Spatial heterogeneity of soil CO_2 efflux at ADVEX site Norunda in Sweden

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Abstract

This study investigates the spatial variation in soil carbon dioxide (CO_2) efflux in a boreal mixed forest mainly dominated by Scots pine *(Pinus sylvestris L.)* and Norway spruce *(Picea abies L.)* in the ADVEX expermental site in Norunda, in central Sweden. Soil CO_2 efflux measurements were performed in 72 collars around the main tower by using a portable LI-6250 infrared gas analyzer connected to a home-made dark chamber. The average soil CO_2 efflux normalized to temperature of 10 ^{o}C (R_{10}) from the forest floor in Norunda as calculated from 72 collars was 2.09±1.36 [µmol m^{-2} s^{-1}]. This was the sum of the total soil respiration mainly originating from root respiration (autotrophic), microbial respiration (heterotrophic) in addition to the respiration from forest floor vegetation which was not removed from the upper soil layer during the measuring of soil CO_2 efflux. Measurements were performed between the 7th and 12th of June 2007 during the daytime between 11 am and 4 pm. The spatial heterogeneity of soil respiration as expressed by coefficient of variation (CV) was 65%, which reflects inconsistency in soil CO_2 efflux among the 72 collars in the study area. In order to investigate the reasons for spatial variation in soil CO_2 efflux, a number of variables were measured in each collar directly after CO_2 efflux was measured. First, depth of the soil layer above boulders showed a significant relationship with R_{10} (R^2=0.48). Second, humus thickness also showed a significant relationship with R_{10} (R^2=0.21). Third, there was a significant difference in R_{10} with micro-topography (between normal and elevated points). Fourth, a weak negative correlation was found between R_{10} and weight of the dry mosses with R^2=0.06. Fifth, a non- significant relationship between R_{10} and distance, diameter and species of the nearest three trees to the collar was found. The variables that measured in the field account about 50% the reasons behind spatial variation in soil CO_2 efflux, therefore others variables are suggested to investigate for future studies.

Keywords: soil CO_2 efflux, spatial variation, depth of the soil, humus thickness, micro-topography, stand and forest floor characteristics.

Sammanfattning

Denna studie undersöker den rumsliga variationen i markens koldioxid-utflöde (CO_2) i en boreal blandskog, huvudsakligen dominerad av tall *(Pinus sylvestris L.)* och gran *(Picea abies L.)* i ADVEX experimentsite i Norunda, centrala Sverige. Mätningar av markens CO_2 gjordes i 72 collars omkring huvudtornet med hjälp av en LI-6250 infraröd gasanalysapparat kopplad till en hemmagjord mörkkammare. Medelvärdet för markens CO_2-utflöde vid en normaliserad temperatur på 10^oC (R_{10}) i Norunda, som beräknats från 72 collars, var 2.09 ± 1.36 [µmol m^{-2} s^{-1}]. Detta var summan av den totala markrespirationen, som huvudsakligen kom från rot-respiration (autotrofisk), mikrobiell respiration (heterotrofisk) utöver den respiration som kom från skogsmarken som inte var borttagen från det översta jordlagret under mätningarna av mark-CO_2-utflöde. Mätningar utfördes mellan den 7:e och 12:e Juni 2007, dagtid mellan 11 på förmiddagen och 4 på eftermiddagen. Den rumsliga heterogeniteten för markrespiration som uttrycks av variationskoefficienten (CV) var 65%, vilket reflekterar inkonsekvensen i CO_2-utföde mellan de 72 collars i studieområdet. För att undersöka orsakerna bakom den rumsliga variationen mättes ett antal variabler i varje collar direkt efter att CO^2-flödet var uppmätt. Markdjup visade ett signifikant samband med R_{10} ($R^2=0.48$). Humustjocklek visade också ett signifikant samband med R_{10} ($R^2=0.21$). Det var en signifikant skillnad i R_{10} med mikro-topografi (mellan normala och upphöjda punkter). En svag negativ korrelation på $R^2=0.06$ upptäcktes mellan R_{10} och den torra mossans vikt. . Ett icke signifikant samband mellan R_{10} och avstånd till, diameter på och art på det närmsta trädet hittades. Variablerna som mättes i fält förklarade inte den rumsliga variationen i mark-CO_2-utflöde och således föreslås att andra variabler undersöks i framtida studier.

Nyckelord: mark-CO_2-utflöde, rumslig variation, markdjup, humustjocklek, mikrotopografi, trädbestånd och skogsmarkskaraktäristik.

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Chapter 1: Introduction

Carbon dioxide is one of the most important components of the atmosphere; it plays a crucial role in the energy exchange between the earth's surface and the atmosphere. It is also considered a limiting factor controlling the rate of the photosynthesis process (where oxygen is emitting by plants and CO_2 is absorbed), which ultimately leads to buildup of the biomass material and sequestrates large quantities of atmospheric CO_2.

A significant increase in atmospheric CO_2 concentration has been observed over the last 250 years; from 280 ppm in pre-industrial times to 385 ppm in 2009. Such an increase may be the reason for the mean air temperature rise of 0.6 ± 0.2 °C during the last 100 years. This rise in temperature has resulted in an increase of the ocean surface temperature which then reduces the water's capability to absorb CO_2. This means more CO_2 in the atmosphere, and a very important insight with consideration to global warming *(IPCC, 2007; Janssen et al., 2001)*. Increasing air temperature also has an effect on the rise of the soil respiration rate, which mainly originates from root respiration (autotrophic respiration) and accounts for about 28-70% of the carbon returned to the atmosphere from the soil surface, and the rest originating from microbial respiration (heterotrophic respiration) *(Raich & Schlesinger, 1992; Hansson et al., 2000).*

Soil respiration as the second largest source of CO_2 to the atmosphere after ocean flux *Schlesinger & Andrew, (2000)*, can store and release considerable quantities of carbon through natural processes including litter deposition as an input of CO_2 to the soil, and microbial respiration through decomposing of soil organic materials as an output of CO_2 from the soil *(Drewitt et al., 2002; Raich & Schlesinger, 1992).* Soil as a main carbon source or sink is very important in carbon budget for many reasons since it plays a vital role in controlling global climate change *(Raich & Schlesinger, 1992).* Additionally, soil is a major biospheric reservoir for carbon (C), containing globally about 1550 Pg of organic carbon, more than twice the amount in the atmosphere and three times as much as stored in the vegetation *(IPCC, 2007; Robert, 2001).*

The boreal forest, which is considered the second largest terrestrial biome in the world, covering approximately $15.6*10^6$ km^2 (*Gower, et al., 2001),* plays a major role in the global carbon cycle. It sequesters about 62 – 78% of the global terrestrial carbon pool, of which about 70% of carbon is stored in the soil *(Dixon et al., 1994; Schimel, 1995).*There is great concern over future increases in temperature of the boreal forest content of organic carbon. Their large soil organic matter content and the magnitude of expected warming at higher latitudes leads to greater releases of carbon dioxide to the atmosphere with increasing temperature *Houghton et al., (2001).*

Therefore, a very small change in this huge quantity of deposited soil organic carbon in boreal forests, as a result of increasing temperature, will lead to accelerated decomposition rates and a greater release of CO_2 to the atmosphere. This will ultimately have significant effects on the global carbon cycle and climate change *(Raich & Tufekcioglu, 2000; Hagedorn et al., 2001)*. Consequently, the traditional sink of carbon dioxide will act as a source of carbon dioxide to the atmosphere. It has been projected that through careful land use management, or forest management, it might be possible to increase the quantity of organic matter stored in the soil. This may thereby offset a portion of fossil fuel CO_2 emissions which is estimated at about 6.5 Gton emitted every year to the atmosphere as a result of human activity (anthropogenic source) *(IPCC, 2001)*. According to Schlesinger & Lichter, (2001) there is evidence that the quantity of carbon that can be stored in soil is either quite limited, or that existing reservoirs of stored soil carbon may act as a net source of carbon dioxide through increases in respiration rates as a result of increased temperatures *(Lashof, 1989)*.

And as a CO_2 concentration in the soil reported by, *Clinton & Vose (1999)* that carbon dioxide concentrations observed in forest soils are commonly at an amount greater than aboveground CO_2 concentration, and show evidence of great temporal and spatial variability. Therefore one obstacle to accurately quantify soil CO_2 efflux is the large spatial heterogeneity in the physical and biogeochemical processes leading to soil CO_2 production and efflux *Scott-Denton et al. (2003)*. Also, it has been mentioned by *Schlesinger (1977)* that soil respiration rates vary significantly among major biomasses depending on the degree of decomposition rates by microbial activity. Therefore, all these variables must be taken carefully because they are very important to estimating soil CO_2 efflux accurately in order to evaluate the carbon budget of an ecosystem.

The rate of soil CO_2 efflux is mainly controlled by the rate of CO_2 production by heterotrophic and autotrophic respiration in the soil. But it is also modified by factors affecting CO_2 movement out of the soil profile (e.g. terrain level (shape) and gravity), influencing on the vertical and lateral movement of the water in the soil which determine dryness and wetness of the soil. And lastly, it controls for differences in soil CO_2 effluxes among different locations *(Western et al., 1998, 1999; Riveros-Iregui et al., 2008)*.

Forests (particularly temperate and boreal forests) have always been considered as net carbon sinks, but Norunda forest is considered a source of CO_2 efflux. This was determined after a research group installed a 102 m high tower equipped for measurements of a variety of fluxes and meteorological data. In Norunda the annual balance of CO_2 efflux is positive which means that the carbon accumulated every year by the terrestrial ecosystem is less than the amount released to the atmosphere.

In Norunda there is a net flux of CO_2 towards the atmosphere with a mean of about 190 g CO_2 m^{-2} y^{-1} (*Lindroth et al., 1998; Materia S., 2004).* The reasons behind this are still unclear, but according to the history of the site, both clear-cut and forest management processes particularly (drainage) are possible factors affecting the carbon balance *(Lindroth et al., 1998; Lindroth et al., 2003).* As mentioned before that central tower site (CTS) measurements in ADVEX project revealed that Norunda has been a source of CO_2. So through this experiment they try to analyze the possible reasons behind this phenomenon.

