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Calibration and analysis of soil carbon efflux estimates with closed chambers at Forsmark and Laxemar

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Summary

The Forsmark and the Laxemar investigation areas are examined by the Swedish Nuclear Fuel and Waste Management Co. for a possible construction of a deep repository for nuclear waste produced at the power plants in Sweden. In the case of a future leakage of waste, the radioactive isotopes could end up in the ecosystems above the repository. The fate of the radionuclides and their possible radiological impacts are then highly determined by ecosystem carbon cycling. An important part of the carbon cycling is the soil carbon effluxes, and in the investigation areas soil carbon effluxes have been examined with the closed chamber technique. This paper is divided into two parts. Firstly, there were problems with the equipment measuring the soil carbon dioxide efflux, and the first part is a description of the problem, how it was corrected and its possible causes. The second part is a manual in how to analyse data and calculate annual estimates of soil carbon efflux.

Part 1. Calibration of EGM-4

Measurements of the soil carbon effluxes were done with an EGM-4 (Environmental Gas Monitor) together with a CPY-2 (Canopy Assimilation Chamber) chamber. To control the equipment and to check if there is a problem with the EGM-4, tests were done between the EGM-4 and a well-calibrated LI-7000 at Lund University in October 2005. In June 2006, new analyses were done between the EGM-4 used in the investigation areas and another well calibrated EGM-4 that was used as a reference. The soil carbon dioxide efflux estimates from the EGM-4 and the reference machines were compared and the conclusion is that the EGM-4 overestimates the soil carbon dioxide effluxes. The problem is slightly increasing with higher soil carbon dioxide effluxes.

Several tests were conducted to find out what could be the problem of the EGM-4. First, the CPY-2 chamber was tested. Measurements of area and volume of the CPY-2 chamber were done and these measurements indicated that they were correct. Other tests also indicate that the problem is not within the chamber since the same chamber was used for both the reference machines and the EGM-4, but still there were only problems in the EGM-4. Measurements were also done with another EGM-4, owned by Lund University. This machine had a similar chamber as the EGM-4 used in the investigation areas but there were no problems with the soil carbon dioxide estimates of the EGM-4 of the university. Also, in the tests done in June 2006, the EGM-4 had a new chamber, but still the problem remained the same.

The problem does not seem to be related to the calibration of the EGM-4. Measurements were done without any changes in the concentration of carbon dioxide, and the EGM-4 did then give correct estimates of the concentration of the carbon dioxide. It was only when there was a change in concentration of carbon dioxide in the chamber that the concentration of carbon dioxide was overestimated.

The tests done to control the area and volume of the chamber indicated that they were the same as the values given in the instruction manual. But, the default values in the EGM-4 were not the same as the ones measured. According to the instruction manual this should not matter since in the equation used for soil carbon dioxide estimations it is the fraction between volume and area that is used. The fraction between volume and area is about the same for the default values and for the measured values. To make sure that this was correct, tests with different setting of area and volume in the EGM-4 were done. These tests showed that the EGM-4 gives the same estimate of soil carbon dioxide effluxes as long as the fraction between area and volume is the same, just as indicated by the instruction manual. The clock of the EGM-4 was also tested against another clock and these tests proved that it is not the clock that is causing the overestimations.

To be able to correct the estimates taken up in the field, regression analysis was done between estimates of soil carbon dioxide effluxes by the EGM-4 and by the reference machines. The power regression was the best correlated regressions and they can now be used to correct the estimates of the EGM-4. For the positive values $F_{C\,R} = 0.6754\ F_{C\,T}^{0.818}$ should be used and for the negative values $F_{C\,R} = -1.4676\ (-F_{C\,T})^{1.042}$ should be used. $F_{C\,R}$ is the corrected soil carbon dioxide efflux and $F_{C\,T}$ is the soil carbon dioxide efflux according to the EGM-4.

Tests were also done to see if the problem had changed in between the two measurements occasions. Correcting the measurements taken up in June 2006 with the correction regression from the measurements of October 2005 tested this. It was tested if the corrected estimates of soil carbon dioxide effluxes by the EGM-4 for June 2006 were similar to the estimates of the reference machine used in the tests June 2006. The test indicated that the problem of the EGM-4 was constant in time, at least in between these two occasions.

Even though many tests have been done, it is still not found what could be the problem of the EGM-4. It is seen in the tests performed that the problem ought to be in the estimates of carbon dioxide concentration. A possible explanation for the overestimations could be disturbances from water vapour in the infrared gas analyser, even though this suggestion is still not tested. The study has shown though that the problem is of a constant character and does not change in time. This is an important conclusion, since otherwise it would be hard to trust the measurements taken up. Correction equations for the overestimated measurements have also been done, which is necessary to retrieve the correct soil carbon dioxide effluxes.

Part 2. Analysis of EGM-4 measurements

The first part of the report is a check of the equipment used for taking up the measurements, while the second part is a manual in how to analyse these measurements. The field measurement by the EGM-4 is just an occasional estimate of the soil carbon efflux at a certain spot and at a certain point in time. To make an interpretation of the measurements, it is essential to analyse the data and to temporally extrapolate them.

It is necessary to prepare the raw data for the analysis. The problems with the EGM-4 doing the measurements at the Forsmark and the Laxemar investigation area makes it necessary to correct the data taken up by this EGM-4. The data should also be separated into soil respiration and gross primary production (GPP). Soil carbon dioxide effluxes should be changed to soil carbon effluxes.

Soil carbon effluxes are strongly controlled by abiotic factors; temperature is the main factor to influence soil respiration and photosynthetically active radiation (PAR) and air temperature are the main factors to influence GPP /Lambers et al. 1998/. Regression with soil respiration against temperature and with GPP against PAR or temperature can therefore be done. These equations can then be used on datasets with temperature and PAR to model soil carbon effluxes temporally.

To make sure that the models give proper and accurate results it is necessary to evaluate them. First, it is necessary to investigate how close the models are to the field measured soil carbon effluxes. To check if this is reasonably close to the real soil carbon efflux value, the 95.6% confidence intervals of the models are needed. If the real value is within the 95.6% confidence interval of the model, this shows that the model makes a proper and accurate estimate to the real ecosystem carbon efflux. The models can then be used to estimate soil carbon effluxes in the Laxemar and the Forsmark investigation areas.

Contents

1 Introduction

In recent years the interest in the carbon cycle has grown. Anthropogenic emissions increases carbon dioxide levels in the atmosphere and it affects the global climate. There is a large risk that the increase in concentration of greenhouse gases will continue to increase the mean global temperature in the future /IPCC 2001/. To be able to understand the connection between the carbon cycle and the global climate, much effort has been put into the study of the potential feedback loops of the carbon cycle.

The carbon cycle of terrestrial ecosystems is the processes responsible for the movement of carbon between the carbon pools in the atmosphere, the biosphere and the lithosphere. To understand how the carbon cycle works, it is of main importance to quantify these processes and the stock of carbon in the pools. The environmental conditions influencing the carbon cycle can be investigated and understood with quantification. One way to quantify the carbon dioxide effluxes from the floor of ecosystems is the closed chamber technique. The increase in concentration of carbon dioxide is measured in a chamber and the carbon dioxide efflux from the ground can hereby be quantified.

With the closed chamber technique, the net ecosystem exchange (NEE) of the ground and soil respiration is estimated. NEE is the total exchange of carbon between the atmosphere and the ground, and it composites of soil respiration and photosynthesis of the ground vegetation. To estimate photosynthesis or gross primary production (GPP) of the ground vegetation, it is therefore necessary to subtract soil respiration from NEE /Schlesinger 1997/.

Today, SKB has the responsibility to investigate and present detailed proposals of how the spent nuclear fuel should be taken care of. In the work of siting a deep repository, extensive site investigations will precede the coming proposal. Two sites in Sweden are investigated for a potentially deep repository of the nuclear waste, the Laxemar and the Forsmark investigation areas. An important part of the site characterisation is the development of site descriptive models that gives an integrated description of the current state of the regions and the processes that might affect this state in the future /Lindborg 2005/. One process that is important in these site descriptive models is the carbon cycling. The work of siting a deep repository also includes a safety assessment, where different types of scenarios are analysed. If a future leakage occurs, the radioactive isotopes could then end up in the ecosystems above the repository. The fate of the radionuclides and their possible radiological impacts are then highly determined by ecosystem carbon cycling since radioactive isotopes often follow the same pathway as stable elements vital for the vegetation /Greger 2004/. It could also be that the ecosystems are affected by the handling of the waste and the activity around the repository. To notice this possible change, it is of main importance to have knowledge about the carbon cycle beforehand, both for the understanding of an unaffected ecosystem and to have something to compare the damaged ecosystem with.

