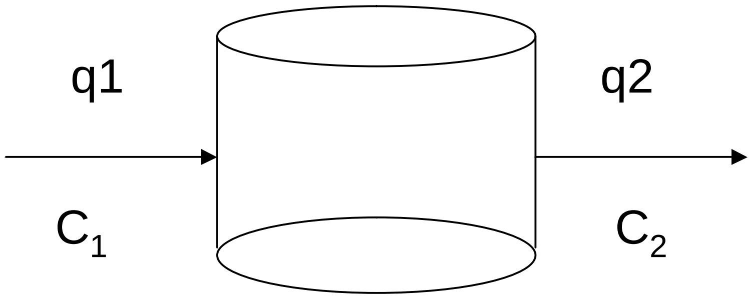
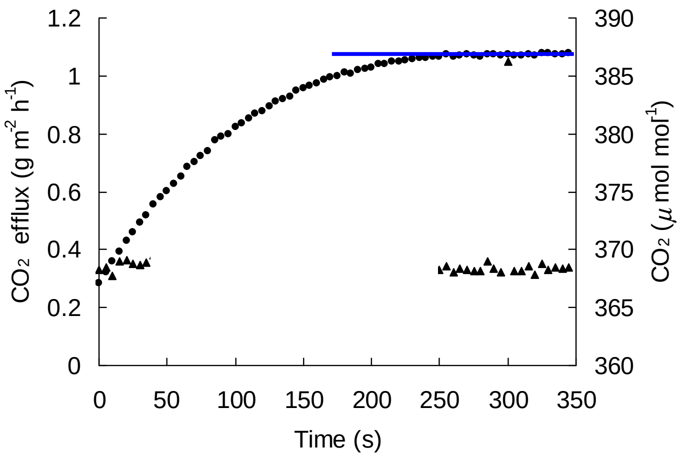
Measuring soil respiration in the field – different chamber designs

Introduction

- Earliest studies on soil respiration were conducted by incubating soil cores in laboratory (Lundegårdh 1922).
- Later a need for undisturbed and continuous measurements.
- Chambers placed over the soil is the most direct way of measuring gas exchange within the soil surface.
- A variety of chamber systems has been developed.
- No single method has emerged as preferable.

Open dynamic chambers (=Steady-state flow-through chambers)





The flux is calculated from the difference in concentrations between the air flowing at a known rate through the inlet and outlet of the chamber after the chamber headspace concentration has reached an equilibrium.

$$F = \frac{q_2 C_2 - q_1 C_1}{A}$$

where

F is gas flux

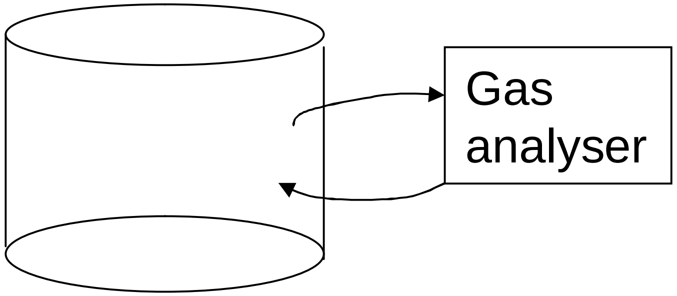
q_1 is gas flow into the chamber

q_2 is gas flow out of the chamber

C_1 and C_2 are gas concentrations in the outflow and inflow respectively

A is surface area

Closed dynamic chambers (=Non-steady state flow-through chambers)

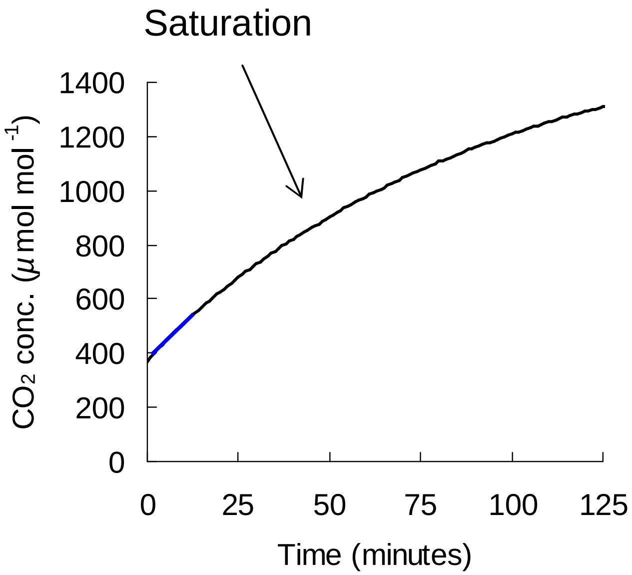


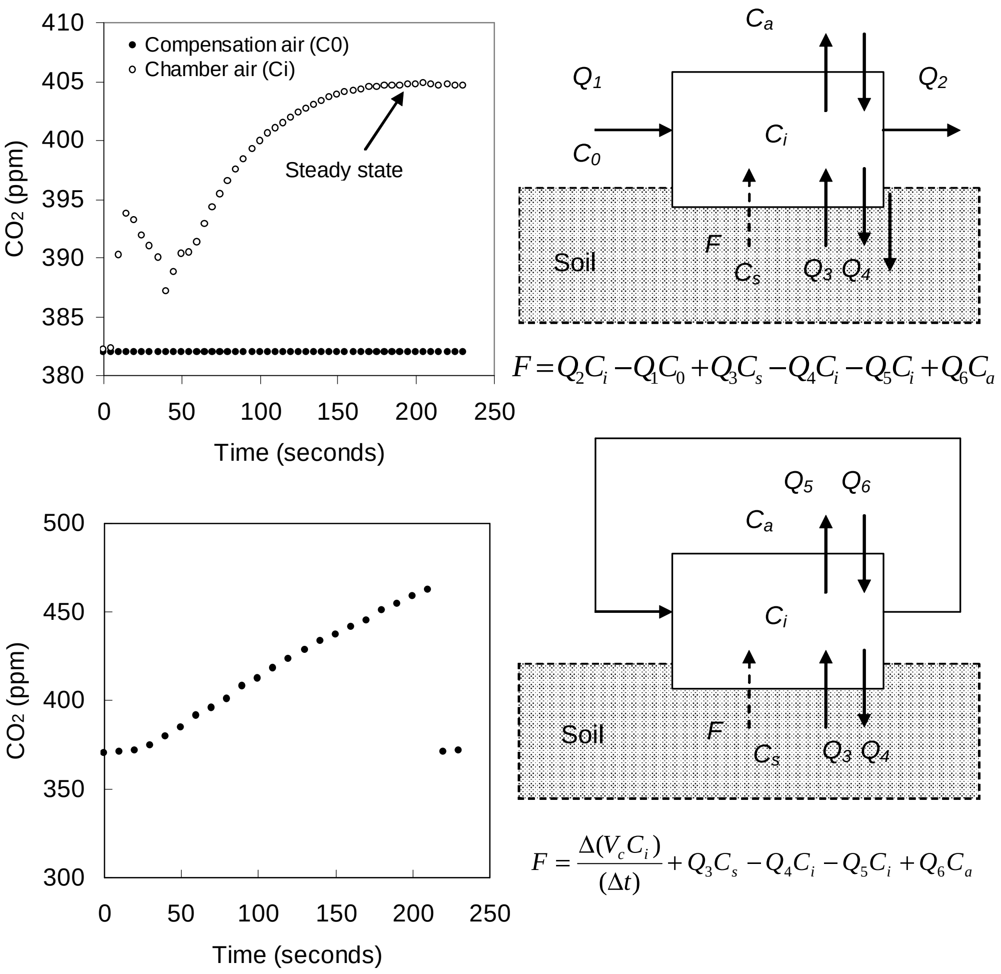
The flux is calculated from the concentration change within the chamber headspace.

$$F = \frac{d(V \cdot C)}{dt \cdot A}$$

where

F is gas flux
C is gas concentration
V is volume of the chamber
A is surface area
dt is incubation time





$$F = Q_2C_i - Q_1C_0 + Q_3C_s - Q_4C_i - Q_5C_i + Q_6C_a$$

$$F = \frac{\Delta(V_cC_i)}{(\Delta t)} + Q_3C_s - Q_4C_i - Q_5C_i + Q_6C_a$$

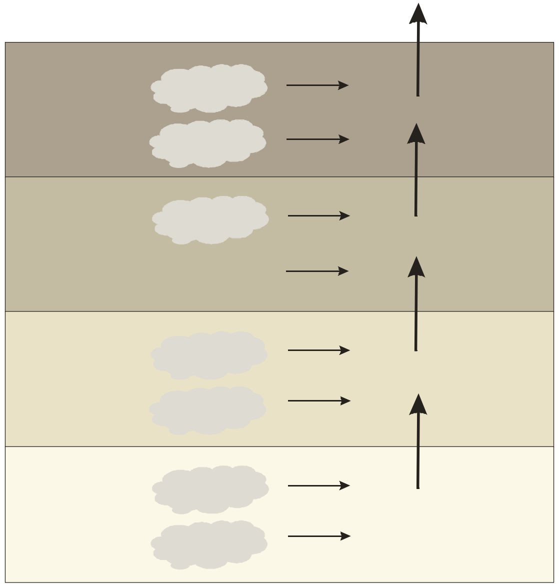
Figure 2.1. (Upper panel) The CO_2 concentration in an open chamber depends on CO_2 concentrations and flow rates of the incoming and outgoing air flows. In addition, possible air flows (Q_3 and Q_4) between the soil air space and the chamber as well as between the ambient air and the chamber (Q_5 and Q_6) can generate additional mass flow of CO_2 in an out of the chamber. When a steady-state concentration in the chamber has been reached, the CO_2 efflux from soil (*F*) can be determined from the mass balance equation shown.

(Lower panel) In a closed chamber (dynamic or static) the CO_2 efflux rate can be calculated from the slope of the CO_2 concentration increase within the chamber. Similarly, possible air flows between the soil air space and the chamber (Q_3 and Q_4) as well as between the ambient air and the chamber (Q_5 and Q_6) can generate additional mass flow of CO_2 in an out of the chamber. When designing both chamber types, air flows of type Q_3-Q_6 should be avoided.

Static chambers (Non-steady-state non-flow-through chambers)

- The CO_2 is trapped with chemicals (NaOH and soda lime)
- The concentration within the chamber remains quite stable.
- The CO_2 efflux can be calculated from the amount of CO_2 in the trapping solution.
- In some chambers, the CO_2 concentration is determined by air samples drawn into syringes and analysed separately with IR or GC. This principle is very close to that of closed dynamic chamber.

Gradient method



- CO_2 concentration in the soil air space is often an order of magnitude higher than in the atmosphere.
- According to Fick’s first law the gas flux is dependent on the concentration gradient and the diffusivity of the soil.