It has been reported by *Raich et al. (1990); Hanson et al. (1993); Xu & Qi (2001); Franklin & Mills (2003)* that soil CO_2 efflux shows a high degree of spatial heterogeneity, particularly across small spatial scales in forest, grassland and farmland ecosystems at different time scales. This is probably due to the interconnections of different environmental, geological and vegetation characteristics. This great variety of factors is what leads to limitation of quantifying spatial variations in soil CO_2 efflux and what makes it more difficult *(Rayment & Jarvis, 2000).* Even supposing that soil respiration and its spatial controlling factors (e.g. root density, uneven distribution of organic materials etc) are critical for accurately estimating the ecosystem C budget and that understanding the response of soil respiration to the land use change and to the global climate change are also important for accurately estimating of ecosystem C budget.

There are still many issues which are not clearly related to the spatial and temporal variation in soil respiration. This is because the soil complexity and spatially heterogeneous mixture of different compounds makes this process more complicated to be studied extensively *Xu & Qi, (2001).* This is what makes Norunda forest interesting to investigate: the reasons behind spatial variation of soil CO_2 efflux. The figure below shows the spatial heterogeneity of soil CO_2 efflux among 72 collars in the ADVEX site in Norunda, which range between 0.30 – 7.68 [µmol m^{-2} s^{-1}]. In Norunda forest spatial heterogeneity of soil CO_2 efflux is a dominant and conspicuous feature, as shown by our measurement data. This variability may be due to several factors that affect soil CO_2 efflux, such as depth of the soil layer *(Jassal et al., 2005)*, humus thickness (*Stork & Dilly*, *1998),* soil microbial population levels *(Klopatek, 2002)*, levels of plant root activity *(Ewel et al., 1987).*
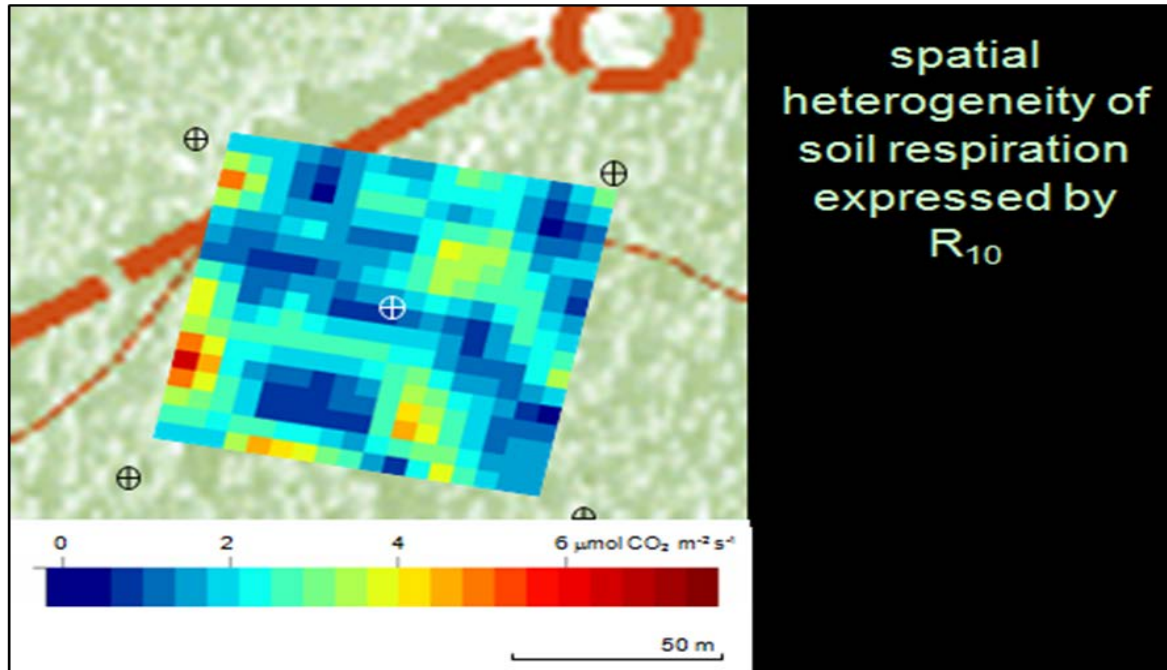
Figure 1: Spatial heterogeneity of soil CO2 efflux in ADVEX site, Norunda, Sweden, ranged between 0.30-7.68 [μmol m^{-2} s^{-1}].

Figure 1 shows the spatial heterogeneity of soil CO_2 efflux at ADVEX site, Norunda, Sweden, which range between 0.30 – 7.68 [µmol m-2 s-1]. There is a very clear inconsistency in soil CO_2 efflux among the 72 collars in the study area.

1.1 Aim of the study

The aim of this study is to analyze the average soil respiration in respect to a number of soil attributes, such as depth of the soil layer above boulders, humus thickness, micro-topography, stand characteristics (distance, diameter and species) of the nearest three trees to the measurement collar and weight of the mosses in each measurement collar. Analysis will also be conducted on soil CO_2 efflux in Norunda boreal forest, which mainly consist of Scots pine *(Pinus sylvestris L.)* and Norway spruce *(Picea abies L.)* growing on a highly heterogeneous till soil with a high content of stones and blocks. This study is an effort to investigate the extent to which these factors influence the spatial heterogeneity of soil CO_2 efflux, which is very important for accurately estimating the carbon budget in an ecosystem. Therefore we hypothesized that:

1. There will be higher soil CO_2 efflux as the depth of the topsoil layer increases, as a consequence of more tree roots and forest floor roots' density and distribution in this active soil horizon.

2. There will be higher soil CO_2 efflux as humus thickness increases, because is assumed there will be more abundant microbial activity.

3. There will be higher soil CO_2 efflux as the diameter increases and distance decreases of the nearest three trees to the measurement collar since more root biomass is supposed to exist under the collar, which is close to the tree trunk with a big diameter.

4. There will be difference in soil CO_2 efflux under trees depending on the litter quality and quantity of the dominant tree species.

5. There will be differences in soil CO_2 efflux depending on the micro-topography of the selected collar location (normal, elevated or deepened).

6. There will be lower soil CO_2 efflux as the dry weight of the mosses increase in the measurement collar, since we expect a negative correlation between moss biomass and root biomass of the existing bushes.

Chapter 2: Background

2.1 Terrestrial carbon cycle

For the global carbon cycle, soil organic carbon represents the largest reservoir of carbon dioxide in interaction between the terrestrial ecosystem and the atmosphere, and is estimated at about 1550 Pg C in one meter depth of the soil *IPCC,(2007); Robert, (2001)*.This is estimated to be twice as much as that stored in the atmosphere (750 Pg) and three times as much as stored in vegetation biomass (650 Pg) *[Schlesinger, 1977; Watson et al, 1999; Robert, 2010]*.
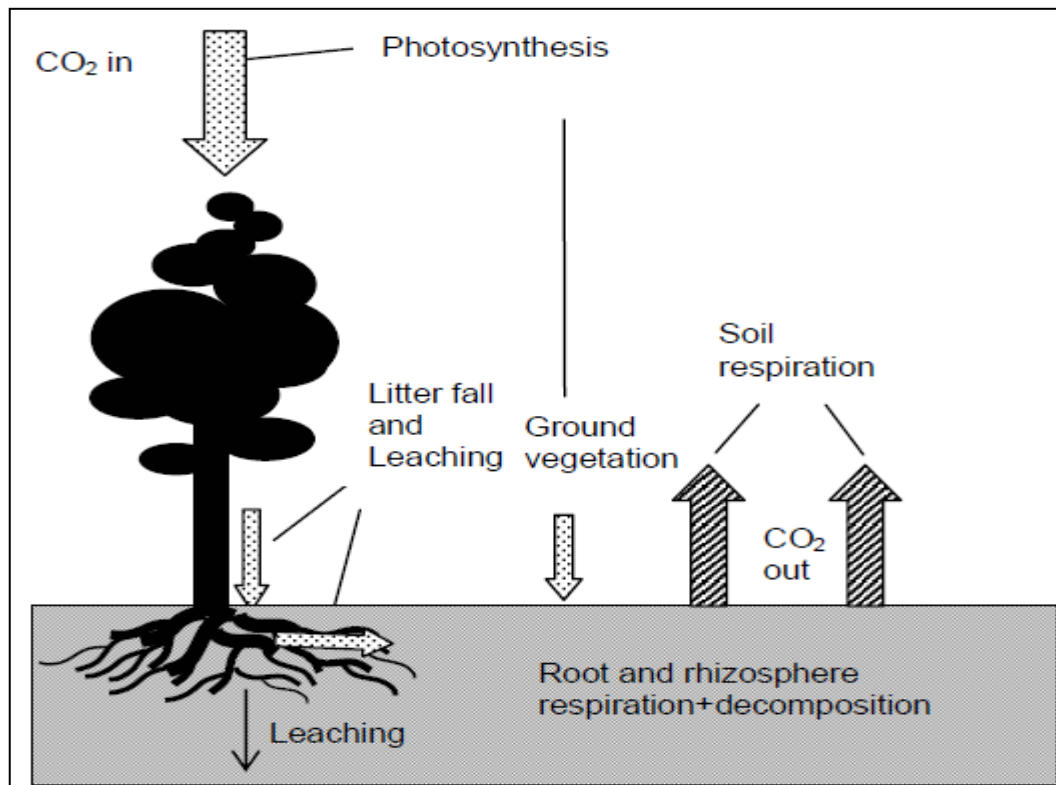
Figure 2: Terrestrial carbon cycle in forest ecosystem, and the factors controlling carbon fluxes. The two major fluxes generated by photosynthesis and respiration, which are of similar magnitude, determine whether the forest is a sink or a source of carbon *(Pumpanen, 2003)*.

Figure 2 shows terrestrial carbon cycle with the most important source of carbon to the atmosphere from terrestrial ecosystem through soil respiration processes which is include root respiration (autotrophic) and microbial respiration (heterotrophic). And also it shows sink of carbon to the terrestrial ecosystem through photosynthesis process by green plants, then litter fall and depositing of carbon to the soil.

