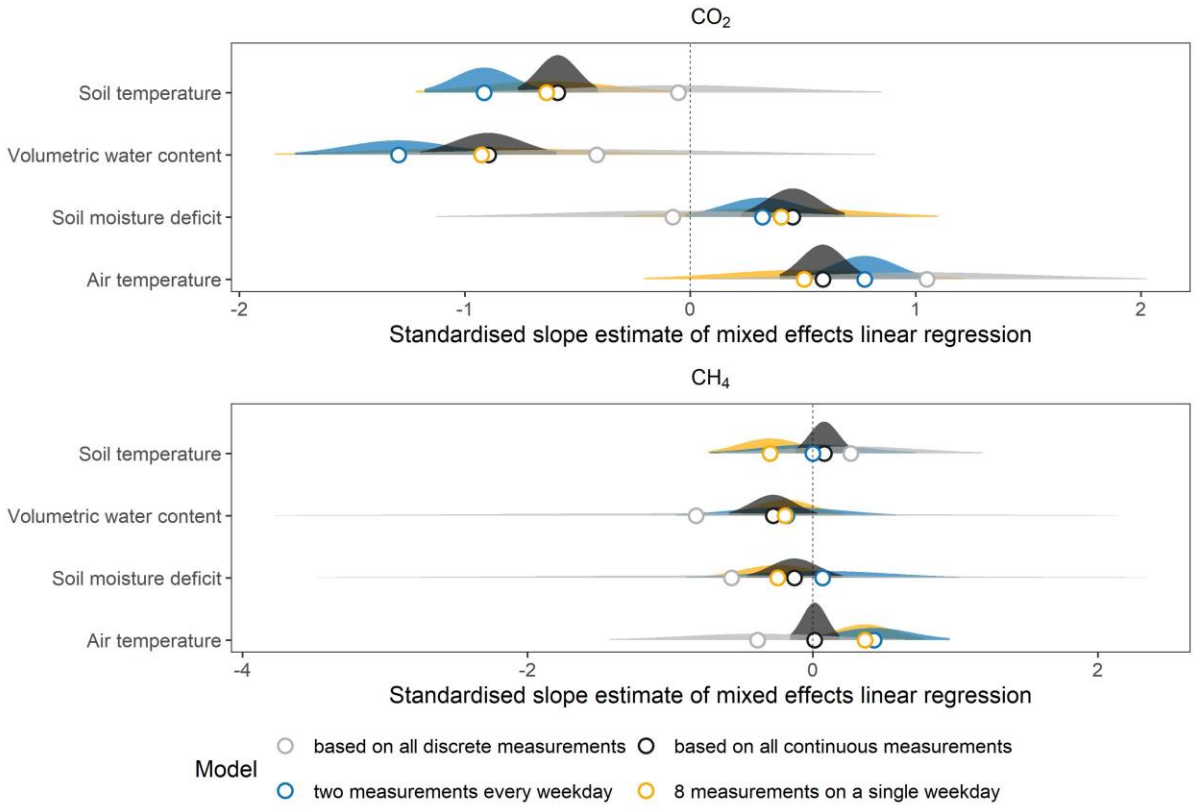


Figure S5. Comparing parameter estimation results of linear mixed effects (LME) models run on the full dataset of continuous (dark grey) and discrete (light grey) measurements with two reduced datasets representing strategies for sparse sampling during the day but on several consecutive days (blue) and sampling more frequent during the day on fewer overall days (yellow). The dots represent the parameter point estimate of the respective model; the area represents the density distribution of the parameter estimate and is horizontally restricted to 95% confidence intervals.

Table S1. Summary statistics for observed GHG fluxes from discrete measurements (n, number of observations; CI, bootstrapped 95% confidence interval around the median).