The gradient method: an example

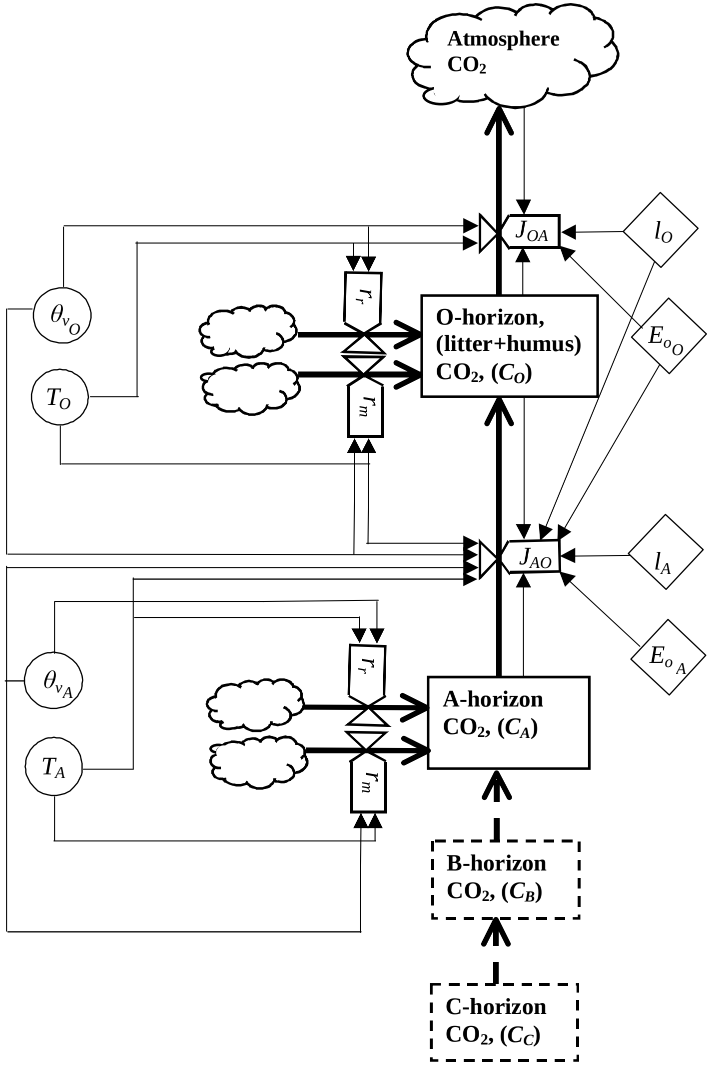
- Soil can be divided into distinct soil layers according to podzolic soil horizons.
- Gas transport in the soil is driven mainly by diffusion.

$$J_{AO} = -D_{AO}\frac{C_O - C_A}{(l_O + l_A)/2}$$

- D is the diffusion coefficient of the soil, C_O and C_A are the amounts of CO_2 in the soil air space, L is the distance between soil layers.
- Soil porosity affects the gas movement within the soil.

$$\frac{D}{D_o} = \left(\frac{E_g - u}{1-u}\right)^h$$

- E_g is the air filled porosity of soil ($m^3\ m^{-3}$) and u and h are empirical parameters, D is the diffusion coefficient of CO_2 in soil and D_0, the diffusion coefficient in air.



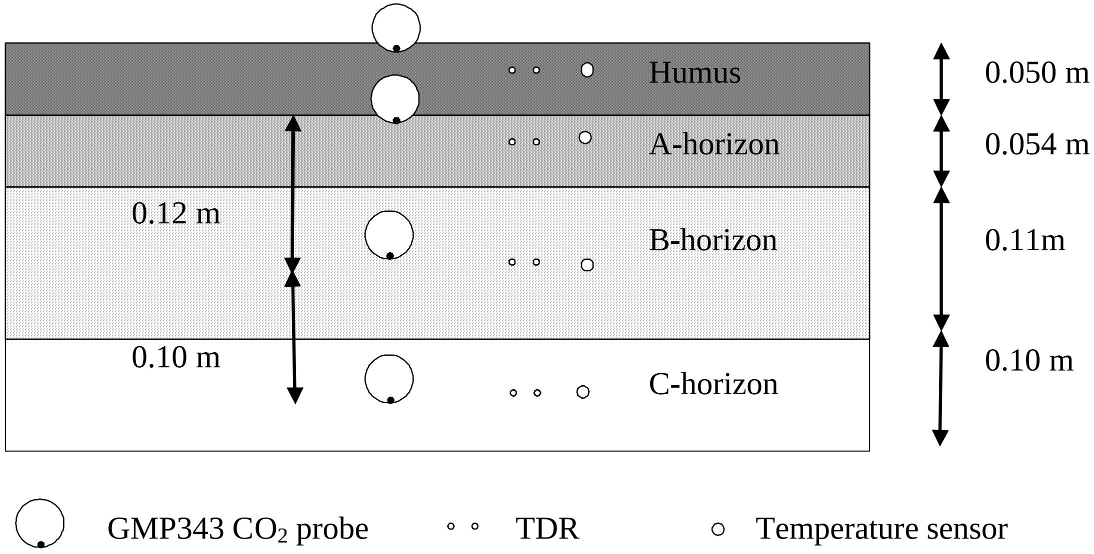
Gradient method

We installed Vaisala GMP343 CO_2 sensors in different soil horizons for determining the concentration gradient

Soil moisture was measured with TDR and soil temperature with thermistors.

Diffusion in the soil was calculated with Fick’s first law of diffusion.

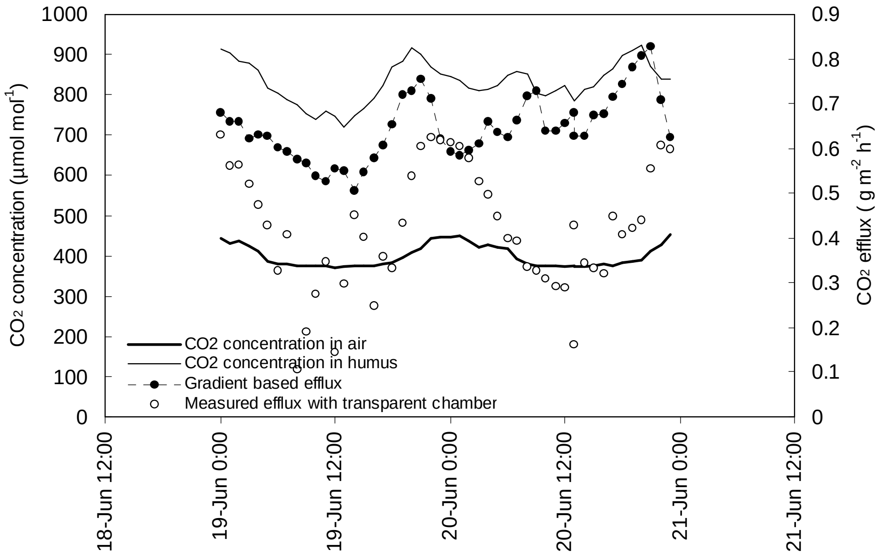
$$J_{H\_ATM} = -D_H \frac{C_{ATM} - C_H}{l_H / 2}$$

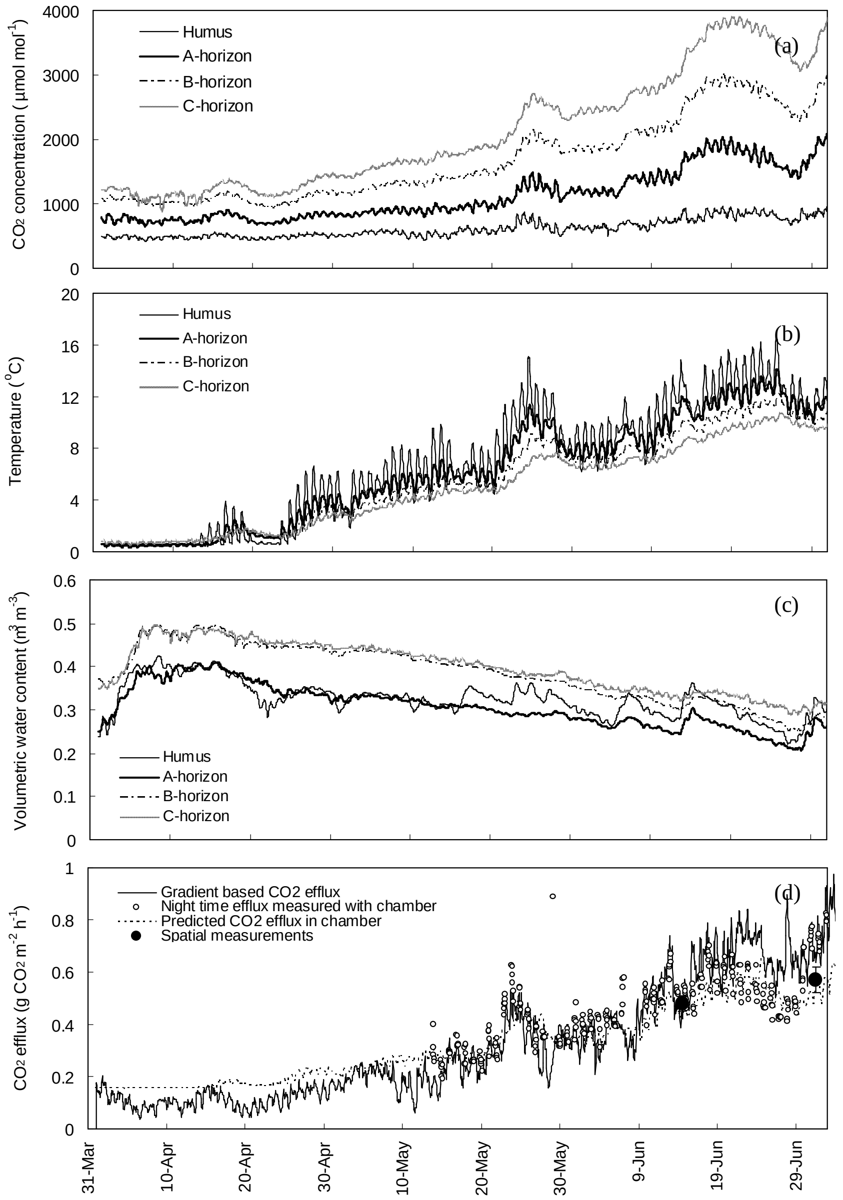


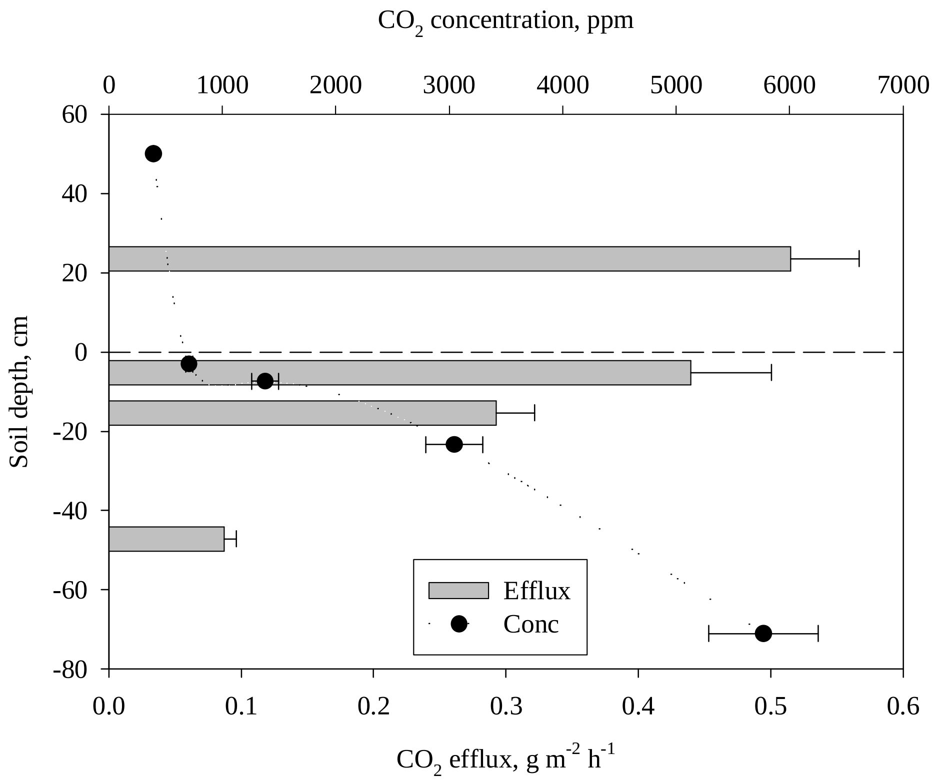
Gradient method

Soil air CO_2 concentration had a clear diurnal and seasonal pattern following soil temperature and soil moisture.