The allocation of carbon between vegetation and soils differs by latitude, with a large part of the vegetation (25%) and soil (59%) carbon pools located in the high latitude forests *(Dixon et al., 1994a)*. It has been reported by *Schlesinger, 1977; Post et al., 1982* that significant amounts of soil organic carbon is stored in boreal forest soil and estimates about 15% of the total terrestrial carbon budget. Carbon storage and fluxes in boreal forest, reflects a balance between photosynthesis and respiration.

As a result of anthropogenic activity, the size and amount of carbon can change between pools through forest management practices. It has been projected by *Brown et al. 1996* that local forest management of carbon conservation and sequestration could mitigate emissions of carbon CO_2 by an amount equivalent to 11-15 percent of fossil fuel emissions. And the forest management practices which are required for increasing carbon sequestration are classified as followed:

a) Maintain existing carbon pools (slow deforestation).
b) Expand existing carbon sinks and pools through forest management.
c) Create new sinks and pools by expanding tree and forest cover.
d) Replace renewable sources of energy instead of those derived from the burning of fossil fuel *(Dixon et al., 1993; Dixon, 1997; Winjum et al., 1992; Dixon et al., 1994b)*

In boreal forests, the decomposition of animals' and plants' organic detritus represents an important part of terrestrial carbon cycle. This is due to vegetation processes which are often slow due to unfavorable climatic conditions (e.g. short growing season, cold soil temperature which is remain between 0-5 C most of the year, high moisture content of the soil, and low ph value (acidic soil conditions). This is a main characteristic of podzolic soil in boreal forests, mainly due to the formation of plants' derived acidic organics in litter decomposition. All these factors lead to limitations of organic matter decomposition and consequently, thick accumulation of carbon rich material on the boreal forest floor *(Harden et al, 1992; Lundström et al, 2000)*. Therefore even a small change in the carbon storage of the boreal region as a result of direct human action (e.g. deforestation, land use change) or climate change, may significantly change the global carbon cycle and lead to an increase in atmospheric carbon dioxide concentration *(Raich and Tufekcioglu, 2000)*. This case has been reported by *(Robert, 2001)*, that as a result of direct human action (e.g. deforestation, expanding of agricultural and pasture land) significant amounts of CO_2 have been released from terrestrial ecosystems into the atmosphere and is estimated at around 140 Pg from 1850 to 1990.

Frequently the major source of CO_2 production in the soil is the heterotrophic microbial respiration. Soil microorganism release CO_2 and H_2O to the atmosphere by oxidizing organic residue in order to produce essential energy for their different activities. The quality and quantity of the organic material, soil temperature, and soil moisture content are the major factors affecting microbial respiration activity.

These factors are highly variable depending on the soil's physical and chemical properties, the geographical location of the site, and the age and species' composition of the forest *(Davidson et al, 1998; Prescott et al, 2000a; Subke and Bahn, 2010).*

Another important source of soil CO_2 efflux are the roots and the rhizosphere respiration, which are also highly variable depending on the amount of the root biomass *Widen and Majdi, (2001)*. It has been reported that the highest respiratory activity is observed in the organic soil layer closest to the soil surface of the boreal forest, where the density of the fine root biomass is highest. However the proportion of new to old roots has an effect on CO_2 production by roots at different depths of the soil, which means a gradual decline in CO_2 production as root tissue becomes more mature *(Singh and Gupla, 1977).*

In order for CO_2 to be transported after production below ground level, there are number of CO_2 transporting pathways from terrestrial ecosystem to the atmosphere. Such methods include molecular diffusion, soil CO_2 movement between soil layer as dissolved in water, the mass flow of CO_2 by convection caused by wind or atmospheric pressure fluctuations which affect CO_2 movement particularly in deep soil, and other factors that affect the vertical movements of soil CO_2, particularly soil's physical properties and changes in lateral movement (*Freijer and Leffelaar, 1996; Simunek and Suarez, 1993; Wood and Petraitis, 1984).*

Chapter 3: Material and Methods

3.1 Site Description

The measurements were carried out at the ADVEX site in Norunda, which is located in central Sweden (60° 05' 11.39" N, altitude 45m). Norunda is about 30 km north of Uppsala, in a cold-temperate to boreal climate. The mean annual temperature in Uppsala is 5.4 C and the annual precipitation is about 520 mm *(Lundin et al., 1999; M. Aubinet et al., 2010).*

The topography is flat; soil is typically of glacial origin, which is rich in clay, sandy and gravelly tills with moderate to high occurrence of large boulders with diameters up to 1.5 m. Granite, sedimentary gneiss and leptite characterize the bedrock of the region. The forest floor is rich in soft mosses, grasses (which is more common in moist and rocky terrain) and Stands of dwarf shrubs which are dominated by (*Vaccinium myrtillus* L. and *V. vitis-idaea* L.) *(Lundin et al., 1999; Lagergren et al.,2005; Feigenwinter et al., 2010).*

The study area is covered by a healthy growing coniferous forest which is dominated by Scots pine (65%, *Pinus sylvestris L.*) and Norway spruce (33%, *Picea abies L.*), which prefer to grow in a location where the soil is wet and deep. Otherwise a small fraction of deciduous trees like birch (*Betulla spp.* (L.)), are spread in a little swamp where the water table is just below the ground.
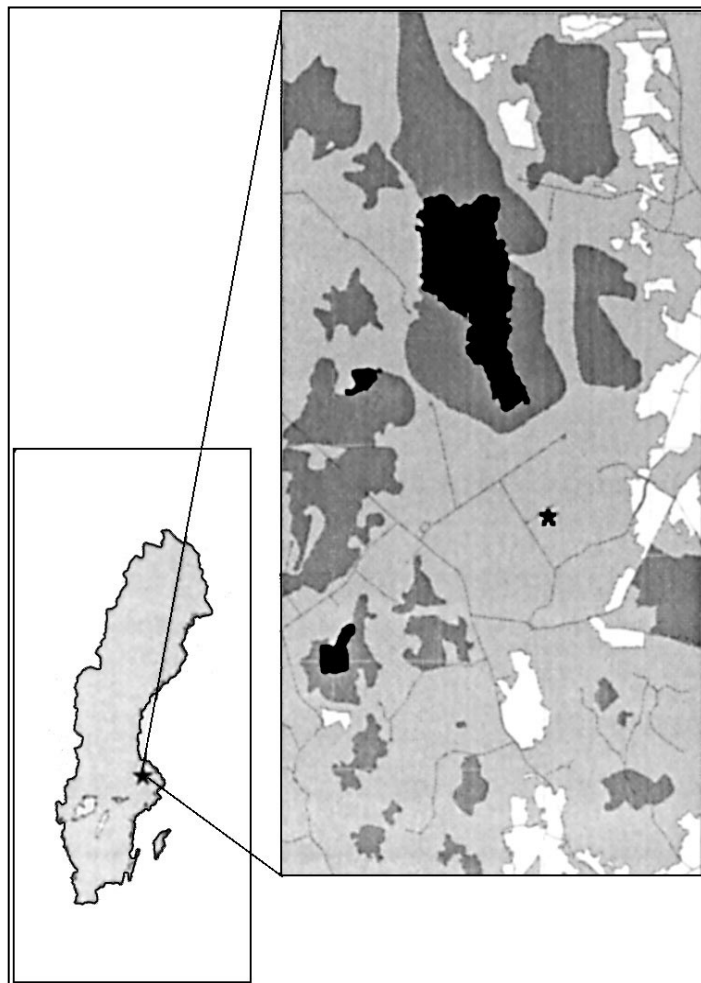
Figure 3: Map of Sweden (scale ca 1 : 5 000 000) showing the location of Norunda Common and land use map showing the area around the tower (marked with aStar). The black areas symbolize lakes; dark grey areas are peat Bogs; light grey areas are forests and white areas are arable lands *(Lundin et al., 1999).*

The maximum height of the trees is about 30 m for some spread pine, extending at least 1 km in all directions from the main tower. In this dimension around the main tower a variety of species composition can be found with the stand age estimated about 70-100 years *(Lagergren et al., 2005; Feigenwinter et al., 2010).*The leaf area index (LAI) in Norunda forest is between 3 and 6 with the higher values for stands dominated by spruce *(Lagergren et al., 2005).* Norunda forest has been managed (drainage, plowing, thinning of the stands and clear cutting) in a planned way at least during the last 200 years, with the last thinning conducted in 1973 (*Lindroth et al., 1998; Valentini et al., 2000; Lagergren et al., 2008*).

3.2 ADVEX project (advection experiment)

The ADVEX project was an extensive experimental activity of the CarboEurope-Integrated project (CEIP) whose overall target was "to understand and quantify the terrestrial carbon balance of Europe and the associated uncertainties at local, regional and continental scale". With this goal in mind, the ADVEX group was formed with the following aims:

a) To apply the best experimental setup for advection experiments.

b) To understand the micrometeorological and biological processes those are responsible for advective CO_2 fluxes.

c) To apply the most suitable method to estimate the components and the total of the advective fluxes.

d) To provide indication of conditions under which advection occurs.

e) And to provide means for correcting eddy covariance fluxes for advection *(Feigenwinter C. et al., 2010).*