Since March 2004, soil carbon effluxes have been estimated with the closed chamber technique in both the Laxemar and the Forsmark investigation areas /Tagesson 2006/. Measurements are done with an EGM-4 (Environmental Gas Monitor) together with a CPY-2 (Canopy Assimilation Chamber) chamber (PP-systems, Hitchin, Hertfordshire, UK). In the first analysis of the field measurements done, the soil carbon dioxide efflux estimations occurred to be incredibly high. To ensure that the closed chamber equipment gave correct estimates, it was checked against other well-calibrated gas analysers. The general aim with this report is to ensure that the ongoing measurements retrieve correct soil carbon efflux values and that the field measurements will be properly analysed. The report is hereby divided into two parts, the fist part is devoted to describe the detected error and to eliminate possible sources of error that may affect the ongoing measurements and the second part is a manual in how to analyse the raw data retrieved after the ongoing measurements.

2 The carbon cycle in terrestrial ecosystems

All living tissues are composed of carbon and all life on Earth is depending on processes in the carbon cycle. Photosynthesis and respiration are together with mortality and different disturbance regimes (fire, storms, drought etc) the processes of main importance for the carbon cycle /Schlesinger 1997/.

2.1 Gross primary production, GPP

The total uptake of carbon through photosynthesis is the gross primary production, GPP, of the vegetation. Photosynthesis is the biogeochemical process that transfers carbon from the atmosphere and its oxidized form, carbon dioxide, into the biosphere and its organic form, carbohydrates.

$6\ CO_2 + 6\ H_2O + \text{sunlight} = C_6H_{12}0_6 + 6\ O_2$

It is the process capturing sun light, which results in plant growth and provides life with energy. The photosynthesis provides the atmosphere with the oxygen necessary for all animal life.

2.2 Respiration

Energy stored by photosynthesis is later used for maintenance, growth or reproduction by living organisms. The process responsible for the breakdown of the carbohydrates is respiration.

$C_6H_{12}0_6 + 6\ O_2 = 6\ CO_2 + 6\ H_2O + \text{energy}$

The plants use about half of GPP for their own maintenance /Schlesinger 1997/ and this carbon dioxide is released back to the atmosphere through autotrophic respiration. Parts of GPP accumulated by vegetation is consumed by herbivores and becomes a part of the animal

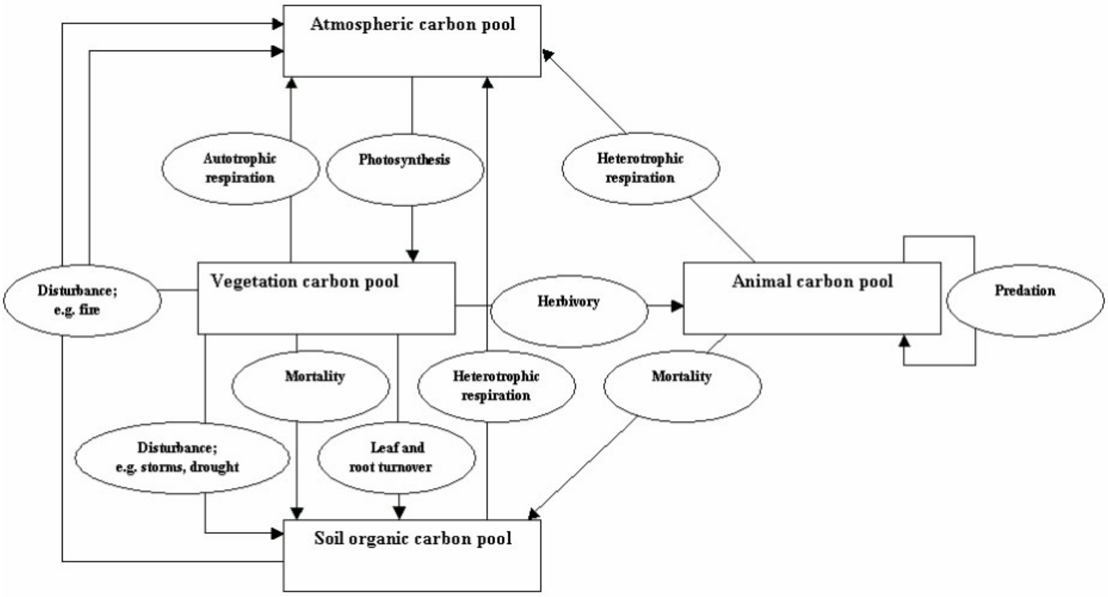

Figure 2-1. *Flowchart over carbon cycle in terrestrial ecosystems. Squares are carbon pools; arrows and circles are processes moving carbon between the pools.*

carbon pool, this carbon is either released to the atmosphere through heterotrophic respiration or transported to the soil through mortality. The rest of the carbon taken up by plants is either released to the atmosphere through disturbance, such as fire, or transported to the soil through mortality of the vegetation. Part of the carbon transported to the soil is decomposed and released to the atmosphere through heterotrophic soil respiration.

Soil respiration varies as a function of soil temperature, soil moisture and chemical composition of material to be decomposed /Schlesinger 1997/. Soil respiration and soil temperature has an exponential relationship in the soil temperature range found in the field; higher soil temperature gives more soil respiration /Widén 2002/. Soil respiration and soil moisture has different relationships at different moisture ranges /Davidson et al. 2000, Janssens et al. 2003/. In dry soils there is a positive linear relationship. Soil respiration can be inhibited due to dryness. In waterlogged soils decomposition is reduced due to anaerobic conditions and there is a negative linear relationship between soil moisture and soil respiration. In between these conditions is a plateau where soil respiration is not affected by soil moisture /Heal 1981/. Nitrogen and lignin content in litter will speed up respectively slow down the breakdown processes /Yao et al. 2003/. In soil organic matter there are different acids that are more or less easy to decompose /Schlesinger 1997/.

2.3 Net Primary Production, NPP

Net Primary Production, NPP, is here defined as the rate at which plants accumulate carbon in their living tissues, GPP minus autotrophic respiration.

$NPP = GPP – R_p$

where
R_p = autotrophic respiration
NEP – Net Ecosystem Production is net primary production on an ecosystem level

$NEP = GPP – R_t$.

where
$R_t = (R_p + R_h + R_d)$
R_t = total respiration
R_d = heterotrophic respiration
R_h = herbivore respiration.

In ecosystems being young or exposed to disturbances, most of the NEP goes to the production of new plant tissues /Giese et al. 2003/. In old and stable ecosystems GPP mainly goes to the maintenance of the vegetation and most of NEP will be allocated to the soil organic carbon pool /Giese et al. 2003/.

Temperature, precipitation and photosynthetically active radiation (PAR) are abiotic factors influencing primary production /Lambers et al. 1998/. High temperature gives a longer growing season increasing annual production of the ecosystems /Hasenauer et al. 1999/. A raise in temperature can have a negative effect due to a rise in evapotranspiration, which is lowering photosynthesis if water is a limiting factor /Sitch et al. 2003/. Biomass contains 80–95% water and insufficient water in the soil can be a limiting factor for biomass production /Lambers et al. 1998/. PAR and primary production has a positive relationship at low irradiance due to PAR being the limiting factor in the transport of electrons in photosynthesis /Lambers et al. 1998/. At higher PAR it is the uptake of carbon dioxide that is the limiting factor and PAR does not have any effect on GPP /Lambers et al. 1998/.

2.4 Vegetation carbon pool

The terrestrial biosphere has an important role in the carbon cycle. Ecosystems can be sources and release carbon to the atmosphere, or they can be sinks and take up carbon from the atmosphere. Different amount of carbon is taken up by the vegetation depending on biotic factors like species of vegetation, age and production of the ecosystem /Grace 2003/. Abiotic factors of importance are temperature, humidity, nutrients, incoming solar radiation and disturbances /Schlesinger 1997/.

2.5 Soil organic carbon pool

NEP is delivered to the soil organic carbon pool as litter fall. Litter is undecomposed dead organic material. Decomposition of litter is a two-part process. It is the breakdown of litter at the soil surface and it is the accumulation of soil organic matter /Olsson et al. 2002/. Decomposition results in release of carbon dioxide, water and nutrients. Soil organic matter is highly resistant humus and it can be divided into two parts /Olsson et al. 2002/. About 15 percent of the soil organic matter is in the bulk of the soil, slowly decomposing and having an age of thousands of years /Schlesinger 1997/. The remaining 85 percent is closer to the surface, fast decomposing and of much more recent origin.

2.6 Human influences

Humans have influenced the carbon cycle since they started to use land for rising crops /IPCC 2001/. Carbon stored in the soil can be released back to the atmosphere when land-use is changed and forests are clear-cut. Since industrial revolution, humans have started a large-scale influence on the carbon cycle. By using fossil fuels, carbon stored in the lithosphere is released back to the atmosphere. Carbon dioxide is a greenhouse gas and it has impact on the global climate. The mean global temperature increased 0.8°C 1860–2000 (IPCC 2001). A reason could be the rise in concentration of greenhouse gases due to anthropogenic emissions.

3 Theory of the EGM-4

3.1 Soil carbon dioxide efflux calculations

The EGM-4 is an infrared gas analyzer. An infrared gas analyzer uses a source that emits infrared light and a sensor that detects the infrared light. Carbon dioxide has a region of strong absorption at 4.26 microns and when the air with carbon dioxide transported from the chamber passes the infrared beam some of the light is absorbed, this difference is registered at the detector /PP-systems 2003/.