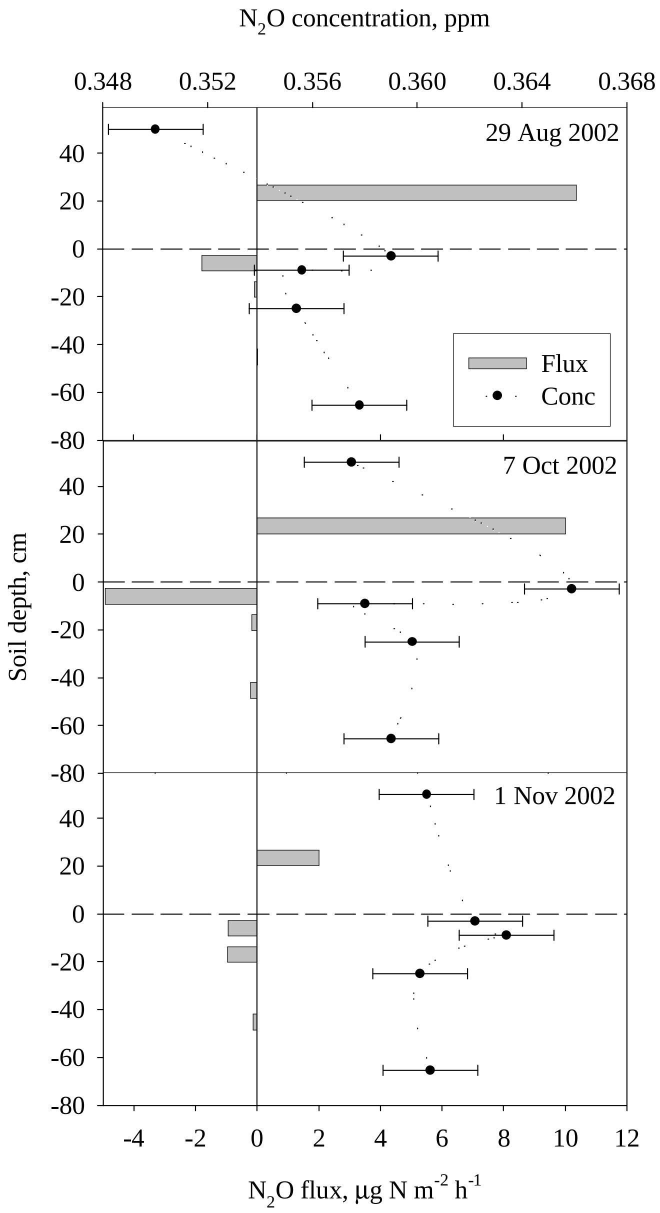
The CO_2 effluxes calculated with the gradient method matched reasonably well with the fluxes measured with chambers.







Mean soil CO_2 concentrations and CO_2 fluxes from each soil layer over all four pits and the whole measurement period 7th June 2002 – 31st July 2003.



Nitrous oxide concentration in the soil profile and N_2O fluxes from the soil in autumn 2002.

Pihlatie et al. 2007

Chambers; advantages and drawbacks

- \+ Relatively easy to use
- \+ Spatial coverage
- \+ Low cost?
- \+ Fast measurements
- \+ Can be used for measuring photosynthesis and evapotranspiration simultaneously with respiration.
- \+ Several gases can be measured simultaneously
- – Chambers affect the flux being measured (collar problem, pressure problem, saturation)
- – Chambers may change the conditions in the soil if left at the same place for a longer period of time
- – Difficult to use in winter
- – Differences between chamber types requires calibration

Gradient method; advantages and drawbacks

- \+ As soon as the soil has been stabilized after the installation, the measurement itself does not disturb the CO_2 fluxes significantly.
- \+ The source of CO_2 efflux can be estimated based on the concentration in different layers.
- \+ Gradient method has a good potential for wintertime measurements
- – Soil porosity is a critical factor when using the gradient method.
- – The diffusion coefficient of the soil is affected by the air-filled pore space as well as the continuity and shape of the pores (Glinski and Stepniewski 1985).
- – Because the diffusion of CO_2 in water is about 10000 times slower than in air, soil water content has a substantial effect on CO_2 movement.
- – Continuous soil CO_2 concentration measurements have been difficult due to the lack of robust sensors.

Commercially available systems

PP-systems SRC-1+EGM Infrared analyser (Technical specifications retrieved from PP-systems home page http:\\www.ppsystems.com)

Dimensions: 100 mm Ø x 150 mm

Weight: 900 g

Voltage: 12V

Working principle: Closed dynamic chamber without CO_2 scrubbing. CO_2 efflux is calculated from the concentration change using linear and non-linear fitting.

Air mixing: Fan inside the chamber

Water vapour correction: No

Soil temperature probe: Yes

Commercially available systems

Li-Cor 6400-09 + Li-Cor LI-6400 portable photosynthesis System

(Technical specifications retrieved from Li-Cor home page http:\\www.licor.com)

Dimensions: diameter 95 mm, volume 991 cm^3, surface area 76.1 cm^2
Weight: 1800 g
Voltage: 12V
Working principle: Closed dynamic chamber with CO_2 scrubbing. Before each cycle of flux measurement, air in the chamber headspace was scrubbed down 3-40 ppm below the ambient CO_2 concentration (depending on the flux), and was then allowed to rise as a consequence of CO_2 efflux from the tank.
Air mixing: Fan is used to push the air through a perforated manifold to distribute the air evenly withing the chamber without causing localized pressure gradients.
Water vapor correction: Available in Li-Cor 6400
Soil temperature probe: Yes

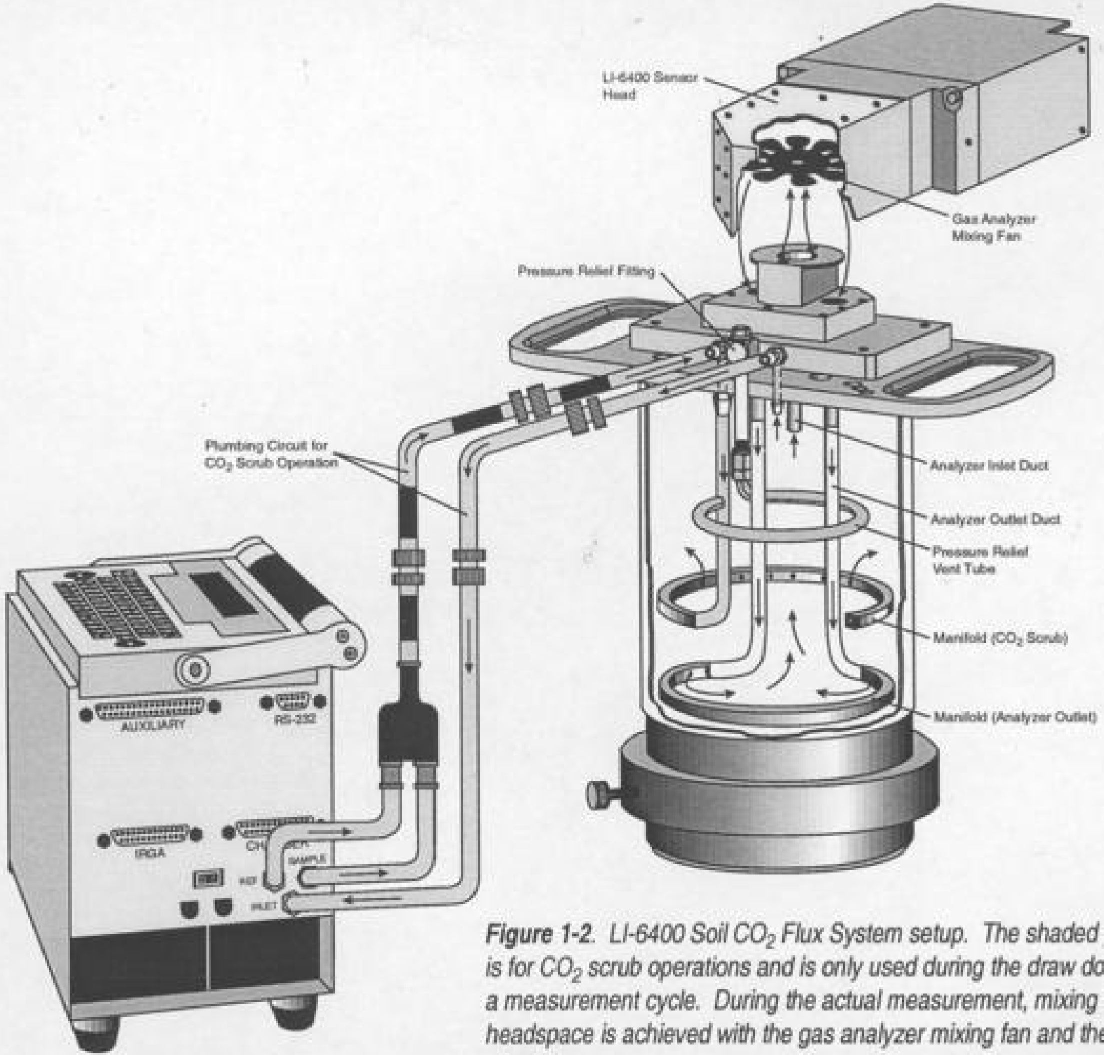
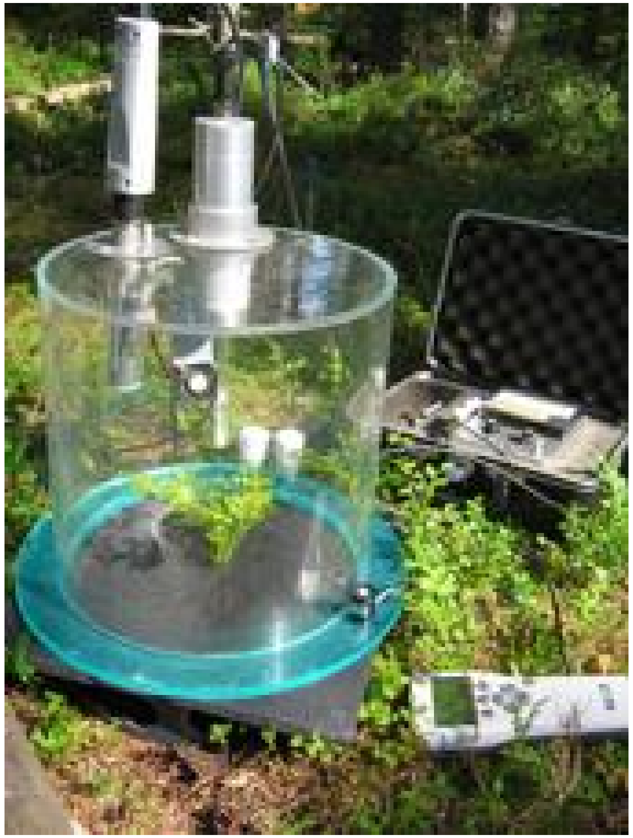


Figure 1-2. *LI-6400 Soil CO_2 Flux System setup. The shaded plumbing circuit is for CO_2 scrub operations and is only used during the draw down portion of a measurement cycle. During the actual measurement, mixing in the chamber headspace is achieved with the gas analyzer mixing fan and the associated plumbing.*