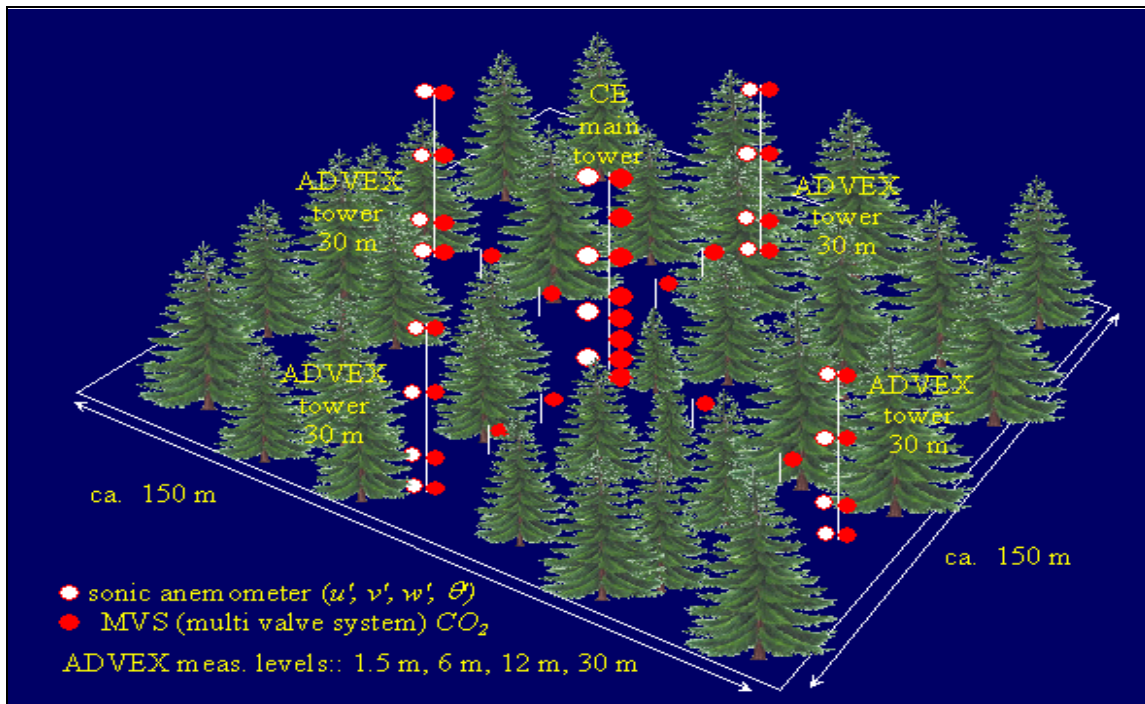Figure 4: General ADVEX experimental setup adapted from *(Feigenwinter et al., 2008)*

Figure 4 shows the ADVEX experimental setup consisting of four 30 m tall towers at about 60 m distance from the main tower with height of 102 m in the center of the study area.

Six teams from five European countries were involved in the ADVEX project, with campaigns performed at three European forest sites, each with different topography.

The experiment was performed from April to September 2005 at alpine slope site Renon/Ritten (Alto Adige, Italy). From April to June 2006 at the hill-crest site Wetzstein (Thuringia, Germany). And from July to September 2006 at the flat site Norunda (Uppland, Sweden) *(Feigenwinter C. et al., 2008 and 2010)*.

One goal of the project was to measure the CO_2 balance under night-time conditions, in an attempt to improve NEE (net ecosystem exchange) estimates.

Four towers with a height of 30 m were fully equipped with wind velocity, temperature, and CO_2 efflux measurements were arranged in a square with the sides of the square about 100 m long around a main tower with a height of 102 m. Equipped with 16 sonic anemometers and CO_2 sampling points, the towers were installed to measure vertical and horizontal advection of CO_2 *(M. Aubinet et al., 2010)*. More details about the ADVEX project can be found in *(Feigenwinter C. et al., 2008 and 2010)*.

3.3 Soil profile description

In Norunda forest which is about 100 years old pine trees are planted, while Norway spruce trees and ground vegetation is naturally regenerated at the end of the 19th century, on Dystric Regosols soil type, which is generally found in coniferous forests, consists of a shallow organic debris layer O-horizon. This should be considered distinct from the layer of leaf litter covering many heavily vegetated areas, which contain no weathered mineral particles and is not part of the soil itself *(Lundin et al., 1999)*.

The next horizon is the A-horizon, the top layer of the soil horizon or 'topsoil'. This layer has a layer of dark decomposed

O-horizon, loose and partly decayed organic matter

A-horizon, mineral matter mixed with some humus

E-horizon, light colored zone of leaching

B-horizon, accumulation of clay from above

C-horizon, partially altered parent material

Unweathered parent material

Figure 5: Typical soil profile under coniferous forest *Wikipedia, 2011& Lundin et al., 1999*. This figure shows different soil horizons (O, A, E, B and C) with special characteristics.

organic materials which increase in thickness and darken in color as the accumulation and decomposition of the plants' and animals' residuals increase.
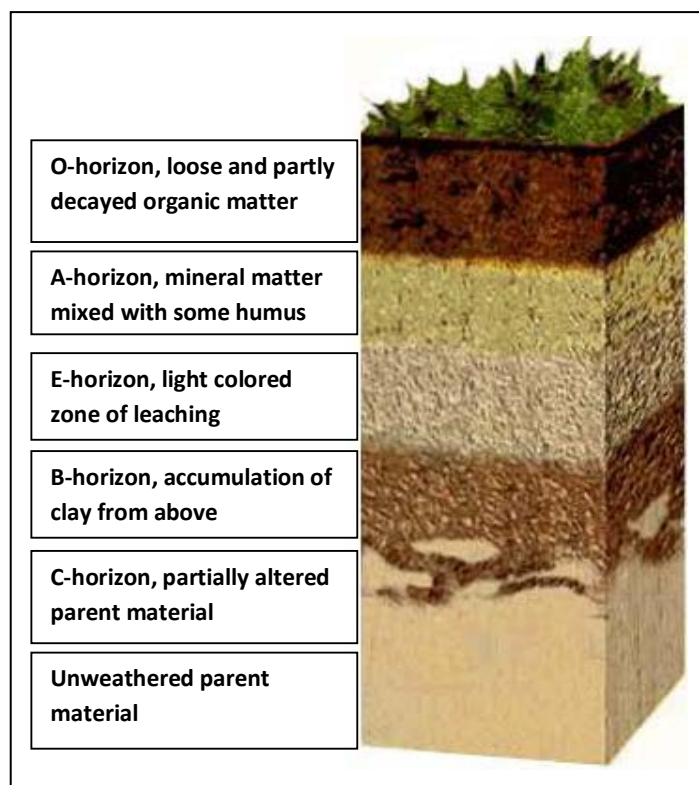
This layer is considered the zone of the most biological activity; soil organisms such as nematodes, earthworms, bacteria, fungi are concentrated there.

Continuous loss of Iron oxides, aluminum and clay from the upper horizon leads to an E-horizon (Eluviations zone). This is most commonly used to label a horizon that has been significantly leached of its mineral and/or organic content, leaving a pale layer largely composed of silicates. This is present only in older, well-developed soils. And generally occurs between the A and B horizons, and is followed by Bt-horizon (Spodic-horizon or illuviation zone) on the top of the B-horizon (subsurface horizon). Produced by continued production, accumulation and downward translocation of iron oxides and silicate clay mineral further reddens the subsoil and creates a distinctly clayey well-developed horizon. Spodic- horizon is followed by the C-horizon. This layer is outside the normal zone of biological activity. It is very little affected by soil forming processes (weathering) and contains large shelves of unweathered rocks and unmodified parent materials.

The thickness of each horizon may differ from one location to another depending on the stage of soil development which is affected by climatic conditions and vegetation cover (tree and forest floor). More information and details about soil's physical properties (e.g. thickness of each horizon) and chemical properties, which are very important for supporting our results, can be found in table 1. The information from table 1 comes from *(Lundin et al.1999)*.

Table: 1: Soil physical properties (fine grain fractions) at Norunda ADVEX site *(Lundin et al., 1999)*.

Horizons under ADVEX stand	Depth (cm)	Clay content (% grav.)	Silt content (% grav.)	Sand content (% grav.)	Porosity (% vol.)
AE/BS1	**0-25**	5-9	26-43	45-63	44.1
BS2	25-40	7	43	48	39.7
BC	**40-51**	4	24	72	39.2
C	51-70	2	24-29	70-74	39.2

3.4 Soil CO_2 efflux measurements

The efflux measurements were performed in the ADVEX experimental site in Norunda, central Sweden. CO_2 efflux measurements were arranged in a square around a main tower, with the sides of the square about 100 m long. This was divided into a grid (10x10 m). In each fixed position a PVC ring (collar with dimensions 19 cm in diameter, height 8.5 cm) was placed and inserted into the soil about 3 cm deep. Each ring was placed in the soil at least 24 h before starting measurements in order to minimize the effect of the disturbance caused to the roots. The total number of rings was 72, which were randomly selected in the grids (10*10 m) on the ground surface of the study area. The under-storey was not cut or removed inside any of the collars.

Soil and under-storey CO_2 efflux measurements were done using three identical systems consisting of a LI-COR 6200 portable system; this included a LI-6250 infrared gas analyzer, connected to the dark homemade chamber. The pump

Figure 6: schematic design of the study area shows the four ADVEX towers arranged in a square around the main tower, with the sides of the square about 100 m long. This was divided into a grid (10x10 m).

in the LI-6250 circulated air from the chamber to the analyzer, where CO_2 concentration was measured and returned to the chamber. Measurements were performed between the 7th and 12th of June 2007 during the daytime between 11 am and 4 pm. This is normally dry and wet period (during growing season) in the summer. The mean average temperature was 19 C during the time the measurements were taken. These measurements were performed by a group of researchers from the Institute of System Biology and Ecology from the Czech Republic in collaboration with a researcher from Germany. For each position, or collar, a set of 15 measurements were done. The average R_{10} and the standard deviation for each individual position were estimated. Values of R_{10} (soil CO_2 efflux normalized to the temperature of 10°C) were calculated for each position in order to estimate soil (include under-storey) CO_2 efflux. These values were calculated using $Q_{10}=2$.
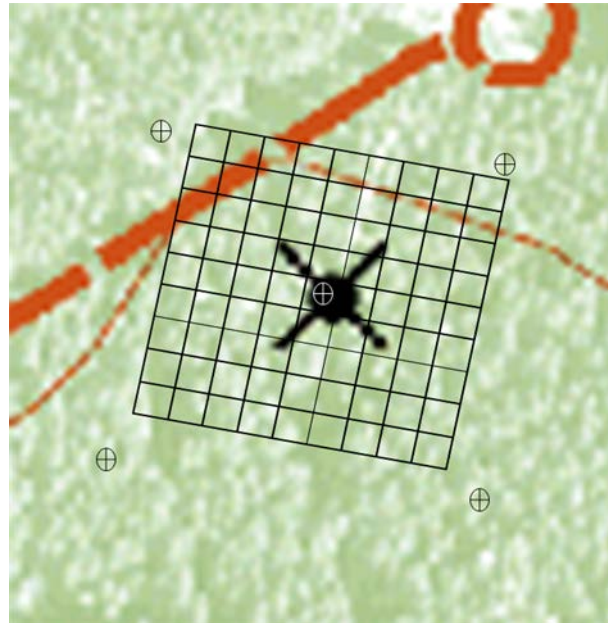
The effect of soil temperature on soil respiration can be removed with a Q_{10} function using a base of the mean soil temperature of the site and a $Q_{10}=2$. The value of the $Q_{10}=2$ was based on fundamental biochemical principles, and always the Q_{10} values for typical chemical reactions are ~ 2.