The CPY-2 is a closed plastic transparent chamber with sensors for PAR (Photosynthetic Active Radiation) and temperature measurements. The chamber is a closed system connected to the EGM-4. Air is transported from the chamber to the EGM-4, where measurements of the concentration of the carbon dioxide are performed. The air is then transported back to the chamber.

From the differences in concentration of carbon dioxide the assimilation rate can be calculated.

$$F_C = (C_n - C_o)\ t_n^{-1}\ V_c\ A_c^{-1} \qquad \text{(Eq. 1)}$$

Where F_C is the soil carbon dioxide efflux (efflux of CO^2 (unit area * unit time)$^{-1}$)

C_o is concentration of carbon dioxide at initial time

C_n is concentration of carbon dioxide at n time (t_n) later

V_c is volume of the chamber and

A_c is area of exposed soil.

With a constant efflux of carbon dioxide into the chamber there would be a linear relationship with the concentration of carbon dioxide and time. To calculate the assimilation rate it would only be to subtract the C_n with C_o and divide by time. However, due to risk of leakage and disturbances from increased CO_2 concentration from the chamber, the relationship might not be linear and therefore a quadratic relationship is used instead.

$$C_n = m + k_1 t_n + k_2 t_n^2 \qquad \text{(Eq. 2)}$$

Where m is a constant and k_1 and k_2 are coefficients of the quadratic regression.

At initial time ($t_n = 0$) the line has the same slope for both the linear curve without any leakage and for the quadratic curve with leakage. Looking at the difference in carbon dioxide concentration in time ($\Delta C\ (\Delta t)^{-1}$) at that point will give the true soil carbon dioxide efflux even if there is a leakage. Therefore taking the derivative of Eq 2. gives

$$\Delta C\ (\Delta t)^{-1} = k_1 + 2\ k_2 t_n \qquad \text{(Eq. 3)}$$

At initial time $t_n = 0$ and the derivative at that point then is

$$\Delta C\ (\Delta t)^{-1} = k_1 \qquad \text{(Eq. 4)}$$

The soil carbon dioxide efflux then is

$$F_C = k_1\ V_c\ A_c^{-1} \qquad \text{(Eq. 5)}$$

The EGM-4 measures the concentration in a volume per volume ratio and to get F as a measurement in mass per unit area and time; k_1 must be changed to mass per unit volume. One mole of carbon dioxide weighs 44.01 kg and it occupies 22.41 m^3 of volume at STP, standard temperature (273.15 K) and pressure (1,000 mbar). Then F_C, the soil carbon dioxide efflux becomes

$$F_C = k_1\ P\ 1{,}000^{-1}\ 273.15\ (273.15+T_a)^{-1}\ 44.01\ 22.41\ V_c\ A_c^{-1} \qquad \text{(Eq. 6)}$$

Where F_C is soil carbon dioxide efflux (kg CO_2 $(m^2\ sec)^{-1}$)
k_1 is difference in concentration per unit time (ppm/sec)
P is the atmospheric pressure (mbar)
T_a is air temperature (°C).

3.2 Corrections due to water vapour, temperature and pressure

Some atmospheric circumstances are effecting the equation; these are water vapour, temperature and pressure /PP-systems 2003/. Water vapour has a diluting effect of the carbon dioxide since adding water vapour to an amount of air would lower the concentration of carbon dioxide compared to a dry sample /PP-systems 2003/. Since there are filters covering the detector, this effect is very small (0.1 ppm/mb). Another effect of the water molecules is that they induce an increase in carbon dioxide absorption due to foreign gas broadening. Both these effects are of similar magnitude but in opposite direction and the net effect are therefore approximately zero /PP-systems 2003/.

Increasing pressure results in an increase in concentration according to the general gas law (PV = nRT). Pressure broadening of the infrared absorption bands also affects the concentration measurements /PP-systems 2003/. Temperature also has a concentration effect due to the gas law. Since the temperature is 55°C constant in the infrared gas analyzer of the EGM-4, there is no risk of temperature broadening /PP-systems 2003/. If these effects are taken into Eq. 6, it turns out to be:

$$F_C = k_1\ 44.01\ V_c\ ((0.75 + 0.00025\ P)\ 22.41\ A_c)^{-1} \qquad \text{(Eq. 7)}$$

It turns out that in the infrared gas analyzer, temperature does not have any effect on the measured soil carbon dioxide efflux and the effect of the pressure is small /PP-systems 2003/. For a closer description of the theory behind the EGM-4 soil carbon dioxide efflux estimates, see /PP-systems 2003/.

4 Calibration of EGM-4

4.1 Background

Between the 23rd of March 2004 and 10th of March 2005, the EGM-4 and the CPY-2 chamber were used to measure and estimate soil carbon dioxide effluxes in the Laxemar investigation area /Tagesson 2006/. After analysing the results, the soil carbon dioxide efflux estimations occurred to be incredibly high. To make sure that the EGM-4 measured correctly, tests against a well-calibrated reference machine were done in a laboratory at Lund University during October 2005. These tests indicated that EGM-4 did give incorrect soil carbon dioxide efflux values.

To get an explanation of what could be the problem with the EGM-4, the manufacturers (PP-systems) were contacted. They could not find any problems but suggested that the default volume and area were incorrectly set in the EGM-4 or that there were a fan failure in the system, which would result in a smaller effective volume than with a properly working fan. They also suggested that the firmware could have calculation problems or finally, the clock could be running erroneous. During all the measurements taken up during 2004 and 2005, fan failure was never recorded, so that should not be the problem. PP-systems checked the firmware and it had no problems. To control the clock and the default area and volume, new tests were done in Laxemar June 2006.

All tests done in October 2005 and June 2006 could be grouped into four parts. Firstly, to check the equipment and to control if there is a problem, secondly, to find what is the problem with the equipment, thirdly, to find out how to correct the measurements taken up, and finally, to control if the problem is of a floating kind or if it is stable in time.

4.2 Method

4.2.1 Control of EGM-4 soil carbon dioxide efflux estimations

In October 2005 it was controlled that the soil carbon dioxide effluxes were estimated correctly by the EGM-4. A LI-7000 (LI-COR INC., USA) in a laboratory at Lund University has been carefully calibrated against gases with known amount of carbon dioxide and this was used as a reference against the EGM-4. Measurements of carbon dioxide concentration were made with both the EGM-4 and LI-7000. Tubes from both the LI-7000 and the EGM-4 entered the same CPY-2 chamber. 38 simultaneous measurements with both instruments were done. Soil was heated, cooled and watered to get measurements with different respiration rates. Soil carbon dioxide effluxes (g CO_2 m^{-2} h^{-1}) for the LI-7000 concentrations were calculated as:

$$F_C = \Delta C\ (\Delta t)^{-1}\ P\ R^{-1}\ T^{-1}\ V_c\ A_c^{-1} \qquad \text{(Eq. 8)}$$

Where

F_C is soil carbon dioxide effluxes (kg CO_2 / (m^2 *sec))

ΔC is difference in carbon dioxide concentration (ppm)

Δt is difference in time (h)

P is atmospheric pressure (atm)

R is the universal gas constant ($8.206 * 10^{-5}$ m^3 atm K^{-1} $mole^{-1}$)

T is temperature (K)

V_c is volume of the chamber (m^3)

A_c is the area of exposed soil (m^2).

The calculated soil carbon dioxide effluxes using the LI-7000 were compared to effluxes measured by the EGM-4. A Linear regression was fitted to the soil carbon dioxide effluxes between both the machines. For all the statistics done throughout the analysis, SPSS 12.0.1 for Windows was used.

4.2.2 Control of the chamber area and volume

Area and volume of the CPY-2 chamber was measured to control that the default values were correct in the EGM-4. The radius was measured with a normal ruler at the bottom of the chamber and the area was then calculated with πr^2.

Volume was measured by taking out 50 ml of air and replaces it with 50 ml of pure Nitrogen during measurements of concentration of carbon dioxide. This was done 7 times and an average in difference in concentration of carbon dioxide was calculated. The volume of the chamber was calculated by

$$V_c = \Delta V\ C_i\ \Delta C^{-1} \qquad \text{(Eq. 9)}$$

Where

V_c is volume of the chamber

ΔV is change in volume of original air

C_i is initial concentration of carbon dioxide and

ΔC is the change in concentration of carbon dioxide.

4.2.3 Control of the EGM-4 calibration

To make sure that the EGM-4 was well calibrated, measurements were made with tubes from both the LI-7000 and the EGM-4 entering the same CPY-2 chamber. The measurements were performed simultaneously against a rubber layer on the ground. The rubber layer was there to ensure that the CPY-2 chamber was tight against the floor and that no air would enter the chamber. No changes in carbon dioxide were seen, which ensured that the chamber were tight against the ground. The concentration of carbon dioxide was checked on both the LI-7000 and the EGM-4. Three different measurements were done.

4.2.4 Comparison between university EGM-4 and LI-7000

At Lund University, there is another EGM-4 with a CPY-2 chamber used by students for educational purposes. After finding out that the EGM-4 used in Laxemar were overestimating soil carbon dioxide effluxes, this set was also controlled against the LI-7000. Eight measurements were done; they were performed the same way as the measurements between the first EGM-4 and the LI-7000.