Commercially available systems



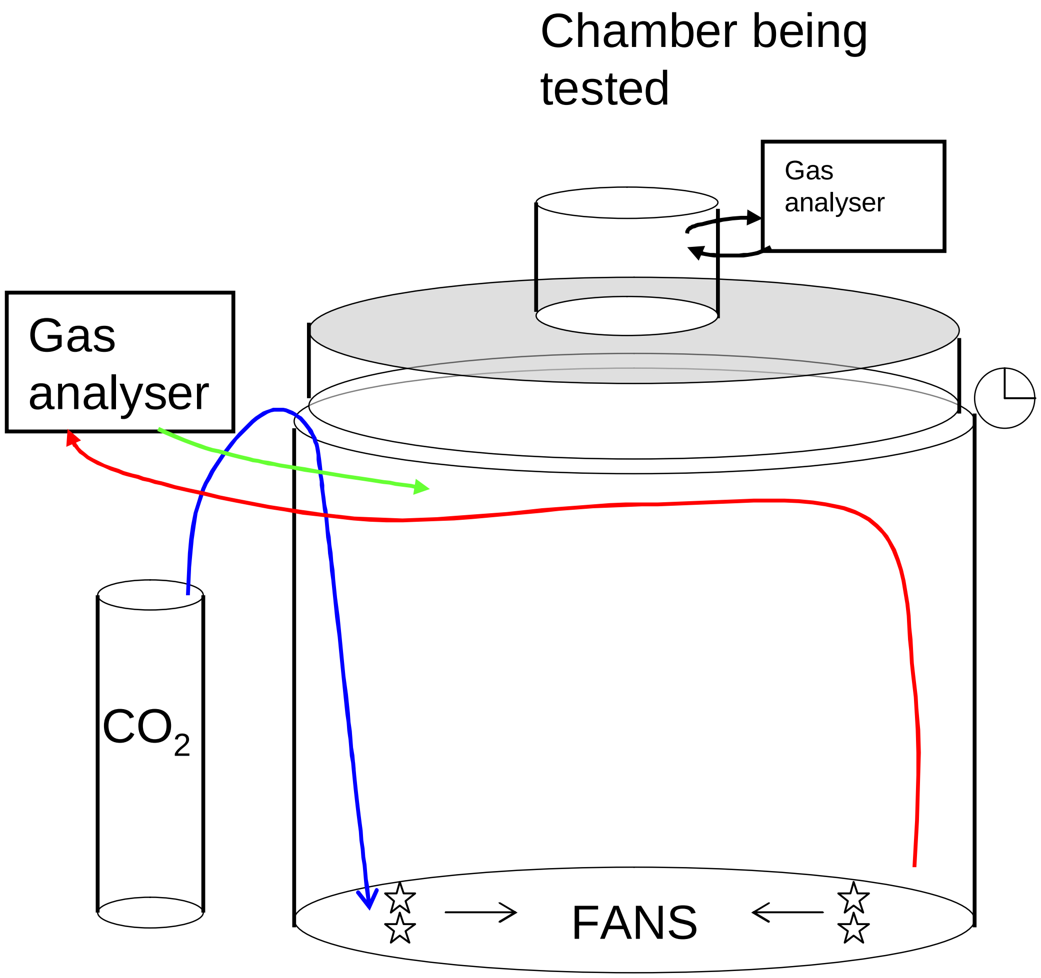
Vaisala Carbocap® Non-dispersive Infrared sensors (GMP220 series and GMP-343 series) + M70 Measurement indicator
GMP-220 series (accurracy 2% of reading) and GMP-343 series (accurracy 1.5% of reading at the calibration points, below 300 ppm ± 5 ppm)

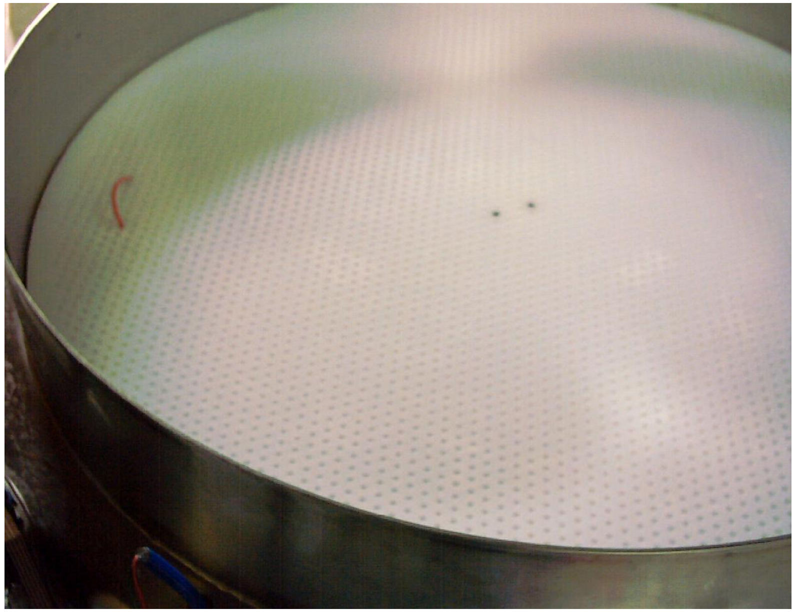
Can be connected to any chamber or installed directly in the soil. Water vapour, temperature and pressure compensations online when using external RH or pressure sensor. Oxygen compensation also available.

ADC, LCA-2, Analytical Development Company Ltd. (Hoddesdon, UK)

Calibration system

- The calibration system is modified from the system developed by Widén and Lindroth (2003).
- The calibration system consists of a steel chamber with a layer of quartz sand on top.
- CO_2 inside the chamber is monitored continuously.
- CO_2 efflux is calculated from the concentration change inside the chamber.



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- During the summer 2002 we calibrated 20 soil respiration chambers from 13 institutes across Europe and USA.
- Closed dynamic systems (=non-steady-state flow-through systems)
  - PP Systems SRC-1+ EGM-1, SRC-1+ EGM-3 and SRC-1+EGM-4
  - Li-Cor 6400-9 (Weizmann Institute of Science, Maz Planck Institute)
  - University of Bayreuth (Reth et al.)
  - Woods Hole Research Center (Savage et al.)
  - Max Planck Institute (Anthoni et al.)
  - Finnish Meteorological Institute (Lohila et al.)
  - University of Helsinki (Kolari, Minkkinen)
- Open dynamic systems (=steady-state flow-through systems) University of Bayreuth (Subke et al.)
  - Kutsch (1996)
  - University of Helsinki (Hybrid system)
- Closed static systems (=non-steady-state non-flow-through systems)
  - University of Helsinki (Pumpanen et al.)
  - University of Joensuu
  - Agrifood Finland

Calibrations

- Calibrations were carried out with dry coarse sand (0.6 mm), fine sand (0.05-0.2 mm) and fine sand with 0.25 $m^3\ m^{-3}$ water content.
- Total porosities were 47% and 53% for coarse and dry sand respectively.
  - Each chamber was calibrated with 6-7 flux rates
  - 2 replicate measurements were done on 1-3 collars with each flux level.

How the effluxes were generated?

Exponential curve was fitted to concentration and time.