Module	Gas	Location	n	Min	Max	Median	CI	Unit
ST	CO_2	Ch 1	25	1.18	18.52	3.50	[2.55; 5.38]	μmol m^{-2} s^{-1}
		Ch 2	26	1.02	7.85	2.63	[1.98; 3.29]	μmol m^{-2} s^{-1}
	CH_4	Ch 1	15	0.05	1.86	0.21	[0.16; 0.48]	μmol m^{-2} s^{-1}
		Ch 2	16	0.06	1.07	0.34	[0.29; 0.42]	μmol m^{-2} s^{-1}
STU	CO_2	Control	109	0.35	15.56	3.06	[2.51; 3.62]	μmol m^{-2} s^{-1}
		PE	276	0.13	18.36	3.00	[2.70; 3.38]	μmol m^{-2} s^{-1}
		SE	277	0.12	18.15	2.73	[2.40; 3.04]	μmol m^{-2} s^{-1}
	CH_4	Control	52	-3.36	0.01	0.00	[-0.01; 0.00]	nmol m^{-2} s^{-1}
		PE	128	-8.01	852.9	0.00	[0.00; 0.00]	nmol m^{-2} s^{-1}
		SE	130	-3.31	437.4	0.00	[0.00; 0.00]	nmol m^{-2} s^{-1}
	N_2O	Control	11	-0.38	0.27	-0.02	[-0.06; 0.03]	nmol m^{-2} s^{-1}
		PE	15	-0.38	0.29	0.05	[0.01; 0.09]	nmol m^{-2} s^{-1}
		SE	19	-0.63	0.35	0.06	[-0.02; 0.08]	nmol m^{-2} s^{-1}
Vent	CO_2	PE	34	0.12	170.15	4.91	[2.69; 7.61]	μmol s^{-1}
		SE	34	0.27	47.75	2.58	[2.07; 3.88]	μmol s^{-1}
	CH_4	PE	23	-0.60	318.0	2.59	[0.23; 11.0]	nmol s^{-1}
		SE	18	-0.80	1.2	-0.06	[-0.23; 0.05]	nmol s^{-1}
	N_2O	PE	13	0.04	5.07	0.41	[-0.02; 0.49]	nmol s^{-1}
		SE	4	0.05	0.16	0.10	[0.00; 0.10]	nmol s^{-1}

Table S2. Summary statistics for observed discrete GHG fluxes from the ST surface, split by site (n, number of observations; CV, coefficient of variation).

Site	Gas	Chamber	n	Min	Max	Median	Unit	CV
Site A	CO_2	1	13	1.22	8.05	3.06	μmol m^{-2} s^{-1}	0.55
		2	13	1.02	4.81	2.02	μmol m^{-2} s^{-1}	0.47
	CH_4	1	8	0.05	1.86	0.20	μmol m^{-2} s^{-1}	1.38
		2	8	0.12	1.07	0.40	μmol m^{-2} s^{-1}	0.63
Site B	CO_2	1	12	1.18	18.52	3.93	μmol m^{-2} s^{-1}	0.95
		2	13	1.15	7.85	3.27	μmol m^{-2} s^{-1}	0.55
	CH_4	1	7	0.11	1.61	0.21	μmol m^{-2} s^{-1}	1.17
		2	8	0.06	0.49	0.33	μmol m^{-2} s^{-1}	0.41

Table S3. Summary statistics for observed GHG fluxes from the ST during continuous diurnal measurements, split by site (n, number of observations; CV, coefficient of variation).

Site	Gas	Chamber	n	Min	Max	Median	Unit	CV
Site A	CO_2	2	284	1.99	14.14	3.81	μmol m^{-2} s^{-1}	0.49
	CH_4	2	280	0.12	7.51	1.17	μmol m^{-2} s^{-1}	0.68
Site B	CO_2	2	220	3.79	7.08	5.83	μmol m^{-2} s^{-1}	0.13
	CH_4	2	220	0.22	0.78	0.28	μmol m^{-2} s^{-1}	0.19

Table S4. Summary statistics for observed dissolved GHG concentrations in the ST (n, number of observations; CV, coefficient of variation).

Site	Gas	Chamber	n	Min	Max	Median	Unit	CV
Site A	CO_2	1	9	2.33	40.99	15.70	mg L^{-1}	0.77
		2	9	5.22	45.87	13.76	mg L^{-1}	0.76
	CH_4	1	8	0.00	1.11	0.21	mg L^{-1}	1.28
		2	8	0.01	1.42	0.49	mg L^{-1}	0.87
Site B	CO_2	1	6	6.32	47.45	25.00	mg L^{-1}	0.59
		2	6	2.49	42.48	12.50	mg L^{-1}	0.83
	CH_4	1	6	0.00	0.64	0.37	mg L^{-1}	0.77
		2	6	0.00	0.70	0.41	mg L^{-1}	0.83

Table S5 Summary statistics for observed GHG fluxes from continuous measurements on the STU (n, number of observations; CI, bootstrapped 95% confidence interval around the median).