A linear regression was fitted between the estimate of the soil carbon dioxide effluxes of the EGM-4 from Lund University and the LI-7000. To test if the estimates differed from one another, a t-test of the linear regression was done. For making a t-test, the confidence intervals (95.6%) of the regression coefficient and the regression constant were needed and they can be found by:

$$95.6\%\ \text{confidence interval} = \pm\, t_{\alpha\ (2)\ (n-2)}\ S_b \qquad \text{(Eq. 10)}$$

Where $t_{\alpha\ (2)\ (n-2)}$ is t from Student's t-statistics and S_b is the standard deviation of the coefficient or constant. Standard deviation is given in SPSS 12.0.1 and $t_{\alpha\ (2)\ (n-2)}$ is found in a table of critical values for t-distribution. To test if the estimates between the two machines are similar the 95.6% confidence interval of the linear regression coefficient must include 1 and the 95.6% confidence interval of the constant must include 0.

4.2.5. Control of clock and the default area and volume of the EGM-4

In June 2006, new comparisons were performed, this time it was the EGM-4 did simultaneous measurements with a new, third, EGM-4. Hereafter, the EGM-4 that previously has been tested is called the test EGM-4 and the new EGM-4 is called reference EGM-4. Tubes from both EGM-4 were coupled to a CPY-2 chamber. This CPY-2 chamber was not the same that were used in the October evaluation. The tubes pumped air into both EGM-4 from the chamber and then the air continued out into open air, i.e. it was an open chamber system. This set-up was used since there were only two tubes coming out of the CPY-2 chamber, one each for the gas in ports of both the EGM-4.

The first test done in October 2005 to control if the area and volume of the CPY-2 chamber were correct indicated that area and volume were the same as the values given in the instruction manual; but the default values in the EGM-4 were not the same as the ones measured. According to the instruction manual, however, this should not matter since in the equation used for soil carbon dioxide estimations (Eq. 7) it is the fraction between volume and area that is used. The fraction between volume and area is about the same for the default values and for the measured values. To make sure that this was correct and that it did not matter which default values that were used, 20 measurements were done. In a bucket of soil, 10 measurements with the set default area and volume and 10 measurements with the measured area and volume were done. The measurements of both EGM-4 were started at the same time to ensure that their measurements were taken up at the same point in time.

All soil carbon dioxide efflux values taken up were used, not just the end values. Independent-sample t-tests between measurements with the different settings of volume and area were done to see if it mattered which area and volume that was used as default values. It was done for both EGM-4.

To make sure that the clock did not run incorrectly on the test EGM-4, it was also checked if the clocks of both machines ran similar.

4.2.6. Comparison between test EGM-4 and reference EGM-4

The measurements taken up to control the default area and volume were also used to test if there was any difference in the estimations of soil carbon dioxide effluxes between the two EGM-4. To test if there were any differences more variation of the measurements were needed. Therefore, another 8 measurements were done at 4 different plots out in the field. 4 measurements with default values and 4 measurements with the measured values of volume and area were done. They were performed the same way as the measurements taken up to control the default area and volume. Soil carbon dioxide efflux values taken up at the same point in time were compared with one another, not just the end values.

Since it could be seen that there was no differences between the different settings of volume and area, all soil carbon dioxide efflux values could be used in a linear regression between both the machines.

4.2.7 Estimation of correction regressions for the EGM-4 measurements

To be able to estimate the proper soil carbon dioxide effluxes, the measurements taken up with the test EGM-4 needs to be corrected. For the positive values, measurements taken up in October 2005 were used. 11 different curve estimation models were fitted between the measurements taken up by the test EGM-4 and the LI-7000.

No negative values were taken up in the tests done in October 2005; for an estimate of how to recalculate the negative values, negative measurements taken up in June 2006 were used instead. The sign were changed from negative to positive and then 11 different curve estimation models were fitted between the measurements taken up by the test EGM-4 and the reference EGM-4. Signs of the best regression were afterwards changed to give correct negative values.

4.2.8 Control if the problem is changing in time

To control if the problem is floating and changing in time, the measurements taken up in October 2005 were compared with the measurements taken up in June 2006. If the test EGM-4 has the same relationship to the reference machines in both the tests, then the problem is constant between these two points in time. If the relationship differs, then the problem is of a floating kind.

In October 2005, it was shown that the best curve estimation model to correct the positive measurements taken up by the test EGM-4 was a power curve. The positive values measured by the test EGM-4 in June 2006 were therefore corrected with this power curve. If the problem was the same in June 2006 as in October 2005, these corrected values should be the same as the simultaneous values measured by the reference EGM-4, and then at least in between these two occasions, the problem would not have changed.

A linear regression was made between the corrected soil carbon dioxide efflux estimates of the test EGM-4 and the soil carbon dioxide efflux estimates of the reference EGM-4. To test if the estimates differed from one another a t-test of the linear regression was done (see subsection 4.2.4).

The measurements taken up in June 2006, had a larger variation than the measurements taken up in October 2005, and to make sure data was trustworthy, a power test for the regression coefficient was done. A power test gives an estimate of how well estimated the correlation coefficient is. A power test is done by:

$$Z_{\beta(1)} = (z - z_{\alpha})\,(n-3)^{0.5} \qquad \text{(Eq. 11)}$$

Where $Z_{\beta(1)}$ is the normal deviate, z is a transformed value of the correlation coefficient (k), (it is necessary to transform the correlation coefficient, because otherwise it will not be normally distributed), z_{α} is the critical value of the z distribution and n is the sample size. z is calculated by

$$z = 0.5 \ln\left((1 + k)\,(1 - k)^{-1}\right) \qquad \text{(Eq. 12)}$$

From a table of proportions of the normal curve, the proportions (β) can then be found. The probability (P) of how correct the correlation is, can then easily be estimated by taking:

$$P = 1 - \beta \qquad \text{(Eq. 13)}$$

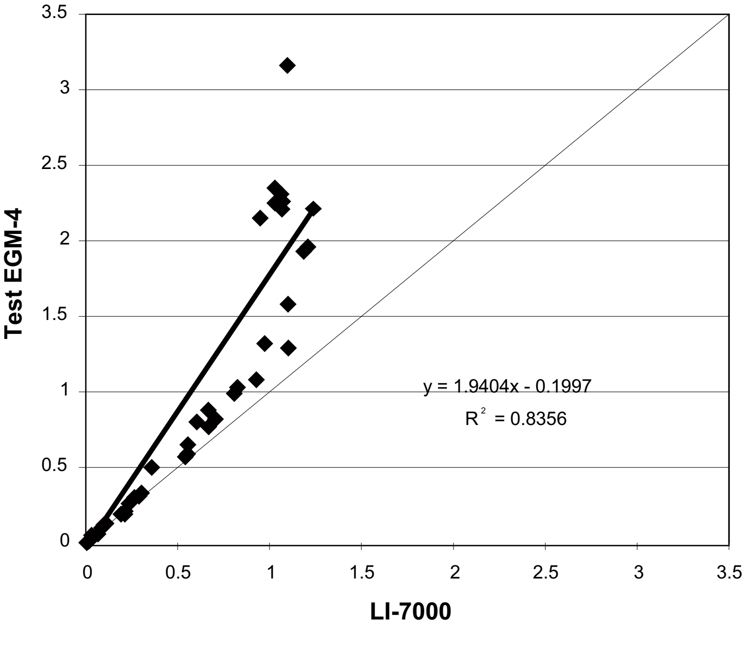

Figure 4-1. *Comparison between test EGM-4 and LI-7000. Soil carbon dioxide effluxes are in g CO_2 m^{-2} h^{-1}. The thick line is the linear regression and the thin line is the one to one relationship.*

4.3 Results

4.3.1 Control of EGM-4 soil carbon dioxide efflux estimations

The comparison between the soil carbon dioxide effluxes estimated by the EGM-4 and by the LI-7000 in October 2005 can be seen in (Figure 1). The linear regression (F-value 182.92; *p*-value 0.000) clearly indicates that the test EGM-4 overestimates the soil carbon dioxide effluxes.

4.3.2 Control of the area and volume of the CPY-2 chamber

The measurements of the area of the CPY-2 chamber gave an area of 169.7 cm^2; this is the same as the area given in the instruction manual 170 cm^2. The seven measurements of the volume gave an average volume of 2,428 cm^3, approximately the same volume given by the instruction manual, 2,465 cm^3.

In the test EGM-4, the default area is 78 cm^2 and the default volume is 1,171 cm^3, i.e. not the area and the volume measured in the tests. According to the instruction manual, these default values can be used since it is the quotient between volume and area that is important, and they are about the same.

4.3.3 Control of the EGM-4 calibration

The comparison of measurements of carbon dioxide concentration between the LI-7000 and the test EGM-4 indicated that it is well calibrated. No differences could be seen in the estimations of the concentration of carbon dioxide when there were no changes in carbon dioxide concentration. This indicates that the test EGM-4 does not overestimate the soil carbon dioxide effluxes due to problems with the calibration.