Flux can be calculated from the concentration change in time

$Q = (dC / dt) * V / A$

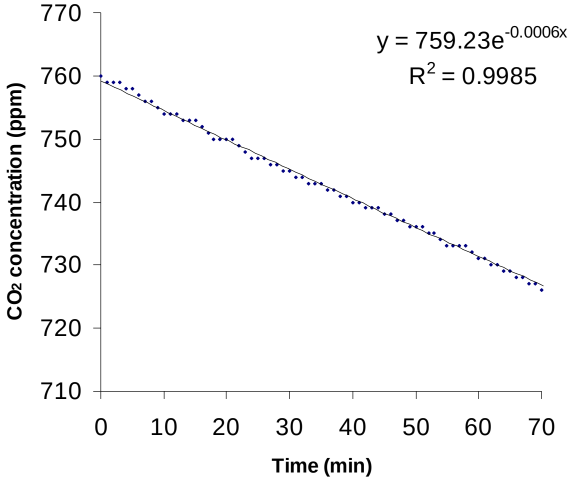
Where

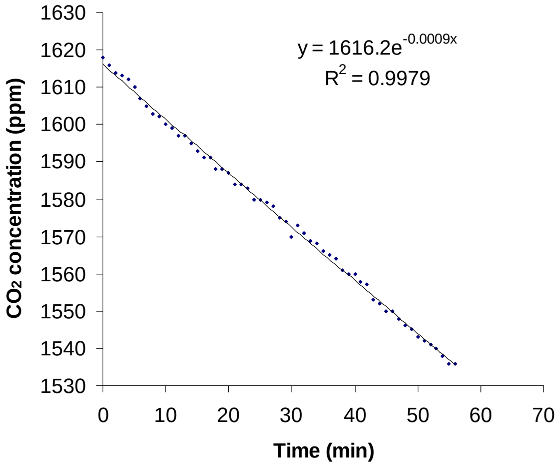
Q is flux

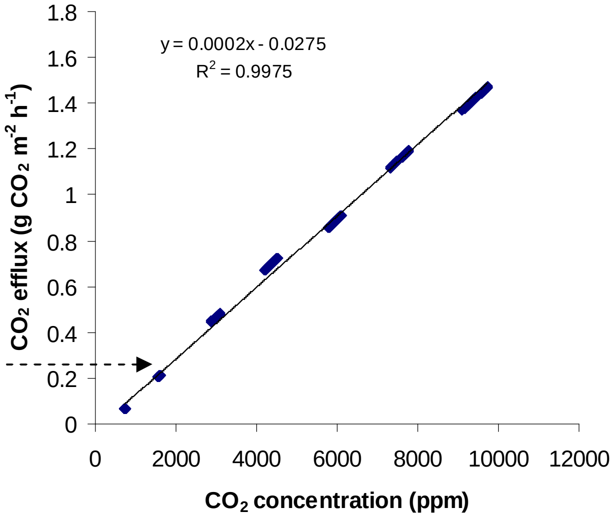
C is concentration in the chamber

V is volume of the chamber

A is surface area of the chamber



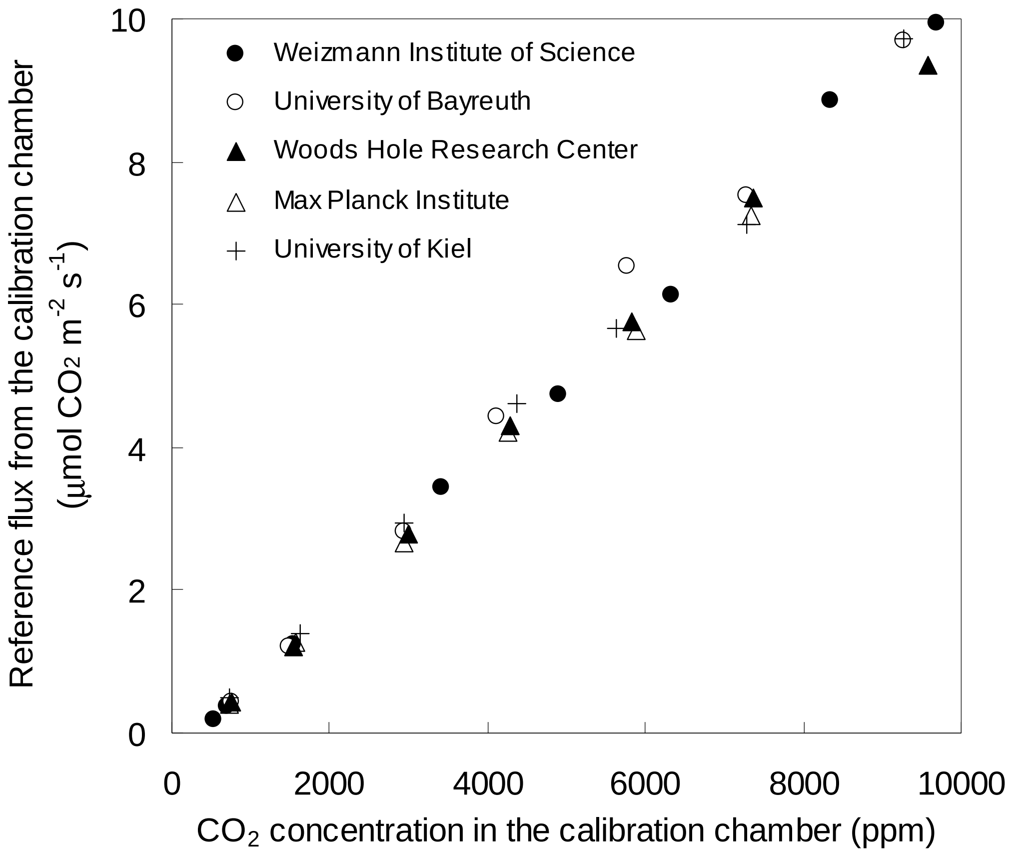




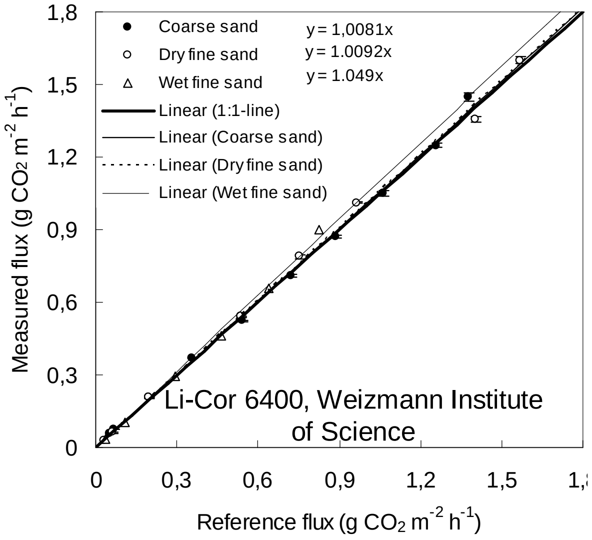
How the effluxes were generated? Repeatability of the effluxes.

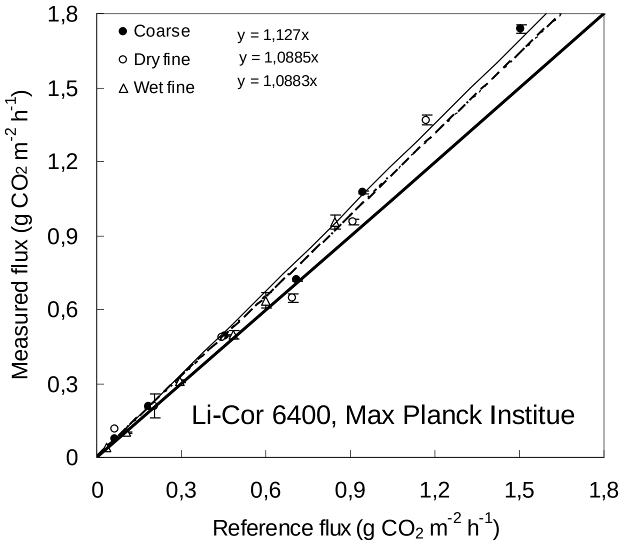
- The effluxes generated during different weeks at similar temperatures deviated less than 6-7% from each other.

- The effluxes were also spatially very homogeneous. The standard error between the three collars used in the measurements ranged from 0.06 to 0.173 with effluxes ranging from 0.35 to 10 µmol m^{-2} s^{-1} (=0.06 to 1.58 g m^{-2} h^{-1}).



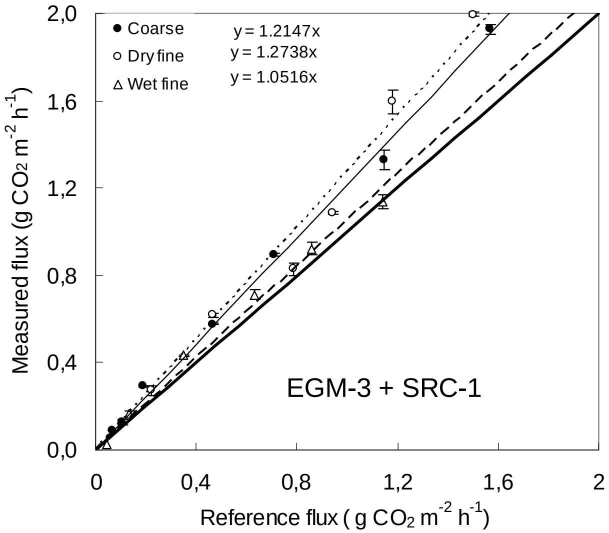
Results: non-steady-state flow-through systems (=closed dynamic systems)

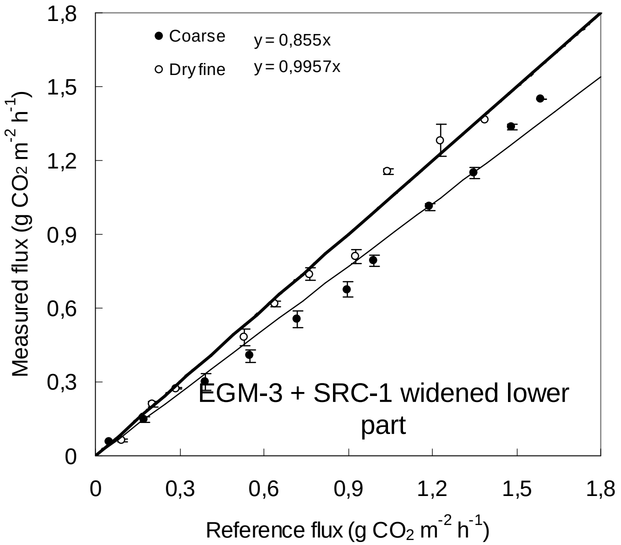




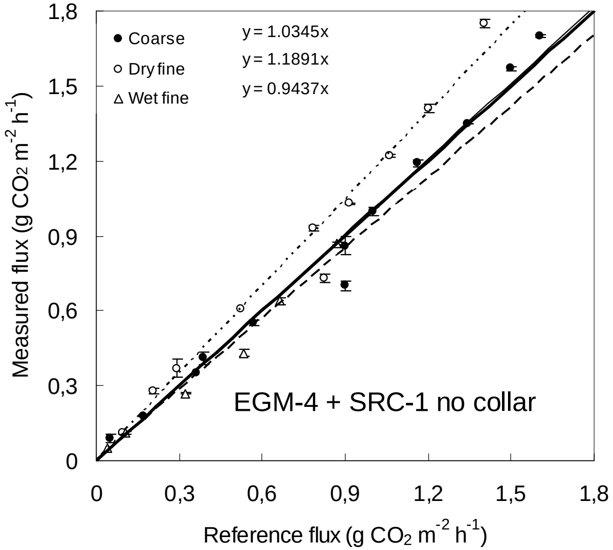
Li-Cor 6400 chamber showed effluxes closed to the effluxes generated by the calibration system.

Results: non-steady-state flow-through systems (=closed dynamic systems)

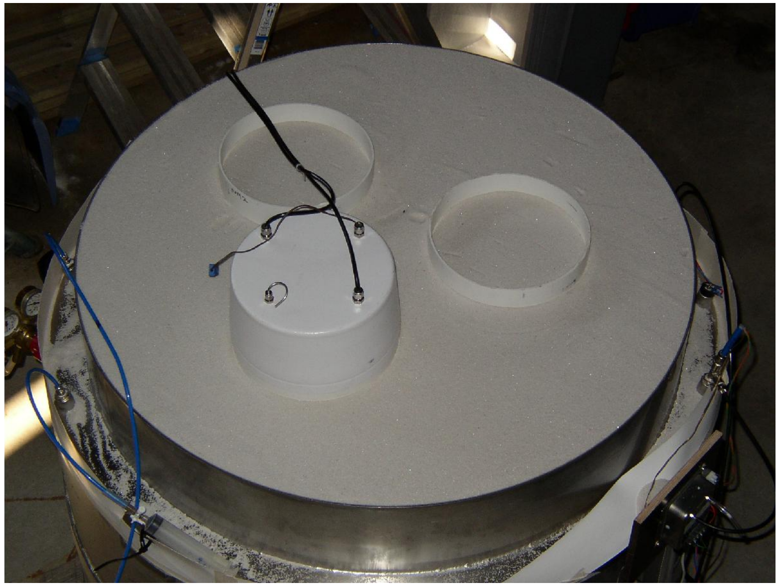


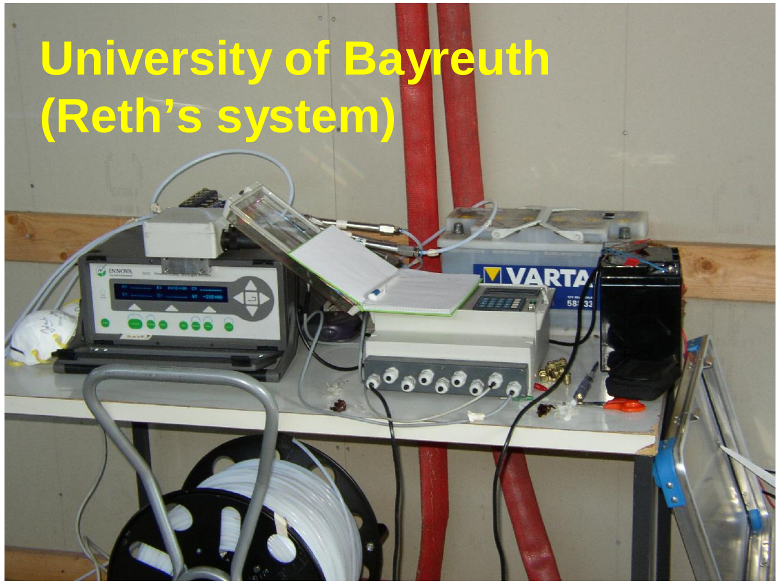


PP-systems overestimated effluxes on all soil types if a collar was used. If collar was not used, the effluxes were closer to the reference. Chamber with widened lower part underestimated effluxes with coarse sand.