Gas	Location	n	Min	Max	Median	CI	Unit
CO_2	Control	5452	0.14	22.20	5.10	[5.03; 5.19]	μmol m^{-2} s^{-1}
	PE	14311	0.01	26.73	2.17	[2.13; 2.22]	μmol m^{-2} s^{-1}
	SE	14393	0.08	34.03	2.10	[2.05; 2.16]	μmol m^{-2} s^{-1}
CH_4	Control	1478	-5.12	90.12	-0.42	[-0.43; -0.41]	nmol m^{-2} s^{-1}
	PE	2534	-5.15	91.50	-0.30	[-0.32; -0.27]	nmol m^{-2} s^{-1}
	SE	1801	-3.75	35.27	-0.37	[-0.39; -0.36]	nmol m^{-2} s^{-1}

Table S6. Summary statistics for observed daily median CO_2 fluxes from continuous measurements over the STU before and during the extended drought conditions in summer 2018 (n, number of observations; CI, bootstrapped 95% confidence interval around the median).

Time	Location	n	Min	Max	Median	CI	Unit
pre-drought	Control	30	2.42	7.49	4.52	[4.11; 5.07]	μmol m^{-2} s^{-1}
	PE	30	0.74	2.67	1.76	[1.47; 1.90]	μmol m^{-2} s^{-1}
	SE	30	1.16	7.49	3.84	[3.12; 4.88]	μmol m^{-2} s^{-1}
drought	Control	28	5.81	9.99	7.23	[6.86; 7.50]	μmol m^{-2} s^{-1}
	PE	28	3.18	7.91	7.91	[5.03; 5.82]	μmol m^{-2} s^{-1}
	SE		2.97	7.92	4.93	[4.63; 5.36]	μmol m^{-2} s^{-1}

GHG measurements from ST

Two different methods were used to measure CO_2 and CH_4 gas fluxes; (i) discrete survey measurements carried out manually whist on site and (ii) diurnal measurements carried out by automated long-term flux chambers. Additional to the flux measurements, water samples were collected to estimate the dissolved CO_2 and CH_4 concentrations.

GHG flux measurements

In order to measure GHG fluxes from the water surface of ST, a sampling setup was adopted from (Leverenz et al., 2010), where a collar was placed in to the septic tank to hold the chamber and create a gas loop between the water surface and gas analyser during measurements. This collar was composed of a rigid PVC pipe (inner diameter 20:3 cm, outer diameter 21:3 cm O.D. and length 19 cm) and supported by three legs (length 210 cm) going to the bottom of the tank, see Figure 1. The collars were placed such that they extended from beneath to above the water level of the ST, see Figure 1b. These inserts were left in place for the duration of the experiment to prevent disturbance in the septic tank.

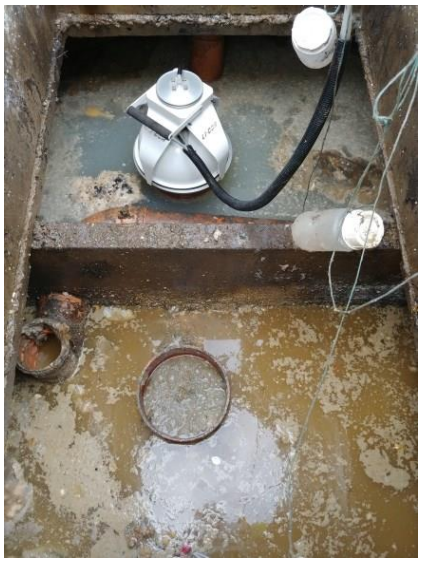
A survey chamber (LI-8100-103 20 cm Survey Chamber, LI-COR Biosciences, Inc.), that was connected to an analyser control unit with two sets of Li-Cor extensions (length: 15 m), was lowered down to the collar in the ST. The lids of the ST was opened in each compartment. One set of the extensions connected the gas lines, the other set of extensions was controlling the survey chamber and providing the gas channel for lowering down and lifting up the survey chamber over the collar between measurements. A pressure/vacuum air ow system expands and contracts a bellows to raise and lower the chambers over a soil collar to make the flux measurement. CO2 fluxes were measured by the non-dispersive infrared CO_2 gas analyser unit of an automated soil gas flux system (LI-8100 Automated Soil CO_2 Flux System, Li-Cor), see Appendix B. In order to measure CH4 fluxes as well, this CO2 flux system was extended with an additional gas analyser (UGGA Ultraportable Greenhouse Gas Analyser, model 915-0011, manufactured by Los Gatos Research). At the occasions when Los Gatos analyser was available, its gas inlet port was connected with the Li-Cor analyser unit outlet port and the gas outlet from the Los Gatos was connected to gas port of the extension going to the survey chamber. During these ux incubations, that were at least 3 minutes of duration, changes in CO2 and CH4 concentrations were observed - increase in concentrations indicating emission.