4.3.4 Comparison between university EGM-4 and LI-7000

The comparison between the EGM-4 owned by the University and the LI-7000 can be seen in (Figure 4-2). The t-test with the regression coefficient and the constant indicated that this EGM-4 estimated soil carbon dioxide similar to what the LI-7000 did. This machine did not have problem with overestimations of the soil carbon dioxide effluxes.

4.3.5 Control of clock and the default area and volume of the EGM-4

The independent sample t-test performed to control if the default area and volume could have affected the estimations of the soil carbon dioxide effluxes indicated that this was neither the case for the test EGM-4 nor the reference EGM-4 (Test EGM-4: *F*-value 1.426, *p*-value 0.844; Reference EGM-4: *F*-value 0.041, *p*-value 0.921). It is the quotient between volume and area that is of importance and not the exact values used.

The control of the clock showed that the clock on both the test EGM-4 and the reference EGM-4 ran similar.

4.3.6 Comparison between test EGM-4 and reference EGM-4

The comparison between the soil carbon dioxide effluxes estimated by the test EGM-4 and by the reference EGM-4 can be seen in (Figure 4-3). The linear regression (F-value 409.03; *p*-value 0.000) clearly indicates that the test EGM-4 still in June 2006 overestimates the soil carbon dioxide effluxes.

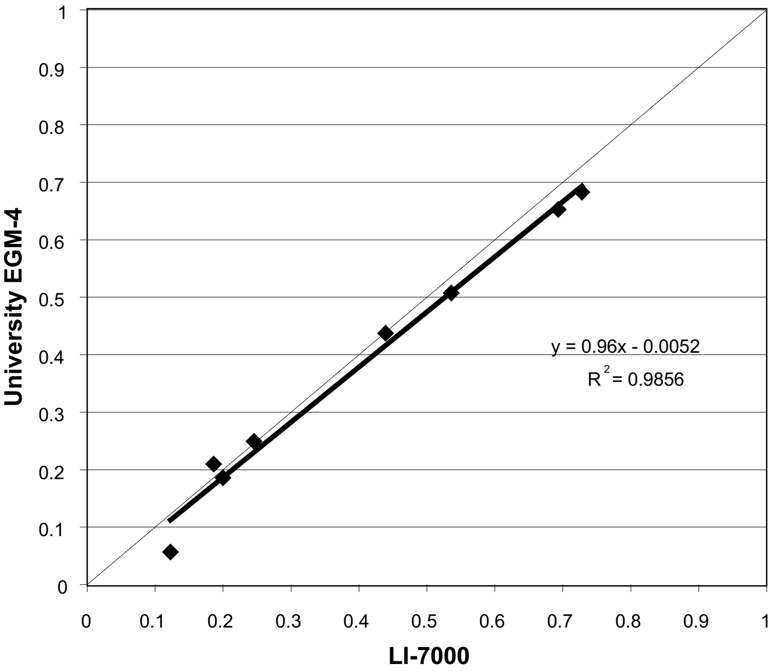

Figure 4-2. *Comparison between EGM-4 of the University and LI-7000. Soil carbon dioxide effluxes are in g CO_2 m–2 h^{-1}. The thick line is the linear regression and the thin line is the one to one relationship.*

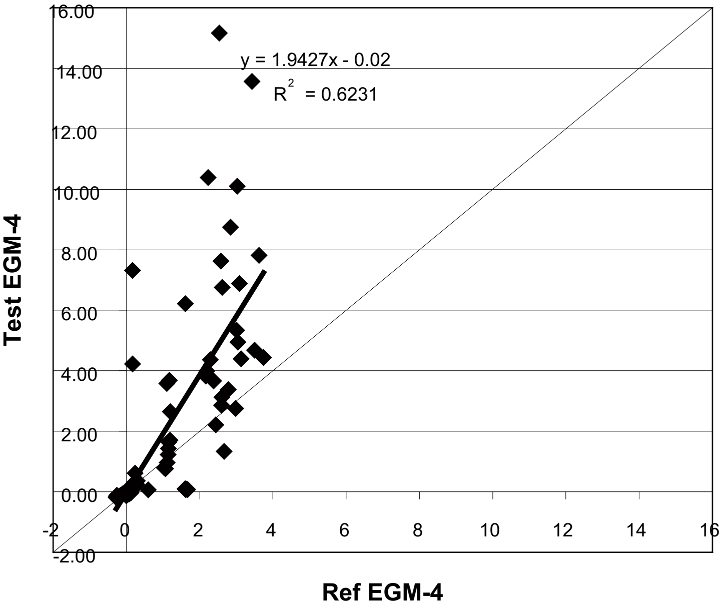

Figure 4-3. *Comparison between test EGM-4 and reference EGM-4. Soil carbon dioxide effluxes are in g CO_2 m–2 h^{-1}. The thin line is the one to one relationship and the thick line is the linear regression.*

4.3.7 Estimation of correction regressions for the EGM-4 measurements

The best curve estimation model for recalculations of the positive soil carbon dioxide effluxes estimated by the test EGM-4 was a power curve (*F*-value 1361.4, *p*-value 0.000, R^2 97.4%).

$F_{C\,R} = 0.6754\ F_{C\,T}^{0.818}$ (Eq. 14)

Where $F_{C\,R}$ is soil carbon dioxide efflux according to the LI-7000 and $F_{C\,T}$ is the soil carbon dioxide efflux according to the test EGM-4.

The best curve estimation model for recalculations of the negative soil carbon dioxide effluxes estimated by the test EGM-4 was also a power curve (*F*-value 101.12, *p*-value 0.000, R^2 82.1%).

$F_{C\,R} = -1.4676\ (-F_{C\,T})^{1.0417}$ (Eq. 15)

Where $F_{C\,R}$ is soil carbon dioxide efflux according to the reference EGM-4 and $F_{C\,T}$ is the soil carbon dioxide efflux according to the test EGM-4.

4.3.8 Control if the problem is changing in time

The comparison between corrected test EGM-4 soil carbon dioxide efflux estimates and soil carbon dioxide efflux estimates of the reference EGM-4 can be seen in (Figure 4-4). The t-test performed with the regression coefficient and constant of the linear regression indicates that the problem is not of a floating kind. At least between October 2005 and June 2006, the problem has been constant. The power test also indicated that this regression was very trustworthy; the probability of the correlation coefficient to be correct is larger than 99.99%.

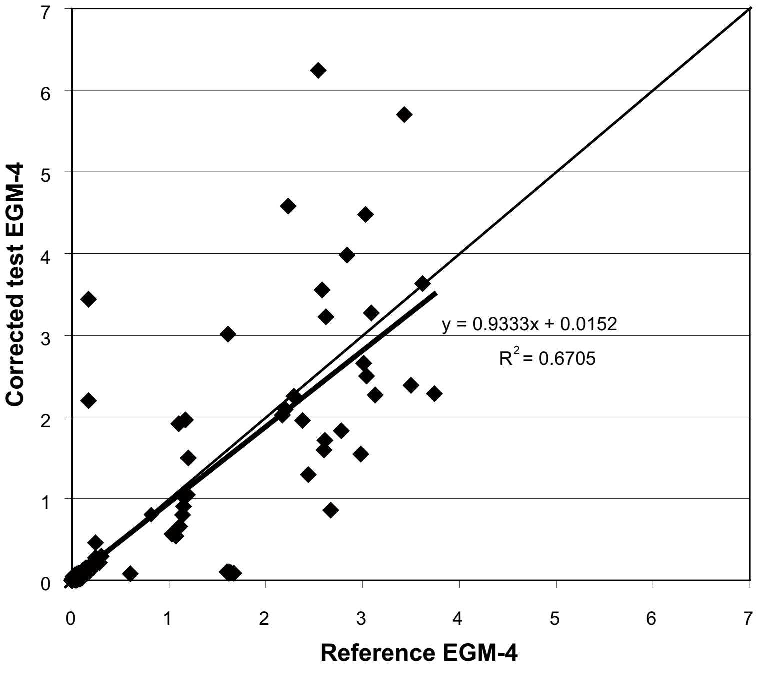

Figure 4-4. *Comparison between corrected test EGM-4 and reference EGM-4. Soil carbon dioxide effluxes are in g CO_2 m–2 h^{-1}. The thin line is the one to one relationship and the thick line is the linear regression.*

4.4 Conclusions

Following conclusions can be drawn from the tests performed.