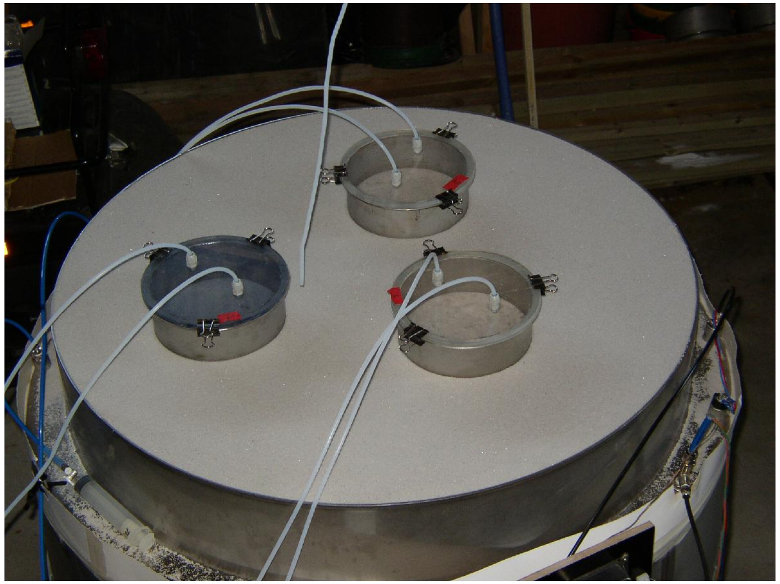


Woods Hole Research center (Savage's system)

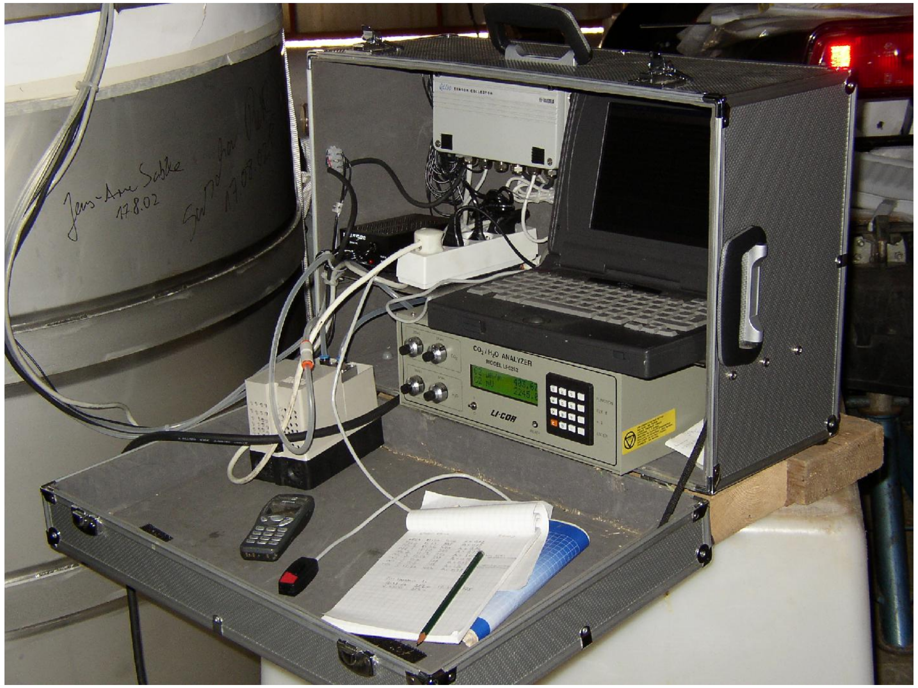




University of Bayreuth (Reth's system)

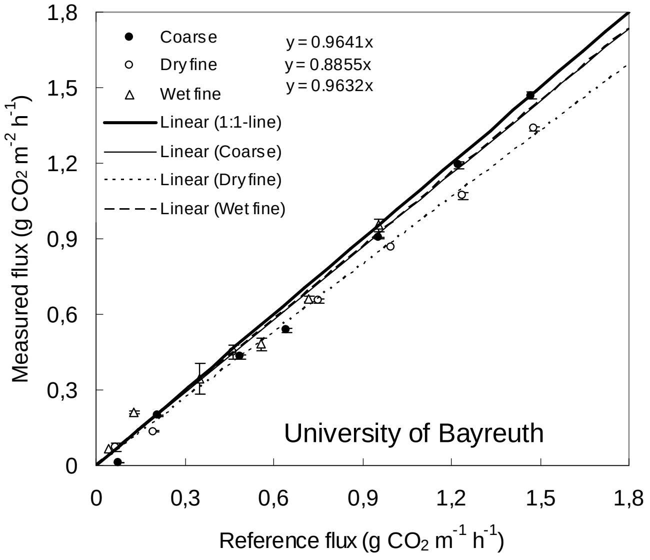


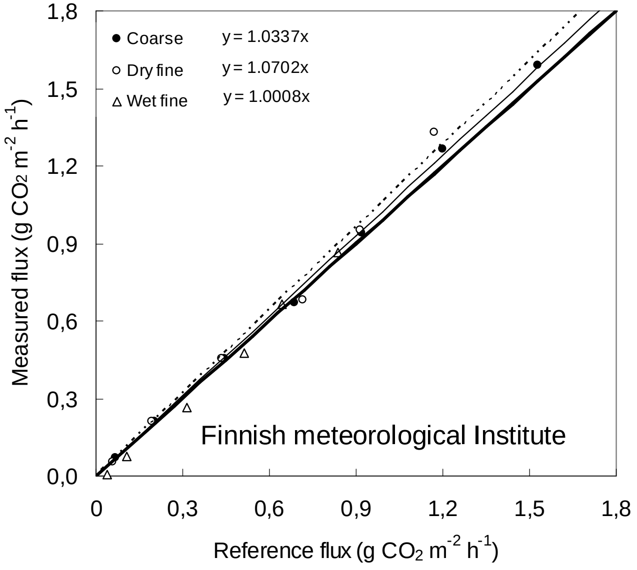
FMI - system
(Finnish Meteorological Institute)

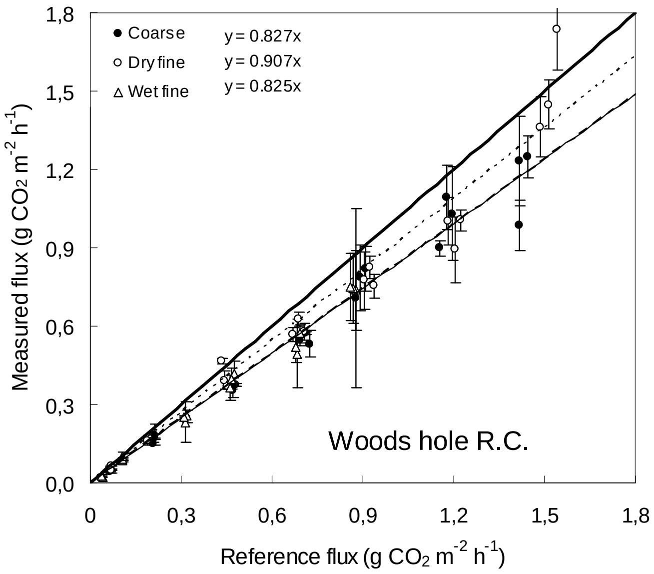


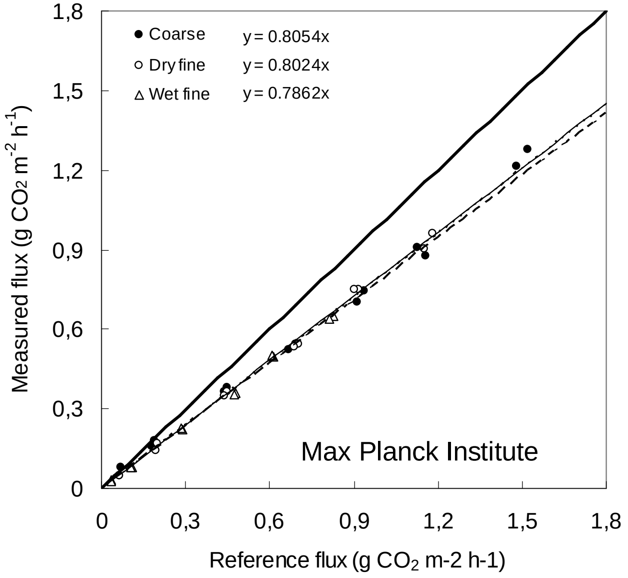
Results: non-steady-state flow-through systems (=closed dynamic systems)

Non-steady-state flow-through systems showed contradictory results depending on the design of the chamber, and if a fan was used or not. University of Bayreuth and FMI system showed effluxes close to the reference. Woods Hole and Max Planck underestimated.

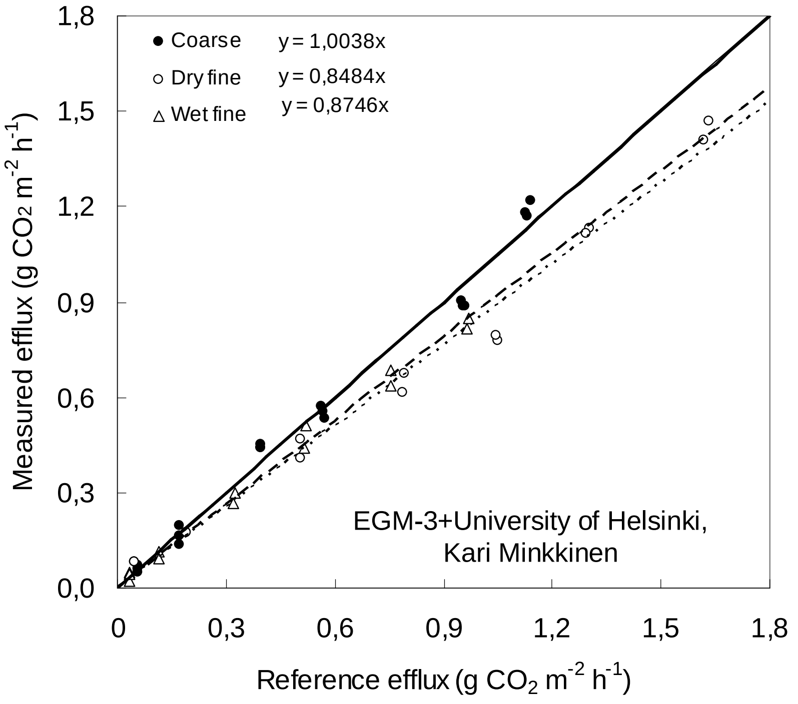


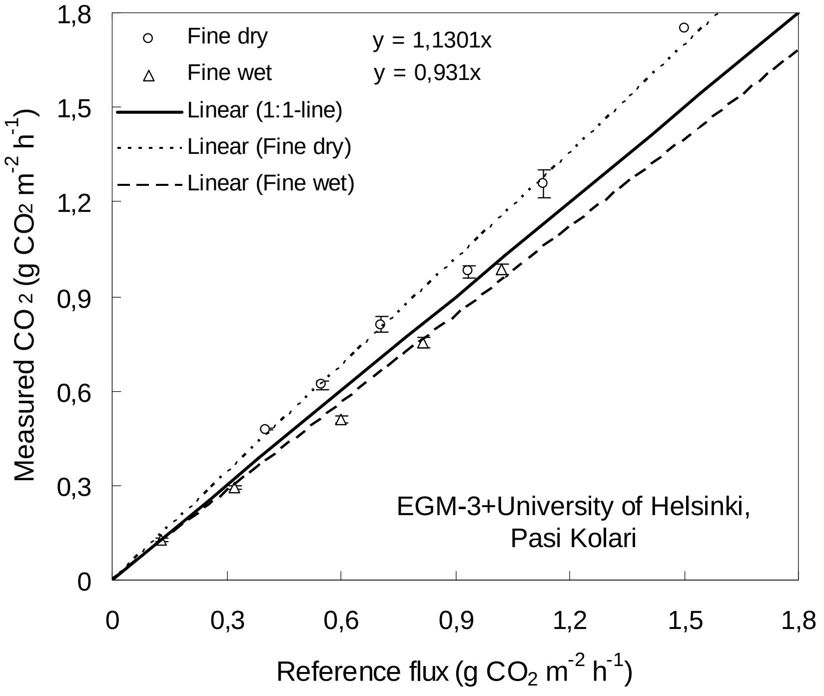






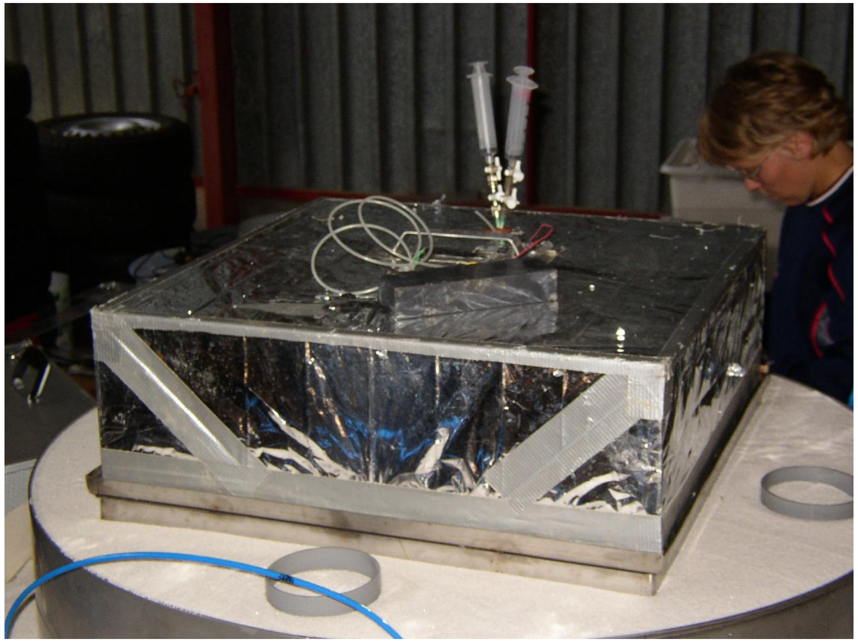
Results:
non-steady-state flow-through systems (=closed dynamic systems)