The temperature sensitivity coefficient (Q_{10}) represents the factor by which the rate (R) of a reaction (e.g. respiration rate) increases for every 10-degree rise in temperature (T). The rate of the reaction (R) may represent any measure of the progress of a process (e.g. the rate at which the products of a chemical reaction are produced, like mmol/s). Typically the rate of the physiological process under investigation is measured at two different temperatures, where $T_2 > T_1$, thus producing R_1 and R_2 from T_1 and T_2 respectively.

Then the Q_{10} of the process can be estimated by using the Q_{10} equation. The Q_{10} value is important because it may be used to reveal mechanistic insight about the physiological process under investigation. The Q_{10} equation is as follows:

$$Q_{10} = \left(\frac{R_2}{R_1} \right)^{\left(\frac{10}{T_2 - T_1} \right)}$$

(Q_{10}) is the *factor* by which the reaction rate increases when the temperature is raised by ten degrees. Q_{10} is a unit-less quantity. (R_1 & R_2) are the measured reaction rate at temperature T_1 & T_2. (If the Q_{10} value that results from the equation is 1.0, it means that the rate of the reaction is totally temperature independent. And if the reaction rate increases with increases in temperature, Q_{10} will be greater than 1.0 (temperature dependent). The capacity for plant respiration, particularly roots at constant temperature (10 °C, R_{10}), differs with changes in the availability of carbohydrate substrate and other aspects of the plant's physiological status including plant moisture content *(Ze-Mei Zheng et al, 2009; Reichstein et al., 2005b; Running and Hunt, 1993)*. The Q_{10} values derived from measured soil respiration and temperature usually decline with temperature because substrate availability decreases as temperature increases. Soil water content also influences temperature sensitivity because diffusivity of soluble substrates is low at low water content and diffusivity of oxygen is low at high water content. Low diffusivity of either soluble substrates at low water content or oxygen at high water content limits soil microbial respiration *(Davidson et al., 2006)*.

3.5 Description of the portable (gas analyzer) chamber

A dynamic closed chamber system for measuring the soil CO_2 efflux has been in development since 1992 at the Center for Land and Biological Resource Research of Agriculture and Agri-food Canada. The system was based on the prototype designed by Dr. John Norman in collaboration with the LI-COR Company. The chamber, made of 3.175- or 6.35-mm non transparent material, was connected to a portable CO_2 analyzer (LI- 6200, LI-COR) which included a LI-6250 infrared gas analyzer. The flux is calculated using the rate of change of CO_2 concentration (ppmv) in the system $[CO_2]$ c:

$$F_{c,s} = \frac{\partial [CO_2]_c}{\partial t} (\frac{m_w}{m_v})(\frac{V}{A})$$

V is the total volume of the system; A is the area covered by the chamber; t is the time and mw and mv are the molecular weight and volume of CO_2, respectively *(Rochette et al., 1997; Davidson et al., 2002).*
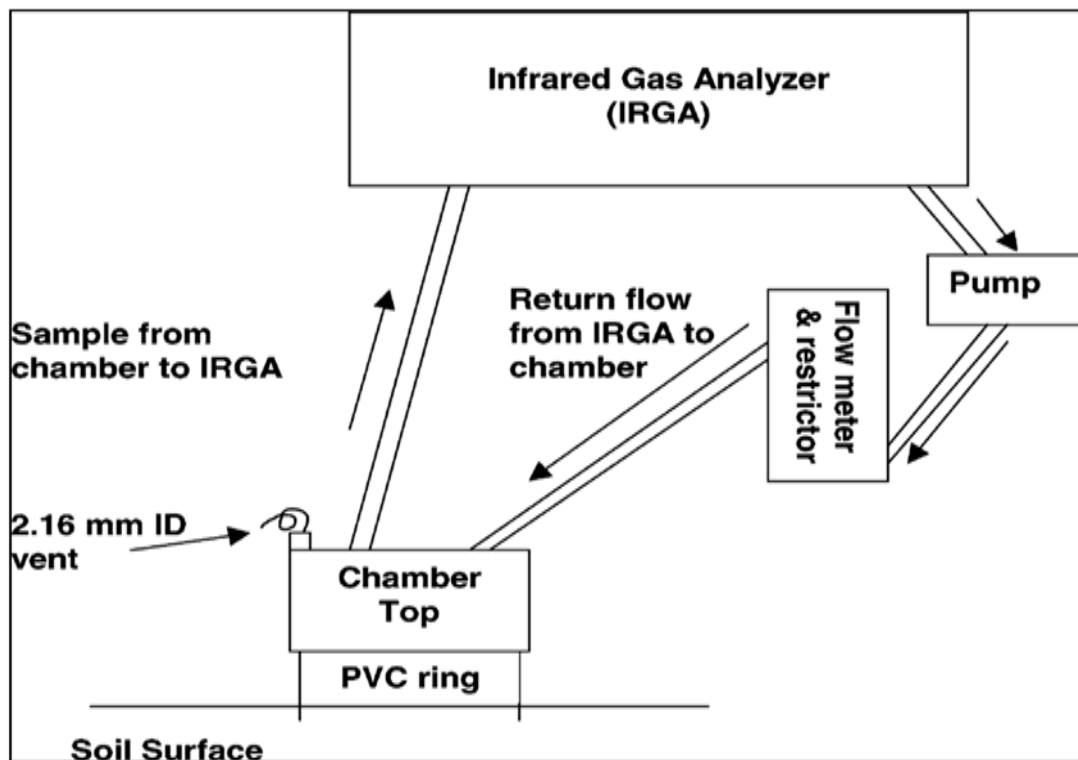

Figure 7: Diagram of the soil CO_2 chamber efflux system. The chamber diameter is 19 cm *(Davidson et al., 2002).*

figure 7 shows the chart flow of the infrared gas analyzer with the chamber, and it explain the mechanism of soil CO_2 efflux measurement by chamber which is connected

to the PVC ring which is already inserted to the soil, and the air circulation from the chamber to the IRGA in order to measure soil CO_2 efflux, and then return the air to the chamber by air pump.

The size and shape of the chamber are determined by two standards: 1) the measured area is maximized in order to reduce the number of replicates required to account for the spatial variability of soil CO_2 efflux; and 2) the height is chosen in regard to the expected magnitude of the flux. The height must be such that the rate of increase of CO_2 concentration is small enough to avoid problems related to CO_2 build-up during the measurement of the soil CO_2 efflux (*LI-COR Inc. 2001*).

Before starting measurements the chamber was attached to a PVC collar which was already inserted into the soil surface at least several hours before taking measurements. The chamber and the collar were connected by clamps that pull on hooks fixed to the underside of the collar. This type of setup is favorable for less soil disturbance than if the hooks were anchored in the soil. The measurement process consisted of a series of two consecutive 20-s calculations of the soil CO_2 efflux without removing and replacing the chamber between calculations (*Norman et al., 1992 & 1997).*

It is important to mention that the LI-COR 6200 portable photosynthesis system which contains LI-6250 infrared gas analyzer is commonly used in combination with different size chambers to measure ecosystem level of soil CO_2 flux in ecosystems with small-statured canopies (e.g. forest understory, agriculture, tundra and grasslands (*Rochette et al., 1997; Janssen et al., 2000).*

3.6 Ancillary (additional) measurements

Many ancillary measurements were taken to determine their relationship with spatial heterogeneity of soil CO_2 efflux at the experimental site. The ancillary measurements were made after soil CO_2 efflux measurements were done in each collar. Soil temperature was measured inside each collar during efflux measurements, taken by a penetration digital thermometer *(Roth, Germany)* at 1.5 cm depth. Humus layer depth was also measured inside each collar. In order to take an accurate measurement of the forest floor depth, the ruler is gently slid through layers of surface litter until it reached a stopping point. Then softly clearing away the surface litter from one side of the ruler, so as to determine if the ruler had reached the A horizon.

The depth of the soil layer above boulders was measured inside each collar by the penetration of a rod (four times) from the surface of the A-horizon at different points inside the collar, until penetration was obstructed by the boulder surface. Then the mean value of the measurements was taken. The weight of the dry mosses was measured inside each collar by cutting the mosses and taking it to the laboratory to dry by oven for 24 h at 70 ^{o}C. The weight of the top soil was measured inside each collar.

Due to the uncertainty in the measurement procedure (e.g. at which depth did they take soil from in each collar? Is it similar depths in all collars?), I therefore excluded this variable from the study. Additionally, distance, diameter at breast height DBH 130 cm above ground level and species of the nearest three trees to each collar were documented. And finally, local terrain level (microtopography) for each collar location was classified as normal, elevated or deepened points.

3.7 Statistical methods

Statistical analysis performed with aim to find a relationship between a number of variables and soil CO_2 efflux. This is to see if those variables are causing the spatial variation of soil CO_2 efflux in the study area. Therefore, variation in soil CO_2 effluxes between different terrain levels (normal, elevated and deepened) was investigated using one-way ANOVA to evaluate if differences exist. Tukey's HSD post hoc test was used to find out between which terrain levels the differences exist *Lund, M., 2005*. Also, differences in soil CO_2 effluxes between different tree species were investigated using one-way ANOVA to evaluate if differences exist, and Tukey's HSD post hoc test to find out between which species the differences exist.