Dissolved GHG concentrations

Dissolved GHG concentrations were measured using the headspace method (Hope et al., 1995) and UGGA (Ultra-Portable GGA, model 915-0011, Los Gatos Research). 100 ml water samples were collected in a 250 ml glass bottle, the bottle was sealed with the cup and

attached and inlet and outlet pipe. The pipes were directly connected to the UGGA, the analyser bubbled out the dissolved gases to enable the equilibrium concentration of the gases in the bottle system to be measured, see Figure 2.

(a)



(b)

Figure 1. Left, stand with the collar that was inserted into the ST. Right, deployment of the survey chamber over the ST.

Figure 2. Bubbling water samples to measure dissolved gas concentration of CH_4 and CO_2.

GHG from vent system

The GHG fluxes were measured from venting system outlets at KM and CC sites at end of each trench. The venting systems were sealed to ensure that the normal air ow was not disturbed. A sampling device (Vent Wizard 800) was constructed from a PVC slip cap and a threaded pipe adapted to fit the cleanout ports, see Figure 3. One port was placed in the slip cap to allow for gas sampling, this port was connected to the UGGA analyser. Air velocity and temperature were also measured in the venting system using a hotwire anemometer (LU8050, TQC Sheen, The Netherlands).

Figure 3. (a) sampling GHG fluxes from the vent system outlet with Vent Wizard 800 (b) deployment of anemometer.

Flux estimation using non-linear regression

Soil CO_2 fluxes F [$\mu molCO_2 m^{-2} s^{-1}$] were calculated using SoilFluxPro 4.0 (LI-COR Biosciences, Inc.), which implements a mass balance approach as,

$$F = \frac{V_{cham}\, p_0 (1 - \chi_w)}{RsT_0} \frac{\delta \chi_c(t)}{\delta t}$$

using the volume of the chamber V_{cham} [m^3], the atmospheric pressure at the beginning of the measurement p_0 [P_a], the chamber air water vapor mole fraction χ_w [mol mol^{-1}], the universal gas constant R [$P_a\ m^3 K^{-1} mol^{-1}$], the soil collar surface area s [m^2], the absolute temperature at the beginning of the measurement $T0$ [K], and the initial change of chamber water vapor corrected CO_2 mole fraction $\delta\chi_c/\delta t$ [µmol $mol^{-1} s^{-1}$] (LI-COR, 2012). $\chi_c(t)$ was calculated using an empirical exponential regression model which is fit to the measured CO_2 concentration data,

$$\chi_c(t) = (\chi_0 - \chi_x) e^{-a(t - t_0)} + \chi_x$$

with the initial water vapor corrected CO_2 mole fraction χ_0 [mol mol^{-1}], and fit parameters χ_x [mol mol^{-1}] and a [s^{-1}]. The fit is used to derive the initial change of chamber water vapor corrected CO_2 mole fraction as the slope of the fit at the time of chamber closure. A non-linear model was chosen in order to reduce the influence of chamber feedback due to increasing resistance to naturally occurring diffusion as the main driver for transport of CO_2 from the soil to the atmosphere following the increase of CO_2 mole fraction inside the chamber during measurement. For each measurement, the $R2$-value of the regressions was used as a quality control parameter and measurements with $R_2 < 0.9$ were rejected (< 0.5% of total measurements).

To compare obtained flux values with previous studies, F_c was converted to per capita mass emission rates E_{cap} [gCO_2cap^{-1}d^{-1}],

$$E_{cap} = \frac{A_{soak}\, M_{CO2}}{n} F$$

assuming a spatially uniform flux distribution and using the number of occupants n in the household, the surface area of the STU A_{STU}, and the molar mass M_{CO2} of CO_2 [44.01 gmol^{-1}] as normalization factors.