1. The problem with the test EGM-4 is that it overestimates the soil carbon dioxide effluxes. The problem is of a slightly increasing character with higher soil carbon dioxide effluxes. The problem is not general for the EGM-4 since tests have been done with three different EGM-4 and it was only the test EGM-4 that overestimated the soil carbon dioxide effluxes.
2. The problem with the test EGM-4 is not caused by the chamber. Firstly, since the chamber did have the correct area and volume. Secondly, since tubes from both analysers entered the same chamber, but there were only problems in the test EGM-4. Thirdly, since measurements with the EGM-4 owned by the Lund University did not have problems even though it had a similar chamber. Fourthly, since the problems remained even when the test EGM-4 had a different CPY-2 chamber. Then there can be problems with the chamber as well, but that is not tested for and it is not specific for this test EGM-4, see 6.1 Shortages of the closed chamber technique.
3. The problem does not seem to be related to the calibration of the EGM-4. When there were no changes in carbon dioxide concentration, the test EGM-4 did measure correct values of the concentration. It was only when the concentration in the chamber were changing that the concentration were overestimated.
4. The test between the EGM-4 owned by Lund university and the LI-7000 indicates that this EGM-4 gives correct values. The same problem could be seen between the test EGM-4 and the reference EGM-4 as were seen between the test EGM-4 and the LI-7000, this indicates that the reference EGM-4 also gives correct values.
5. It does not matter if the default area and volume are the ones that are set in the EGM-4 or the real area and volume of the CPY-2 chamber, as long as the fraction between them are the same, (also indicated by the instruction manual).
6. The clock of the test EGM-4 went similar to the reference EGM-4 and this indicates that it is not the clock that is causing the overestimations.
7. The field measured soil carbon efflux values that were overestimated can be corrected with the power regressions estimated in this study. For the positive values, $F_{C\,R} = 0.6754\ F_{C\,T}^{0.818}$ should be used and for the negative values, $F_{C\,R} = -1.4676\ (-F_{C\,T})^{1.042}$ should be used. $F_{C\,R}$ is the corrected soil carbon dioxide efflux and $F_{C\,T}$ is the soil carbon dioxide efflux according to the test EGM-4.
8. The test EGM-4 overestimated the soil carbon dioxide effluxes as much in June 2006 as in October 2005 and this indicates that the problem of the test EGM-4 is constant in time at least between these two occasions.

This study has shown that the EGM-4 has a problem with overestimations of the soil carbon dioxide effluxes. Many tests have been done to explain the problem, but it is still not shown what causes these overestimations. When performing the tests, it has been seen that the concentration of carbon dioxide increases faster in the test EGM-4 than in the reference machine, so the problem should be in the estimates of carbon dioxide concentration. A possible explanation for the overestimations could be disturbances from water vapour. In the infrared gas analyser, water vapour absorbs some of the infrared light emitted, and this results in an overestimation of the concentration of carbon dioxide. This suggestion is still not controlled though.

This study has also made equations for the correction of the overestimated measurements, which is necessary to retrieve the correct soil carbon dioxide efflux. It has also been shown that the problem is of a constant character and does not change in time. This is an important conclusion, since otherwise it would be hard to trust the measurements.

5 Analysis of EGM-4 measurements

5.1 Introduction to analysis of EGM-4 measurements

The field measurements taken up by the EGM-4 is the raw data of soil carbon effluxes. These measurements are estimates of soil carbon effluxes at a specific spot and at a certain point in time. To make an interpretation of the measurements and to make estimates of a longer time period, it is essential to analyse the data and to temporally extrapolate them.

The EGM-4 measures net ecosystem exchange (NEE) and soil respiration. NEE is the total exchange of carbon between the atmosphere and the ground, and it composites of soil respiration and photosynthesis of the ground vegetation. To estimate photosynthesis or gross primary production (GPP) of the ground vegetation, it is therefore necessary to subtract soil respiration from NEE /Schlesinger 1997/.

Soil carbon effluxes are strongly controlled by abiotic factors. Temperature is the main factor to influence soil respiration /Kirschbaum 1995/ and for GPP, the main factors to influence are photosynthetically active radiation (PAR) and air temperature /Lambers et al. 1998/. Soil respiration and soil temperature has an exponential relationship in the soil temperature range found in the field /Widén 2002/. PAR and GPP has an exponential relationship at lower PAR values, but it levels of and saturates at higher values /Lambers et al. 1998/. GPP against air temperature has the same sigmoidal shape as an Arrhenius equation /Cannell and Thornley 1998/, which is exponential at low temperatures, levels of at intermediate values and drop at high temperature values.

These types of simple empirical models are the most common way to temporally extrapolate soil carbon effluxes. The equations with soil respiration or GPP against temperature or PAR can be used on an annual dataset of temperature or PAR to estimate annual values of soil respiration and GPP /e.g. Janssens et al. 2003, Olsrud and Christensen 2004/.

To make sure that these models gives correct values; it is necessary to evaluate the models. The best would be to evaluate the models against field measurements that are not used in the model, but since most of the time there is a lack of field data, and it is necessary to use all data in the modelling process; the same field data that is used in the model estimations must also be used in the evaluations of the model. To evaluate the model, residuals should be calculated. Residuals are a subtraction of the modelled result from the field-measured estimates and it gives an indication of how well estimated the model is in relation to the real ecosystem soil carbon effluxes. The residual tells how close the model is to the field measured soil carbon effluxes, but it does not enlighten if the model is close enough to give statistically significant proper estimates. To test if the model is statistically significant, it is necessary to estimate the standard deviation of the model. If the real value are within t times the standard deviations of the model, i.e. the 95.6% confidence interval, then the model is accurate and can be used to estimate soil carbon effluxes. If the field measured estimates of soil carbon effluxes are outside the 95.6% confidence interval of the model, then the model does not give correct estimates and cannot be used for soil carbon efflux estimates.

The analysis of the estimates of soil carbon effluxes by the EGM-4 is divided into five different parts. Firstly, it is necessary to prepare the raw data for the analysis. In the second part, the soil carbon effluxes are analysed against abiotic factors. This is done to retrieve an equation that can be used for modelling the soil carbon effluxes. In the third part, a proper dataset with annual values of abiotic factors is prepared. In the fourth part, this dataset is used with the regression equation for modelling annual values of soil carbon effluxes. Finally, the model is evaluated against the field-measured values to make sure that the model gives proper estimates. /Tagesson 2006/.

5.2 Preparation of field measured data

Soil carbon efflux measurements are taken up by the EGM-4. In the dataset it is the end estimates of soil carbon effluxes that are going to be used in the analysis, while other estimates should be omitted. The end values shall then be corrected according to Eq. 14 for the positive measurements and according to Eq. 15 for the negative values. First the measured NEE and soil respiration values shall be corrected, afterwards the GPP estimates shall be calculated. GPP is estimated by taking

GPP = NEE – soil respiration (Eq. 16)

GPP now is negative, but GPP is an uptake of carbon by ground vegetation and therefore the sign of all GPP values should be changed to become positive.

Finally, to change the soil carbon dioxide effluxes to soil carbon effluxes, the corrected NEE, corrected soil respiration and the calculated GPP values should be multiplied with 0.2729. This is the fraction of carbon in carbon dioxide.

5.3 Analysis of soil respiration against temperature

5.3.1 Separation of the data into different parts of the year

For each ecosystem all soil respiration values shall be separated into different seasons of the year, the narrower parts the better. Start the year from the beginning of the growing season. The data in Laxemar were separated into three parts of the year: the first half of the growing season (15th of March–14th of July), the second half of the growing season (15th of July–31st of October) and winter (1st of November–14th of March). In 2004, the growing season started 15th of March and ended the 31st of October. The growing season starts when the average daily temperature is more than 5°C three days in a row and it ends when it is less than 5°C three days in a row.

When separating the data, try to find as narrow time periods as possible but still with significant regressions to the climate variables. The result of the regressions is set to be significant if the *p*-value is lower than 0.05, a trend if they are between 0.05 and 0.1 and insignificant above 0.1. In the Laxemar study, regressions were used for modelling if they were significant or if they were a trend. If no significant relationships exist for the winter, average field measured values can be used for these months instead.

5.3.2 Analysis of soil respiration against abiotic factors

First, all negative soil respiration values shall be excluded to make exponential regressions possible. Then, One-Sample Kolmogorov-Smirnov tests shall be done to control if soil respiration is normally distributed. Remember that it is the opposite in One-Sample Kolmogorov-Smirnov tests; they are normally distributed if the *p*-values are insignificant. If the soil respiration data are normally distributed exponential regressions can be fitted between soil respiration and air and soil temperature. If they are not normally distributed, try to take the natural logarithm of the data (ln R) and make a new One-Sample Kolmogorov-Smirnov test. If these values are normally distributed then use a linear regression between ln R and air and soil temperature. To make the linear regression to the logarithmic soil respiration values easier to work with change the regression to exponential regressions against normal soil respiration values instead:

$$\ln R = \ln R_0 + kT \Rightarrow R = R_0\, e^{kT}$$

where R is soil respiration and R_0 is soil respiration at the reference temperature of 0°C and T is the temperature (°C). Taking the exponential of the logarithmic values changes the regression.

Other regressions can also be tested for, but it is then important to remember that these regressions are not valid for all climate circumstances. These regressions are only valid for the range in the climate parameter that was included in the regression. For example, if field measurements are taken up with air temperature up to 20°C, then it is only possible to use these other regressions with soil respiration against air temperature up to 20°C. The exponential regression is at least on a theoretically basis supposed to be valid under all circumstances. Remember that some regressions cannot be fitted to negative data since it is not possible to take the square root of a negative number; in these cases the negative values have to be taken away. Other regressions can be fitted to negative values and then all data shall be included.