The correlation between soil CO_2 effluxes and all independent variables (depth of the soil layer, depth of the humus layer, weight of the mosses, distance and diameter of the nearest three trees) was explored by calculating Pearson's correlation coefficient and testing it for significance. Regression models were evaluated by testing the independent variable for significance. Assumptions for these parametric tests, such as equal variance and normal distribution by using Kolmogorov-Smirnov test, were controlled for before undertaking the tests *Lund, M., 2005*. All statistical tests were performed in SPSS version 17.0 software (IBM Company, USA). And all figures were performed by Microsoft Office Excel 2007.

Chapter 4: Results and discussion

4.1 Average soil respiration expressed by R_{10} in ADVEX site

The average soil CO_2 efflux normalized to 10 $^{\circ}$C (R_{10}) from the forest floor in the Norunda site, as calculated from 72 collars, was 2.09 ± 1.36 µmol m^{-2} s^{-1}. This was the sum of the total soil respiration mainly originating from root respiration (autotrophic) and microbial respiration (heterotrophic), in addition to the respiration from forest floor vegetation which was not removed from the upper soil layer during the measuring of soil CO_2 efflux. Measurements were performed between the 7th and 12th of June 2007 during the daytime between 11 am and 4 pm.
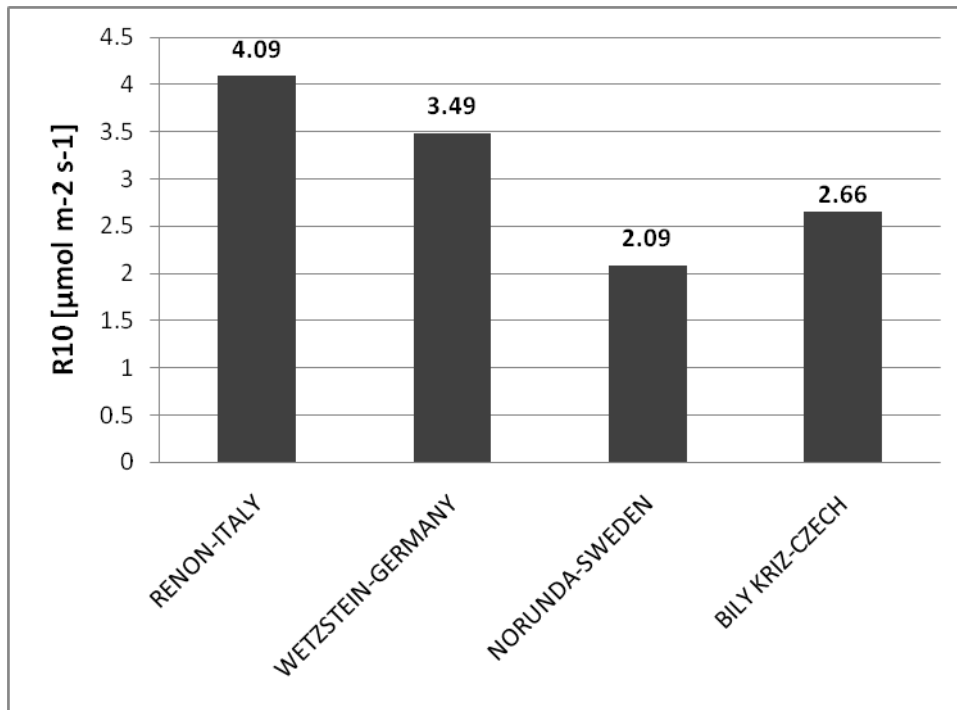

Figure 8: Averaged soil respiration expressed by R_{10} in four ADVEX sites in Europe.

Figure 8 shows a clear variation in soil CO_2 effluxes between the four ADVEX sites. A lower efflux average was measured in the Norunda site around 2.09 ± 1.36 µmol m^{-2} s^{-1}. In comparison to the highest efflux average which measured in Renon-Italy at 4.09 ± 1.23 µmol m^{-2} s^{-1}, followed by Wetzstein-Germany at 3.49 ± 1.14 µmol m^{-2} s^{-1} and Bily Kriz-Czech at 2.66 ± 1.04 µmol m^{-2} s^{-1}.

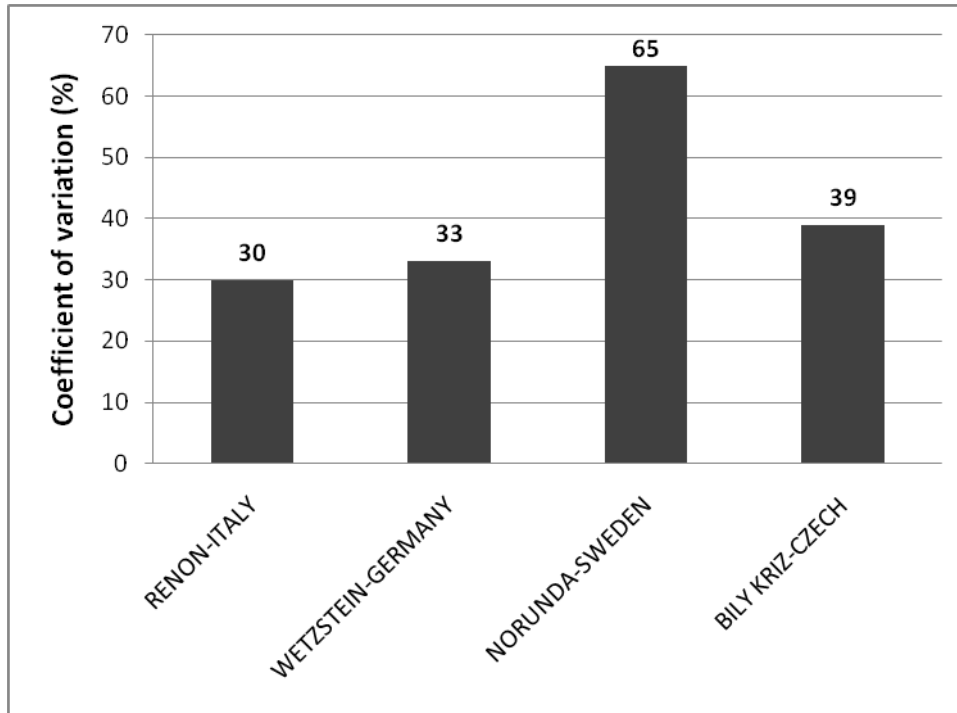## 4.2 Spatial heterogeneity of soil respiration expressed by coefficient of variation (CV) in ADVEX sites

Figure 9: Spatial heterogeneity of soil respiration expressed by coefficient of variation CV (%) in four ADVEX sites in Europe.

Figure 9 shows a high degree of spatial heterogeneity in soil CO_2 efflux between ADVEX sites as a consequence of different ecosystems' climatic conditions and topographic properties and conditions. A higher CV value (65%) in the Norunda site reflects an inconsistency in soil CO_2 efflux among the samples (collars) in the study area. While the lowest value of CV (30%) in the Renon site reflects more homogeneity in soil CO_2 efflux among the collars in the study area, followed by the Wetzstein site with CV (33%) and the Bily Kriz site with CV (39%). The variability of soil CO_2 efflux that found in Norunda does not have to be unusual due to the many biotic and abiotic factors controlling the spatial variability in soil respiration (e.g. land surface topography, the heterogeneity of vegetation coverage, root biomass, depth of the top soil layer, litter quantity and quality, soil organic matter, soil temperature and moisture content etc.) *(Fang et al., 1998; Xu and Qi, 2001; Maestre & Cortina, 2003; Epron et al., 2004; Jassal et al., 2005; Tang & Baldocchi, 2005).* Coefficient of variation (CV) is the ratio of standard deviation to the mean multiplied by 100%.

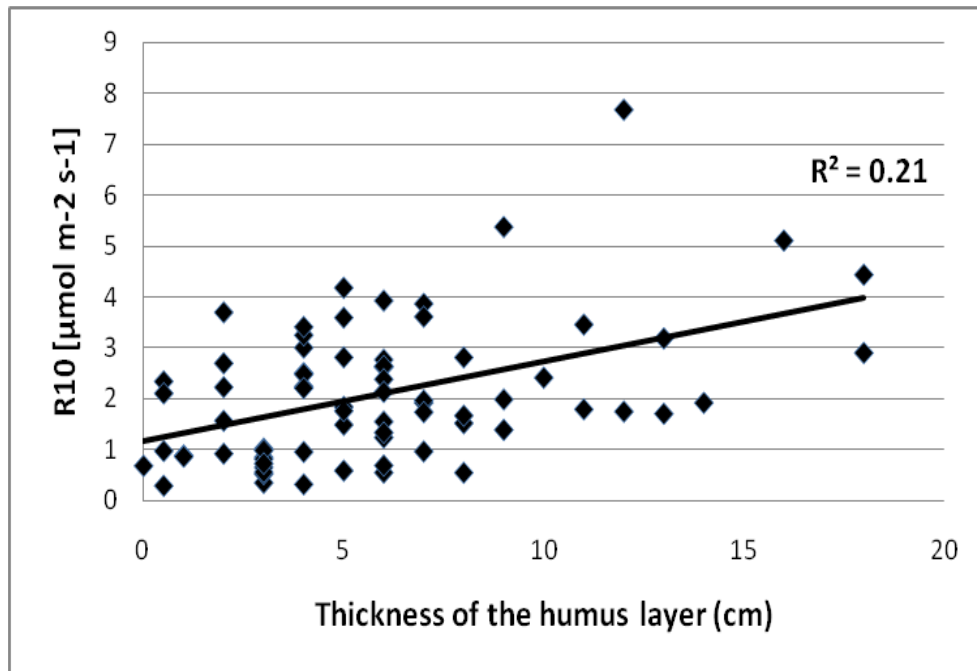## 4.3 Soil CO_2 efflux R_{10} with thickness of the humus layer

Figure 10: Relationship between soil CO_2 efflux normalized to 10° C (R_{10}) and thickness of the humus layer, N=72, R^2=0.21, P-value <0.001.

The figure above shows a significant relationship between R_{10} and thickness of the humus layer with the R^2=0.21, and is highly significant with a P-value under P <0.001.