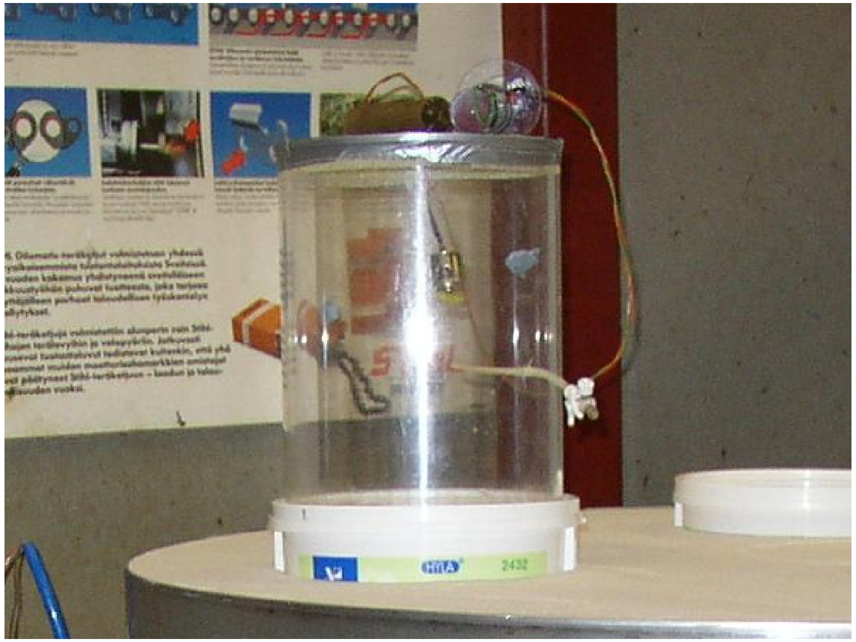


Non-steady-state non-flow-through systems(=closed static systems)

NSNF-system (Agrifood Finland)



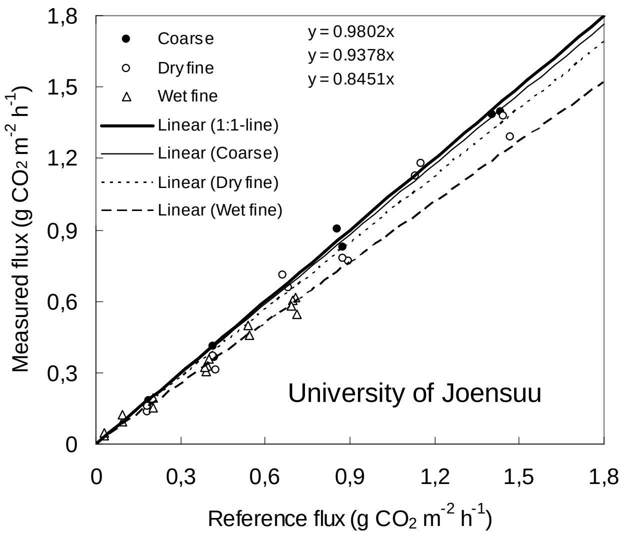
NSNF-system (University of Helsinki, Jukka Pumpanen)

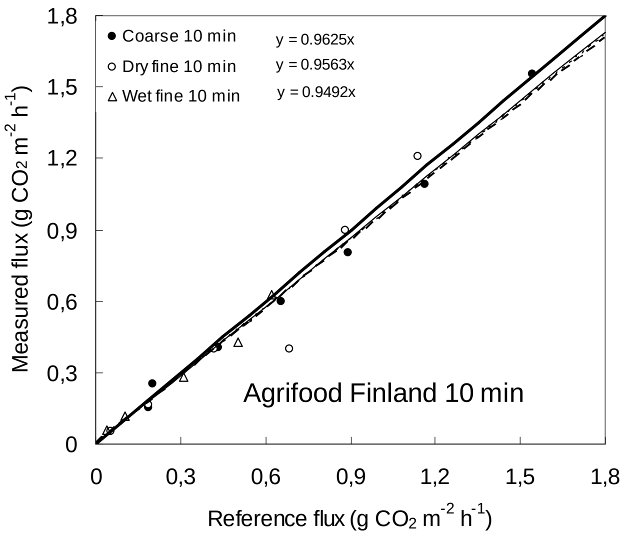


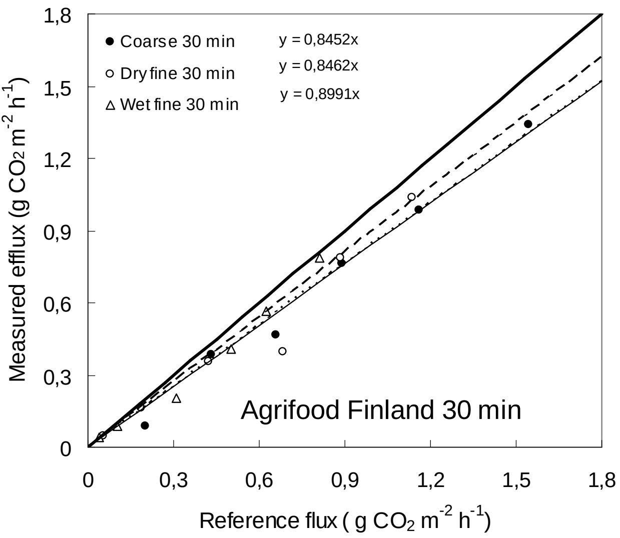
Non-steady-state non-flow-throug systems(=closed static systems)

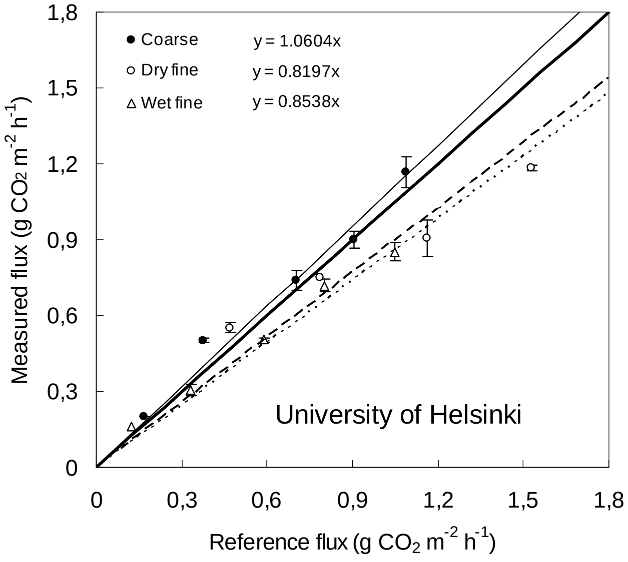
NSNF-chambers underestimated effluxes on average by 4-13%. The underestimation was smallest with wet sand.

Incubation time and headspace concentration affected the results.