In the exponential equation k is related to Q_{10}, the relative increase in soil respiration when soil temperature is increased by 10°C. Q_{10} can be calculated by using the formula /Strömgren 2001/.

$$Q_{10} = e^{10k} \qquad \text{(Eq. 17)}$$

5.4 Temperature modelling

5.4.1 Modelling air temperature dataset

At the climate stations in the Laxemar and Forsmark investigation areas, air temperature is measured every half hour. During the field measurements, air temperature is also measured in each ecosystem. To retrieve an air temperature dataset for the different ecosystems, linear regressions with air temperature measured in the field against air temperature measured at the climate station should be done. The air temperature from the climate station should be taken up at the closest half-hour from when the field measurements were done. This linear regression can then be used on the air temperature measured at the climate station to get a dataset with half hour values of air temperature for the different ecosystems.

5.4.2 Modelling soil temperature dataset

If soil temperature is logged somewhere in the surrounding area exactly the same thing can be done with the soil temperature measurements as were done with the air temperature to retrieve a modelled soil temperature dataset for each ecosystem. If soil temperature is logged for a part of the period, use the method under "3.4.2 Soil respiration modelling" in /Tagesson 2006/. If soil temperature is not logged at all, the model that was used by /Tagesson 2006/ to estimate a soil temperature dataset in the Laxemar investigation area must be used.

If the soil temperature model by /Tagesson 2006/ in Laxemar is going to be used, first calculate the average daily air temperatures measured at the closest climate station. This should be done for the entire period over which the models span. Then to change average daily air temperature to average daily soil temperature, use the regression:

$$T_{as} = 0.7875\ T_{aa} - 1.0272 \qquad \text{(Eq. 18)}$$

Where T_{as} is average daily soil temperature and T_{aa} is average daily air temperature.

To get the diurnal variations of soil temperature, the amplitude for the soil temperature (A_s) for every day is needed. The amplitude is an estimate of how much the temperature oscillates over the day. The amplitude of the daily air temperature (A_a) is calculated by taking the range of air temperature for each day and divide it by two, i.e. for each day subtract minimum air temperature from maximum air temperature and divide it by two. The range in temperature should be found in the statistical program used. Then to calculate the amplitude for the soil temperature (A_s) use the regression:

$$A_s = 0.2991\ A_a^{0.858} \qquad \text{(Eq. 19)}$$

The temperature variation within the day, i.e. the diurnal variation, $\cos(\omega\, t + 1.7252))$, should be added to the equation. 1.7252 is added to adjust for the time lag between soil and air temperature. The soil temperature can now be modelled for the entire period /Hillel 1980/.

$T_s(t) = T_{as} + A_s(\cos(\omega t + 1.7252))$ (Eq. 20)

where

$T_s(t)$ is modelled soil temperature (°C) at day time t

T_{as} is average daily soil temperature

A_s is modelled amplitude of diurnal variation in soil temperature

ω is 2π and

t is time in fraction of the day that has passed for each half hour, i.e at 00:00 it is 0.0 and at 12:00 it is 0.5 etc.

Now the soil temperature of the climate station is modelled. To retrieve the soil temperature for each ecosystem, make linear regression with field measured soil temperature against modelled soil temperature at the closest half hour from when the field measurements were taken up.

5.5 Soil respiration modelling

The exponential regression equations with soil respiration against air and soil temperature can now be used on these both datasets to model soil respiration for the same period as the extent of the datasets. To get annual values of soil respiration, add modelled values for an entire year together. Average values for the different months can also be calculated for the seasonal changes in soil respiration. If no significant relationships exist for the winter, average field measured values can be used for these months instead.

5.6 Analysis of GPP against PAR and air temperature

5.6.1 Analysis of the effect of GPP on soil carbon effluxes

GPP taken up during the growing season should be separated from the data taken up for the other parts of the year. For each ecosystem, GPP taken up during the growing season should be included in One-Sample Kolmogorov-Smirnov tests to control if GPP values are normally distributed. Again, remember that they are normally distributed if the *p*-values are insignificant. If data is normally distributed a One-Sample t-test against zero should be done and if data is not normally distributed a Mann Whitney U-test against zero should be done. These tests are done to control the effect of GPP on soil carbon effluxes; if GPP is significantly separated from zero then the ground vegetation takes up a significant part of the soil carbon effluxes from the ground. If GPP is not significantly separated from zero, then the vegetation does not take up enough carbon to significantly alter the soil carbon effluxes.

5.6.2 Analysis of GPP against abiotic factors

For those ecosystems where GPP has an effect on soil carbon effluxes, the effect of air temperature and PAR on GPP can be analysed for. The most theoretically correct regression for the GPP-air temperature relationship is the Arrhenius equation. To make it easier, the cubic regression with the same sigmoidal shape as the Arrhenius equation can be used /Cannell and Thornley 1998/.

The cubic regression:

$GPP = GPP_0 + b_1T_a + b_2T_a^2 + b_3T_a^3$ (Eq. 21)

Where T_a is the air temperature, GPP_0 is GPP at 0°C and $b_{1,2,3}$ is coefficients of the regression.

The most theoretically correct relationship between GPP and PAR is the light response curve:

$$GPP = -(GPP_1 + R_d)\,(1-e^{((-k*PAR)/(GPP1+Rd))}) + R_d \qquad \text{(Eq. 22)}$$

Where GPP_1 is saturated GPP, R_d is deduced respiration and k is quantum efficiency; these are coefficients in the light response curve. Saturated GPP is the plane where GPP levels out, deduced respiration is NEE at zero PAR and quantum efficiency is the initial slope of the curve. Quantum efficiency gives the efficiency of the vegetation to take up PAR.

The cubic regression can be fitted in any good statistical program, whereas the light response curve must be fitted in a table curve-fitting program such as Table-curve Windows v 1.0.

Other regressions can also be tested for, but as told before it is then important to remember that these regressions are just valid for the climate circumstances that were included in the regression. Eq. 21 and 22 is at least on a theoretical basis valid under all circumstances. Remember that some regressions cannot be fitted to negative data since it is not possible to take the square root of a negative number. Then the negative values have to be taken away.

5.7 GPP modelling

GPP modelled against PAR can only be done in ecosystems without a canopy, due to the shading factor of the trees. At the closest climate station, global radiation is measured every half hour. The climate station measures radiation in W m^{-2}, but the EGM-4 measures PAR in micromoles m^{-2} s^{-1}. W m^{-2} can be changed to micromoles m^{-2} s^{-1} by multiplication with 4.6 (Hickler pers. comm.). During the summer months, i.e. for the growing season, PAR can be calculated by taking 0.45 of the global radiation /Monteith and Unsworth 1990/. The light response curve with GPP against PAR can then be used on the PAR dataset to extrapolate GPP throughout the growing season. To get annual values of GPP, add all modelled values for an entire year together. Average values for the different months can also be calculated to observe the seasonal changes in GPP.

To model GPP against air temperature, the modelled air temperature dataset from 4.4.1 for each ecosystem should be used. The cubic regression with GPP against air temperature can be used on the dataset over the growing season for each of the ecosystems. To take away nighttime GPP in the air temperature model, the modelled GPP values with zero PAR shall be set to zero. To get annual values of GPP add all modelled values together for the entire growing season.

5.8 Model evaluations

5.8.1 Residual estimations

To make sure that the models gives proper and accurate results it is necessary to evaluate them. Residuals are necessary in this evaluation. They are an approximation of how close the model estimates the soil carbon effluxes to the real values. Residuals are calculated with modelled soil carbon efflux values subtracted from field-measured soil carbon effluxes. The modelled value should be modelled at the closest half-hour from when the field measurements were taken up. Afterwards, calculate average residuals for each measurement occasion. Residuals should be calculated for all models and all ecosystems.

5.8.2 Standard deviation estimations

To control that the models are acceptable and gives proper estimates of the soil carbon effluxes it is necessary to calculate the standard deviation of the models. For the regression models without propagation errors in them, standard deviation is given in the statistical program used, but in the other cases it is necessary to calculate them with the formula for error of propagation /Tagesson 2006/.

Standard deviation of PAR modelled GPP

For PAR modelled GPP, there is no propagation errors and standard deviation from the light response curve is therefore given directly in the table curve-fitting program used. But, since the field measurements were corrected for the overestimation by the EGM-4, it is also necessary to add the standard deviation from this part. Standard deviations cannot be added together, but variances can. Therefore, firstly, it is necessary to change the standard deviation from the light response curve to variance by squaring the standard deviation. Variance is just standard deviation (s_b) squared $(s_b)^2$. Secondly, calculate the variance from the correction of the GPP data. This is done by taking 0.0072 for all the negative values that are used in the model and by taking 0.0121 for all the positive values used in the model, as found in table 1. An average variance value for all values used in the model should then be calculated. It is this average value that should be added to the variance from the light response curve.

$$s_{b\,(\text{PAR model})} = s_{b\,(\text{light response curve})} + s_{b\,(\text{correction})} \qquad \text{(Eq. 23)}$$

Afterwards calculate the standard deviation again by taking the square root of this sum.