Humus layer (O-horizon) consists of a biochemical substance that is produced from residual (organic matter) plant and animal lives in soils. It's in a different stage of decomposition (little decomposable O1-horizon, more decomposable O2-horizon) which makes the bottom layer of the O-horizon more dark in color, becoming the most important haven for different microorganisms. Increases in the thickening of the humus layer are indicated by increases in microbial population density and consequently, more CO_2 efflux to the atmosphere (*Ponge, 1998*). Soil microbial (e.g. fungi and bacteria) decompose the organic substances to a semi-soluble chemical matter which is accumulated in O2-horizon and A-horizon and supplies the nutritional requirements for the plants' growth, and consequently leads to increasing productivity of the ecosystem in general. From a biological point of view, the forest floor, especially the surface humus layer, can be expected to provide a stable and predictable habitat for soil microbial.

There is a range of biotic factors (e.g. abundance of several arthropod groups in pine humus) and abiotic factors (temperature and moisture content) that determines their distribution, activity, and contribution to the decomposition and nutrient cycling *(Berg et al., 1998)*.

It has been reported by *Michael, P., & Scott, J. (2006)* that most of the microbial activity is concentrated near the surface layer of the soil (Humus layer). It has further been estimated that one cubic centimeter of humus layer can be the habitat for more than 1,000,000 bacteria, and a hectare of pasture land in a humid climate condition can contain more than one million earthworms and several million insects. This is an extremely important fact considering insects' ability to improve soil condition (high porosity) by mixing and aeration which leads to increased movement of the water and air from the soil surface to the deeper layers where roots exist. Increases in air and water availability to roots have a significant positive effect on plants' productivity. As a consequence of all the conditions mentioned above and related to different biological activity that occur in humus layer and the correlation between humus thickness and microbial activity, soil CO_2 efflux and other greenhouse gases like N_2O are expected to significantly increase with increased thickness of the humus layer, particularly under availability of favorable climatic conditions (temperature and moisture content).

In conclusion for this case, when the thickness of the humus layer increases, is expected there will be higher microbial density and activity per unit area under favorable conditions (e.g. temperature and moisture content). Consequently, higher CO_2 production and emission to the atmosphere as a heterotrophic respiration by abundance of soil microbial. And to a lesser extent by autotrophic respiration (root respiration) which is denser and distributed below this horizon particularly in A-horizon where there is more accumulation of decomposable organic materials. This finding is consistent with the study done by *Stork & Dilly, (1998)* who found that the thickness of the humus layer (O-horizon) significantly reflects increases in soil microfauna's activity and respiration.

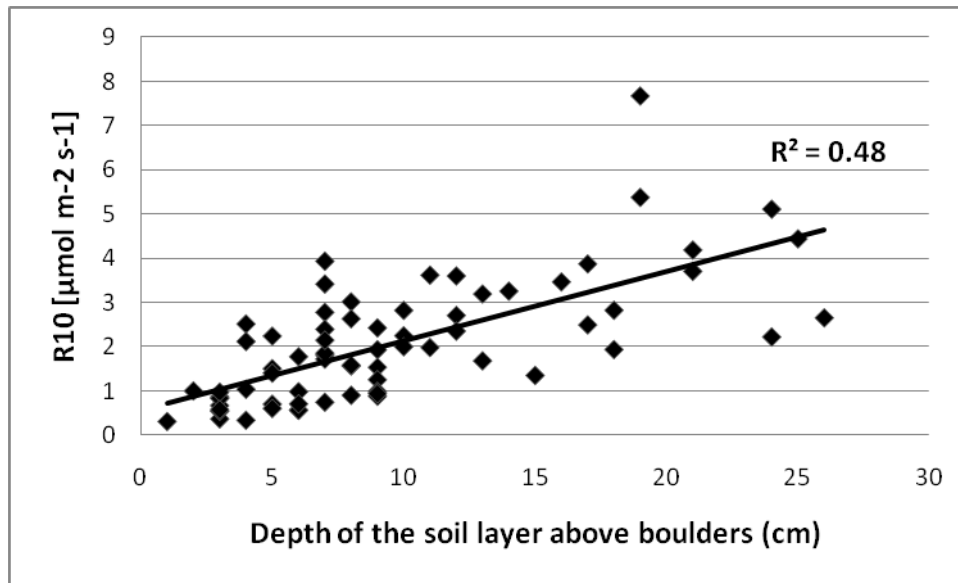## 4.4 Soil CO_2 efflux R_{10} with depth of the soil layer above boulders

Figure 11: Relationship between soil CO_2 effluxes normalized to 10 ^oC (R_{10}) and depth of the soil layer above boulder, (N=69). The line is representing linear regression (R^2=0.48) by ignoring data of the three outlier points.

Figure 12 shows a strong significant relationship between R_{10} and depth of the soil layer above boulder with R^2=0.48, and a highly significant P-value under P<0.001 after excluding three outlier points from the data, which have the depth of 50, 60 and 61 cm with average soil respiration 1.76, 1.75 and 2.91 µmol m-2 s-1 respectively for the three outlier points. There was an inverse relationship between R_{10} and depth of the soil layer when its became more than 50 cm depth.

There is a clear significant relationship between depths of the topsoil layer ranged around 1-30 cm depth and R_{10}, which has been suggested in the hypothesis 1. This is probably due to the main distribution of the fine roots of forest trees and forest floor vegetation cover (root biomass) in the upper soil layer shallower than 20 cm. The microbial activation for the decomposition of organic materials is also more active in this layer due to the substrate availability and more favorable climatic condition for decomposition (e.g. soil temperature, moisture contents). *Britta and Majdi, (2001)* found in a study performed in the ADVEX site in Norunda that most of the fine root biomass and root length density are located in the upper soil layer 0-20 cm with no mentioned fine root biomass at depths more than 40 cm.

Jassal et al., (2005) found that most of the CO_2 production and fluxes are concentrated in the top 20 of the soil layer, where more than 75% of soils CO_2 effluxes originate.

The main reasons for excluding the three outlier points are because, when the depth of the soil layer above boulders becomes 50 cm depth and more, it may be reach the depth were the soil moisture content is very high. And also, it may be because we measured these points from different habitats—small wetlands patches or mire in the south of the main tower in the study area. Principally wetland has a different soil condition and biogeochemistry than surrounding dry land. In wetland soils, high moisture content (high level of ground water table) leads to a lower diffusion coefficient and oxygen is depleted quickly. Diffusion of O2 into the soil is too low and methane can be formed. Also CO_2 production and diffusion is low which leads to a lower CO_2 flux *(Conrad, 1996)*.

It has been estimated that CO_2 concentration at depths ranging between 0 and 20 cm increase with increases in soil temperature, likely due to rises in CO_2 production, and also with increases in soil water content due to decreased diffusivity or increased CO_2 production, or both *(Jassal et al., 2005)*. It has also been reported by *Glinski & Stepniewski, (1985); Jassal et al., (2004); Jassal et al., (2005)* that a deeper soil does not necessarily lead to higher soil respiration when the soil humidity is not taken into account at the same time. Soil wetness can increase soil respiration when water is limiting for the microbes, but lead to decrease soil respiration when oxygen get limiting due to high diffusion resistance. In order to describe the influence of soil water content on soil CO_2 production and effluxes different relationships have been suggested. Generally, CO_2 production decreases at both very low and very high soil water contents.

The reduction at very low soil water content is caused by inhibition of soil microbial and root metabolic activity, whereas at very high soil water content, the reduction may be caused by lack of oxygen, or the accumulation of CO_2, as a result of the soil pore spaces being filled with water *(Glinski &Stepniewski, 1985)*. In general, temperature, soil moisture content and substrate quality and quantity regulate decomposition rates and CO_2 effluxes *(Schlesinger, 1997)*. Therefore in our result we can obviously see with the points that it is supposed to be measured in wetland. Even if the depth of the soil increases it does not affect the rate of the soil CO_2 effluxes, because in this case ground water table rising is the limiting factor for soil CO_2 effluxes. This finding is consistent with the results found by *(Jassal et al., 2005)*.

The second reason according to the table 1, *Lundin et al. (1999),* who identified the soil profile in Norunda site, that depth of the C-horizon ranges from 50-95 cm which means that the outlier points we measured could be located in this horizon (C-horizon). This horizon is very little affected by soil forming processes (weathering), and may contain lumps, or more likely, large shelves of unweathered rock and unmodified parent material.

Therefore soils in Norunda forest are very compact, below 70 cm; very few roots were found in the compacted subsoil B&C-horizon in comparison to the A-horizon *(Lundin et al., 1999).* As a consequence most of the root densities, root activities and microbial activity—the main two sources of soil respiration—are expected to exist in the upper soil layer.

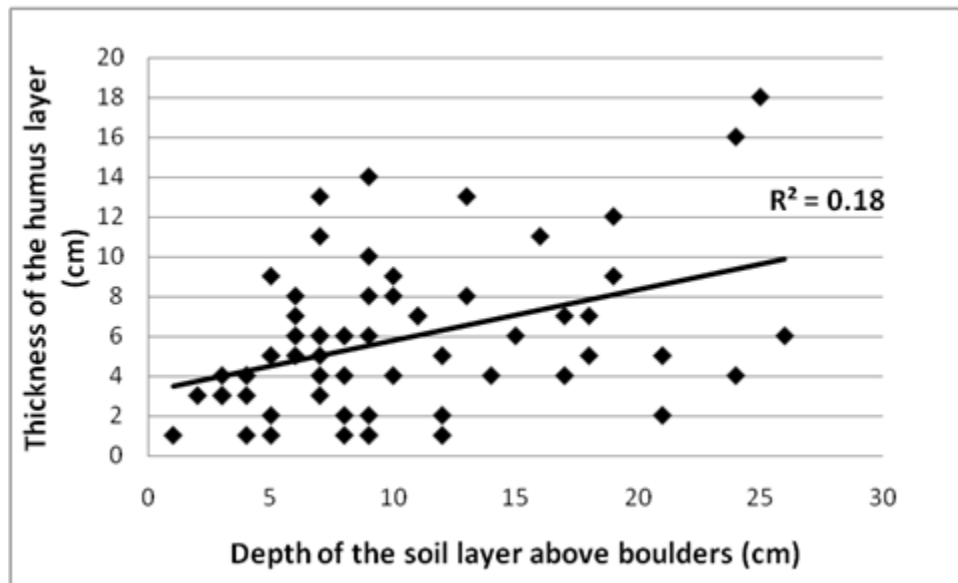## 4.5 Thickness of the humus layer with depth of the soil layer above boulders

Figure 12: Relationship between thickness of the humus layer with depth of the soil layer above boulders, (N=69), R^2=0.18, P-value ‹0.001.