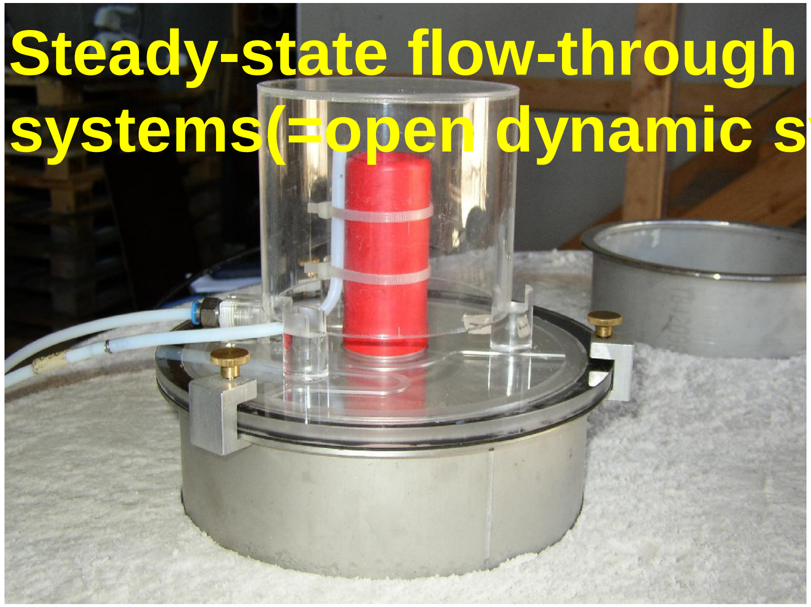


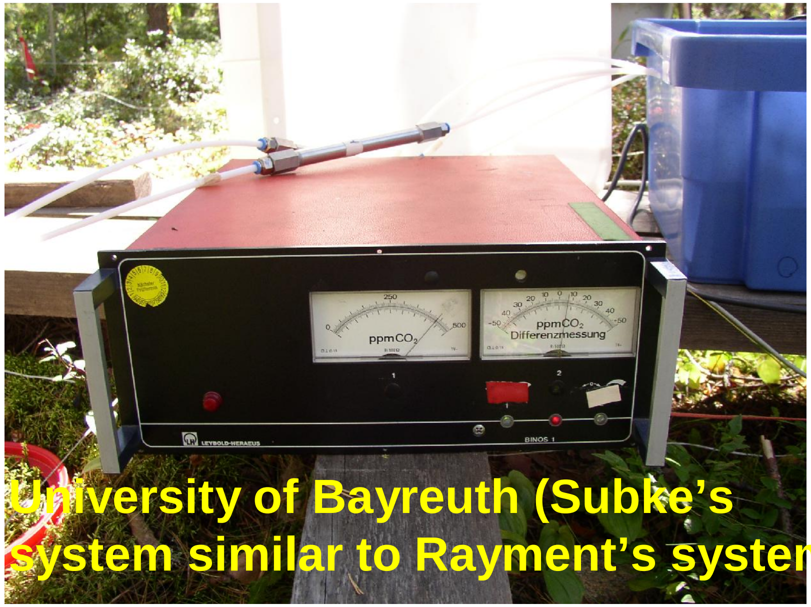




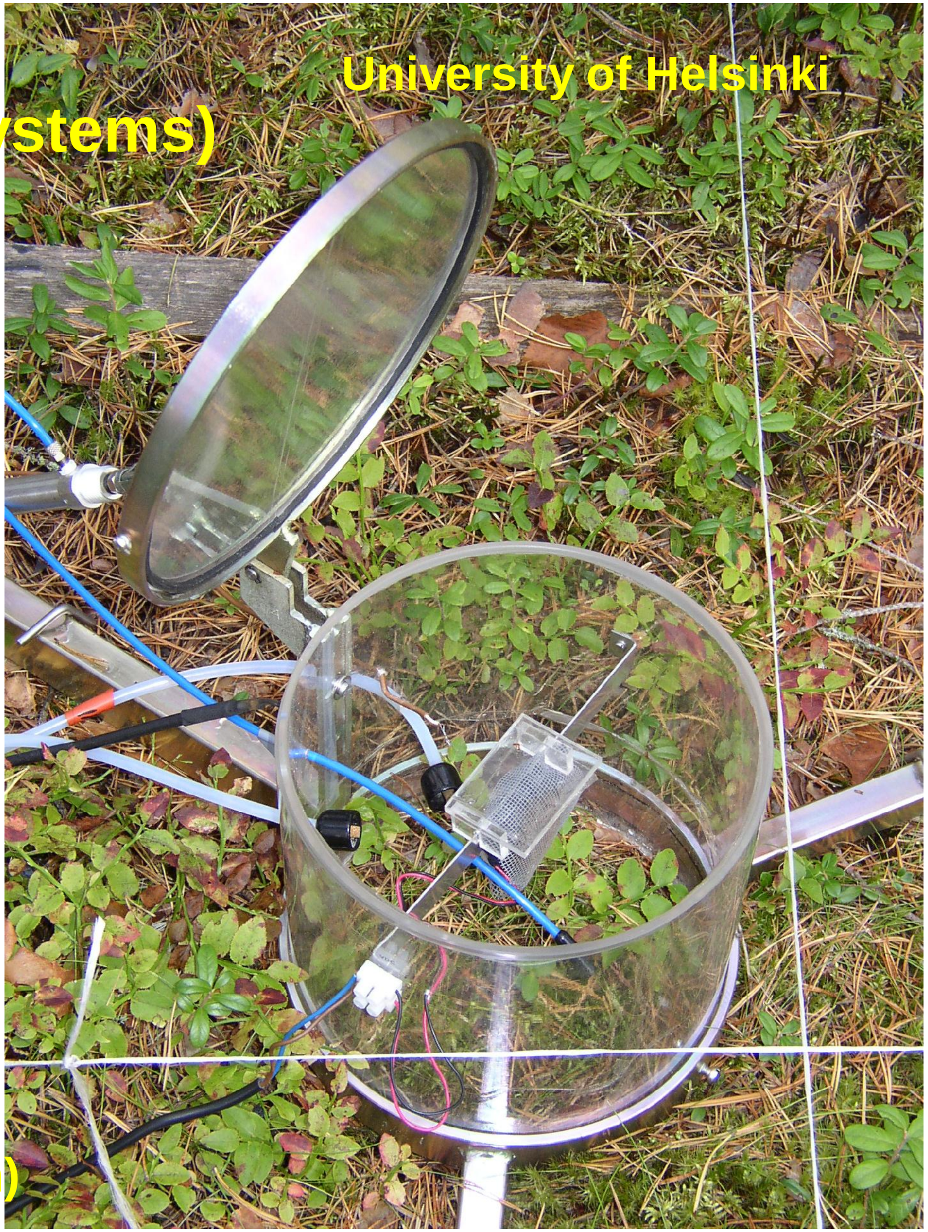


Steady-state flow-through systems(=open dynamic systems)





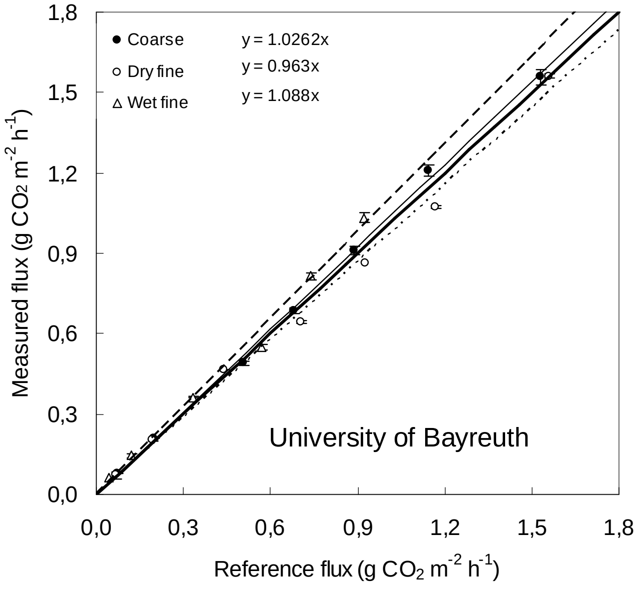
University of Bayreuth (Subke's system similar to Rayment's system)

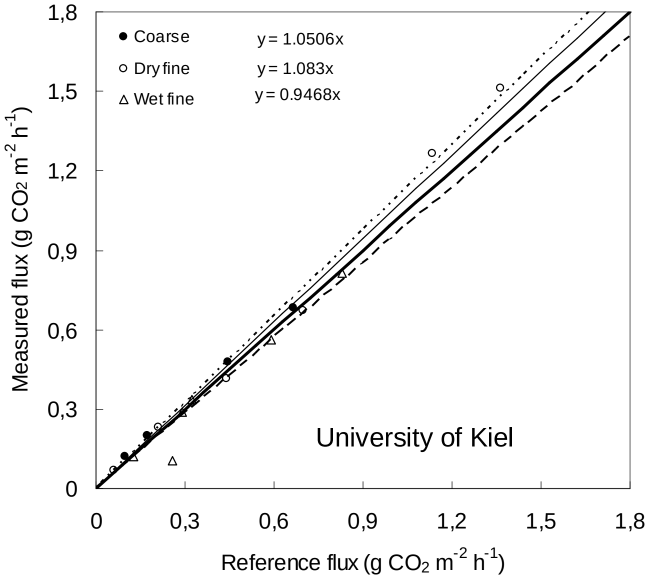


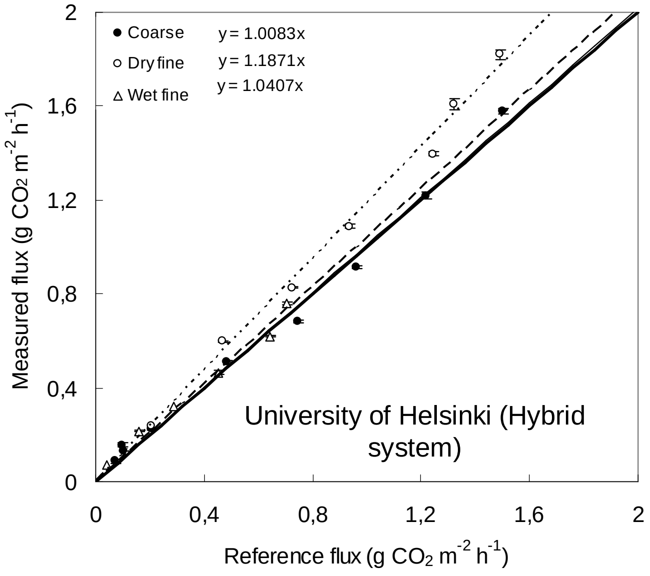
University of Helsinki

Steady-state flow-through systems (=open dynamic systems)

Steady-state systems showed effluxes close to the reference. The hybrid system of the University of Helsinki overestimated effluxes with dry fine sand.







Conclusions

- Reliability of the chamber system was not related to the measurement principle.
- Good results can be achieved with steady-state chambers as well as with non-steady-state chambers.
- General trend was that non-steady-state non-flow-through chambers underestimated systematically by 4-14% whereas significant differences between flow-through chambers were not observed.
- Soil porosity affected the results, probably due to mass flow within the soil beneath the chamber.
- Special attention should be paid to the mixing of air within the chamber. Excessive turbulence may cause mass flow of CO_2 between soil and the chamber.
- However, some kind of mixing is needed in non-steady-state chambers, because the CO_2 concentration has to be evenly distributed within the chamber headspace.
- Headspace concentration should be as close as ambient possible, to avoid altering the concentration gradient between the soil and the chamber.

Summary table

Table 1. Correction factors for different chambers. Each chamber can be scaled to the reference flux obtained from the calibration tank by dividing the measured flux by the correction factor of a specific soil type.

Chamber type*	Coarse sand	95% confidence interval	Dry fine sand	95% confidence interval	Wet fine sand	95% confidence interval
NSF-1 (Licor 6400-09)	1.01	0.99 - 1.03	1.01	0.98 - 1.04	1.05	1.01 - 1.09
NSF-1b (Licor 6400-09)	1.13	1.07 - 1.18	1.09	0.98 - 1.19	1.09	1.04 - 1.14
NSF-2 (EGM-3+SRC-1)	1.21	1.17 - 1.26	1.27	1.15 - 1.39	1.05	0.97 - 1.13
NSF-3 (EGM-3+SRC-1 widened collar)	0.86	0.82 - 0.89	1.00	0.94 - 1.05	-	-
NSF-4 (EGM-1+SRC-1 no collar)	1.03	1.01 - 1.06	1.19	1.14 - 1.24	0.94	0.86 - 1.03
NSF-5 (EGM-4+SRC-1 mesh)	1.16	1.12 - 1.19	1.19	1.11 - 1.27	1.33	1.20 - 1.47
NSF-6 (University of Bayreuth)	0.96	0.91 - 1.02	0.89	0.86 - 0.92	0.96	0.87 - 1.06
NSF-7 (Finnish Meteorological Institute)	1.03	1.01 - 1.05	1.07	0.99 - 1.15	1.00	0.92 - 1.08
NSF-8 (Woodshole Research Center)	0.83	0.79 - 0.86	0.91	0.86 - 0.96	0.83	0.80 - 0.85
NSF-9 (Max Planck Institute)	0.81	0.79 - 0.83	0.80	0.79 - 0.82	0.79	0.77 - 0.80
NSF-10 (University of Helsinki)	1.01	0.96 - 1.05	1.19	1.14 - 1.23	1.04	0.96 - 1.13
NSF-11 (University of Helsinki)	1.00	0.96 - 1.03	0.85	0.81 - 0.87	0.87	0.84 - 0.89
NSF-12 (University of Helsinki)	-	-	1.13	1.08 - 1.18	0.93	0.87 - 0.99
NSF- Average	1.00		1.04		0.99	
NSNF-1 (University of Joensuu)	0.98	0.95 - 1.01	0.94	0.89 - 0.98	0.85	0.81 - 0.88
NSNF-1 (University of Joensuu with extension)	0.95	0.86 - 1.05	0.98	0.92 - 1.03	0.85	0.75 - 0.94
NSNF-2 (Agrifood Research Finland, 10 min).	0.96	0.91 - 1.01	0.96	0.76 - 1.15	0.95	0.84 - 1.06
NSNF-2 (Agrifood Research Finland, 30 min).	0.85	0.79 - 0.90	0.85	0.71 - 0.98	0.90	0.80 - 1.00
NSNF-3 (University of Helsinki)	1.06	0.96 - 1.17	0.82	0.63 - 1.01	0.85	0.78 - 0.93
NSNF-4 (University of Helsinki)	-	-	0.65	0.56 - 0.74	0.84	0.81 - 0.87
NSNF- Average	0.96		0.86		0.87	
SSFL-1 (University of Bayreuth)	1.03	1.01 - 1.05	0.96	0.92 - 1.01	1.09	1.02 - 1.15
SSFL-2 (University of Kiel)	1.05	0.99 - 1.11	1.08	1.01 - 1.15	0.95	0.80 - 1.09
SSFL - Average	1.04		1.02		1.02	

* NSF = non-steady-state flow-through chamber, NSNF = non-steady-state non-flow-through chamber
SSFL = steady-state flow-through chamber

Thank you!