Variances calculated with the formula for error of propagation

For all other models, which included several modelled variables, the formula for error of propagation should be used since both the values of the x- and y-axis is modelled /Tagesson 2006/. In this analysis, it is necessary to calculate the standard deviation for all models but the PAR model, since air and soil temperature is modelled.

$$\sigma^2(f) = (\partial f/\partial x)^2\, \sigma^2(x) + (\partial f/\partial y)^2\, \sigma^2(y) + (\partial f/\partial z)^2\, \sigma^2(z) +$$

$$(\partial f/\partial a)^2\, \sigma^2(a) + 2\,\mathrm{cov}\,(x, y)\,(\partial f/\partial x)\,(\partial f/\partial y) \qquad \text{(Eq. 24)}$$

Where

$\sigma^2(f)$ is variance in modelled result

$\sigma^2(x)$ is variance of factor in function, i.e. R_0 and GPP_0

$\sigma^2(y)$ is variance of coefficient in function, k

$\sigma^2(z)$ is variance of variable in function, $T_{air,}$ and T_{soil}

$\sigma^2(a)$ is variance of soil carbon effluxes

cov (x, y) is covariance between factor and coefficient in function

$(\partial f/\partial x,y,z,a)^2$ is the square of the partial derivative of the regression analyzed in respect to the variable x or y or z or a.

In all models, it is necessary to add the variances from the correction of soil carbon efflux data, done in the first part of this report. In case the soil temperature model in subsection 5.4.2 from /Tagesson 2006/ is used, it is also necessary to add variances from this part in the soil temperature modelled soil respiration. These variances needed in the formula for error of propagation are given in table 1.

Table 1. Variances from previous studies needed in the calculation of variances.

Model	Variance
Soil temperature	1.416
Correction of negative soil carbon dioxide effluxes	0.0072
Correction of positive soil carbon dioxide effluxes	0.0121

An example in how to calculate variance with the formula for error of propagation

The variance of the air temperature modelled soil respiration is to be calculated. The exponential regression with soil respiration against air temperature looks like:

$R = R_0\, e^{kTa}$

In the first part of the formula for error of propagation, i.e. $(\partial f/\partial x)^2\, \sigma^2(x)$, you first have to take the derivative of the exponential regression in relation to R_0. Then you square this derivative and multiply it with the variance of the factor R_0. The variance of the factor R_0 can be calculated from the standard deviation that is given in the statistical program.

Then the second part needs to be done $(\partial f/\partial y)^2\, \sigma^2(y)$, where you first take the derivative of the regression in relation to *k* squared and then multiply it with the variance of the factor *k*. And then since air temperature is modelled the third part $(\partial f/\partial z)^2\, \sigma^2(z)$ is also needed. Again, the derivative of the regression in relation to air temperature squared is taken times the variance of the air temperature. The variance of the air temperature is given in the statistical program used when the linear regression were done for calculations of the air temperature for each ecosystem. When the same thing is done for the soil temperature model, the variance is given in table 1.

Since the soil respiration data also needed to be corrected because of the problem with the EGM-4, the variance from this part also needs to be added, this is the fourth part $(\partial f/\partial a)^2\, \sigma^2(a)$. The derivative of the exponential regression in relation to R is just 1, and therefore this variance is just needed to be added. Since all negative values are taken away in the exponential regressions, the variance for the correction of these models is just the variance for the correction of the positive values, i.e. 0.0121. Otherwise, the variance from the correction of the data is found by taking the average of the variance for all values that are used in the regressions, as explained above in the part about calculation of standard deviation for the GPP-PAR regression.

Finally, two times the covariance between the two coefficients should be added. The 2 is there since the covariance is between both coefficients. The covariance can be given in a statistical program. In SPSS 12.0.1, the covariance can only be given for linear regressions. Therefore to find the covariance for all exponential regressions, you need to take the logarithm of the data and make a linear regression. To find the covariance between the coefficients and not just the between the x and y axis, you need to add a column with 1 in it. The same amount of 1 should be put in, as there is data in the regression. Then in the linear regression you add this new column as an independent variable. Under statistics, you set that you want the covariance matrix and under the options you set exclude the constant in the equation. This covariance between the coefficients is then multiplied with 2, the partial derivative of the first coefficient and the partial derivative of the second coefficient.

To get the final variance of the entire function, add all these values together.

Variances for regressions with several modelled coefficients

For the cubic regression, with several modelled coefficients, it is necessary to make a similar analysis. The cubic regression looks like:

$GPP = GPP_0 + b_1 T_a + b_2 T_a^2 + b_3 T_a^3$.

For each of the coefficients, it is necessary to make a similar step as explained above, i.e. the formula for propagation of errors is just extended to include all the regression coefficients. It is the same thing with the covariances, the covariance between all coefficients must be included in the formula. To get covariance for the cubic regression cannot be done so the regression must be transformed to a multiple linear regression; this is pretty straightforward to do. All you need to do is to add two variables with transformed values of the temperature measurements. The first transformation is to take the square of the temperature measurements and the second transformation is to take the cube of the temperature measurements. Then, you can make a linear regression with several variables. Just as in the calculation of the covariance for the exponential regressions, it is also necessary to add one column with 1. Then again you extend the formula for propagation of errors and add two times the covariance between all possible combinations of coefficients times the partial derivative of both the coefficients.

Evaluation of the models

The variance should be calculated for every modelled value of the entire period, which means that variances should be calculated for every half hour modelled value for the entire year, if the dataset with half hour values from the climate stations has been used. Then, to get the variance for the annual estimates of the modelled values add the variances together. Variance is given in g C (m^2 hour)$^{-1}$ and if the variances are modelled for every half hour value, the added sum must be divided by two. To calculate the standard deviation of the annual estimates by the models the square root of the variances shall then be taken.

Finally, to evaluate the model the 95.6% confidence interval is needed. The 95.6% confidence interval is found by taking t times the standard deviations of the models (Eq 10). t is from the Students t-test and it can be found in a table of critical values for t-distribution. The t-value found in the t-table should be the one that is for the number of measurements used in the model.

Then finally, it is going to be checked if the model gives proper and accurate estimates of soil carbon effluxes that are significantly close to the real soil carbon efflux values measured in the field. The average residuals calculated under subsection 5.8.1 should be taken against the estimated 95.6% confidence interval. The 95.6% confidence interval used should be the one that is calculated for the same point in time as the field measurements were taken up. If the residuals are within the interval, the model is accurate and acceptable and it can be used for soil carbon efflux estimates in the Laxemar and Forsmark investigation areas.

Good luck!!!

6 Discussion

6.1 Shortages of the closed chamber technique

The measurement of soil carbon effluxes with chambers is the most commonly used technique for estimating soil carbon effluxes. It has been used widely for several decades and the main potential sources of error are hereby well known /Davidson et al. 2002/. The trouble with the closed chamber technique is that the chamber always affects the soil that it does its measurements on, since the concentration of carbon dioxide in the chamber is altered and this affects the concentration gradient from the soil /Davidson et al. 2002/. When the concentration in the chamber increases it results in a decrease of the diffusion gradient, which results in an underestimation of the soil carbon dioxide effluxes. This problem can be corrected for by using a quadratic relationship in the curve fitting (see subsection 3.1) and by using short measurement periods.

The large problem with the estimates of soil carbon dioxide effluxes is caused by under or overpressure in the chamber /Widén and Lindroth 2003/. Over and under pressure in the chamber can occur due to circulating gases and warming or cooling of chamber air. In an over pressurized chamber soil carbon dioxide effluxes is slowed down while in an under pressurized chamber carbon dioxide is sucked out of the soil /Davidson et al. 2002/. These problems can be avoided with properly designed chambers.

/Pumpanen et al. 2004/ did a study where several different chambers frequently used in the estimations of soil carbon dioxide effluxes were compared to a known CO_2 flux. Their study showed that chambers under and overestimated soil carbon effluxes with between –21 to + 33%, depending on type of chamber and method used for mixing the air in the chamber. In average the estimates of the chambers were within 4% of the reference flow /Pumpanen et al. 2002/. Tests were done with SRC-1 chambers from PP-systems and it ranged between underestimates of the soil carbon dioxide effluxes with between – 14% to overestimates with + 33%. The differences depended on which sand and which soil moisture that the measurements were done on and if collars were used or not.

Most of the times the SRC-1 overestimated the soil carbon effluxes and this were explained by turbulences from the fan. The use of collars also resulted in a larger increase than when no collars were used. In measurements with collars, the chamber gets tightly sealed to the ground and the better results without the collar could be explained by leakage of CO_2 from under the edges of the chamber, which would compensate for the disturbance of the fan. In the CPY-2 measurements done in Laxemar and Forsmark, collars were not used. Without a collar the estimates of the SRC-1 chamber were between 0.94 and 1.19, with an average of 1.05 of the reference flux. The SRC-1 chamber is different from the CPY-2 chamber though; it is made out of aluminum and it is nontransparent. It is hereby hard to tell if 1.05 is a correction factor, which also could be used for the CPY-2 chamber. The best would naturally be if tests were done with a CPY-2 chamber against a known reference flow.

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