Figure 12 shows a significant relationship between thickness of the humus layer and depth of the soil layer above boulders with the R^2=0.18. It's highly significant with a p-value under P   ‹0.001. This is a g efflux increases or varies with increasing depth of the soil layer? It is because there is a

positive correlation between thickness of the humus layer and depth of the soil layer above boulders.

It is clear that the most important determinant factors of humus developments are vegetation type and productivity. And the major factors influencing plant productivity are climatic conditions (temperature and moisture) and nutrient availability in the soil for absorption by plant roots. So a deeper soil layer (particularly A-horizon, which is known as a central zone of the most important biological activity) has a larger humus layer, resulted of a higher productivity and thus a higher root density. So as a result of substrate availability, more microbial abundance and activity is expected. Consequently, supplying the essential nutritional requirements for absorption by plant roots leads to increases in below-above ground productivity, and hence more humus thickness from plant detritus. It has been reported by *Rehfuess, 1990; Ponge et al., (2002)* that forest management practices, climate conditions, geological substrate, vegetation type, ecosystem productivity, soil faunal and microbial activity and the stage of forest evolution are the most important determinants influencing on the processes of humus development under coniferous forest.

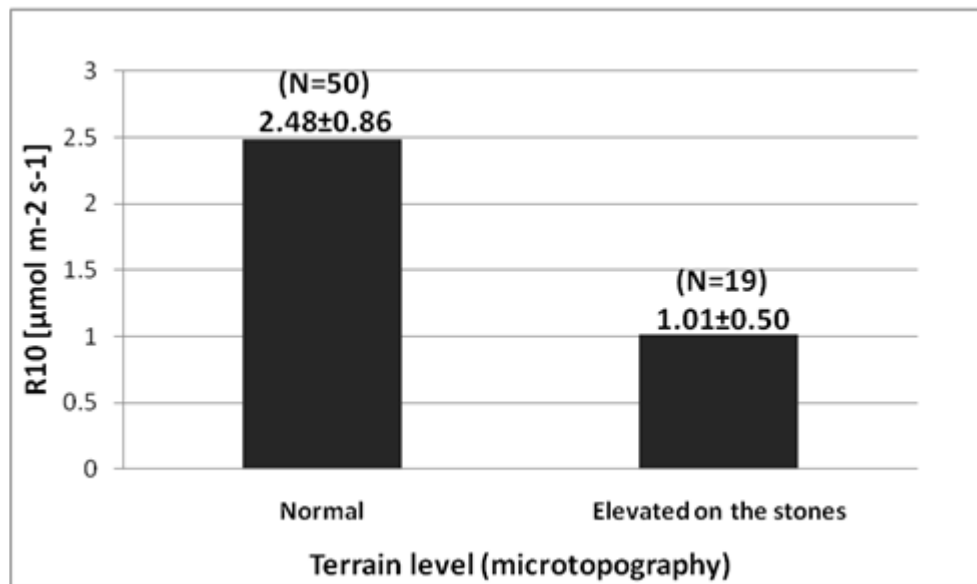## 4.6 Variation in soil CO_2 efflux R_{10} between different microtopographical collars

Figure 13: Comparison between elevated points (on the stone) and normal points on the surface, in soil CO_2 efflux (R_{10}) measurements, N=69, P-value ˂0.001.

Figure 14 shows a clear difference in soil CO_2 efflux R_{10} between elevated points on the stones and normal points on the surface, with a highly significant P-value under < 0.001. The deepened points have been excluded from the analysis because just two observations (N=2) has been measured in the field, it was very few in comparison to normal points (N=51) and elevated points (N=19).

The reasons behind differences in soil CO_2 efflux between normal and elevated points are due to the higher accumulation of soil mineral particles and humus material on the normal surface than the elevated one. Elevated surfaces are more prone to erosion by wind, rain and snow melting. Therefore these materials will accumulate on the lower surface, and consequently there will be high thickness of soil layer and humus layer and lead to more soil CO_2 effluxes on the normal surface.

It's worthy to remember that Norunda forest is a rocky terrain with moderate to high occurrences of large boulders with diameters up to 1.5 m. The height of these boulders is at different levels, some of them are higher than the earth surface, some at the level of the earth surface and others below the earth surface. Therefore stones higher than the earth surface are only covered by a thin humus layer and a very thin soil layer in comparison to the thicker humus layer and thick soil horizon (particularly A-horizon) under normal points.

Variation in all variables against micro-topography was investigated using one-way ANOVA to evaluate if differences exist. Tukey's HSD post-hoc test was used to find out which variables and micro-topography level (normal, elevated) causes the differences to exist. From the test we found no significant variation, except the significant variance in soil depth and humus thickness between normal and elevated points with a P-value=0.002 and P=0.004 respectively.
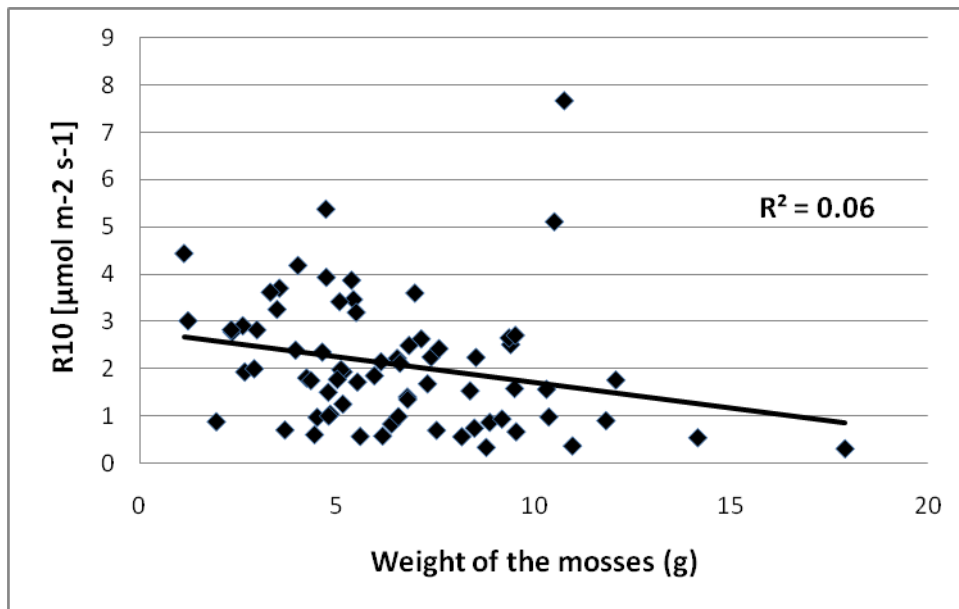
4.7 Soil CO_2 efflux R_{10} with weight of the mosses

Figure 14: relationship between soil CO_2 effluxes normalized to 10 ^{o}C (R_{10}) and the weight of the mosses. (N=72), R^2=0.06, P ˂0.03.

Figure 15 shows a weak negative significant relationship between R_{10} and weight of the dry mosses with R^2=0.06 and P-value=0.03. It's clear that there is an inverse relationship between moss biomass and bush roots or vascular plant roots, which is the main source of CO_2 efflux. So is assumed as green mosses' biomass increases there will be more photosynthesis and higher CO_2 uptake by green mosses and there will be lower vascular plant roots densities and lower CO_2 efflux to the atmosphere. It is understandable that the litter of the mosses in general is very slow to decompose, especially under conditions of cool and high soil moisture content which hampers microbial activity and consequently affects soil CO_2 effluxes. Therefore the contribution of the peat decomposition has been considered a small portion of the total soil respiration in the upland boreal forest *(Dioumaeva et al., 2003)*. So in conclusion for this case and in view of the fact that there is a negative correlation between mosses biomass and vascular plant roots density and as well very slow decomposition rate of mosses, it is expected to have lower CO_2 efflux with increasing moss biomass.

4.8 Soil CO_2 efflux R_{10} with distance and diameter of the nearest three trees to each collar

We found no significant relationship between soil CO_2 efflux R_{10} and distance, diameters of the nearest three trees to each collar. This is because in Norunda forest the abundant of forest floor vegetation of blue berry and lingon berry will overrule the idea of decreasing root density with distance.

It has been reported by *Millikin & Bledsoe, (1999)* that root biomass decreases with increases in distance from a large tree with DBH of 0.29 m, and the majority (82%) of the root biomass was within the crown area. *Jackson et al., (1990)* also mention that 90% of root biomass is located under tree canopy. As a consequence of root biomass distribution in the soil, respiring roots directly below the measurement chamber are supposed to exert a significant influence on soil CO_2 effluxes, since CO_2 efflux from roots comprise 10-90% of the total soil respiration in forests ecosystem *(Widen & Majdi, 2001;Hanson et al., 2000).*

In our experiment the mean average distance of the 1st nearest tree group to the measurement chamber was 2 m, for the 2nd nearest tree group it was 2.70 m and 3 m for the 3rd nearest tree group. It seems that the distance values are very close to each other. At the same time the extent of the root system of Norway spruce and Scots pine, the two dominant tree species in the study area, are ranged between 8-15 m from the stem depending on the density of the stand, stand structure and site type *Taskinen et al., (2003).*

It is worthy to mention that the collar selection in the field was randomly selected not in transect. Therefore we suggest that the overlapping effect of the trees root system is another main factor behind blocking the effect of tree distance on soil CO_2 efflux in selected collars.

4.9 Soil CO_2 efflux R_{10} with the tree species of the nearest three trees to each collar

We found no significant relationship between soil CO_2 efflux and tree species (Scots pine *(Pinus silvestris,* L.) and Norway spruce *(Picea abies,L.)*), the two dominant tree species in our study area. It is known that the rate of decomposition is affected by litter quality. But our results are not consistent with the hypothesis mentioned by *Johansson, (1995)* that due to the difference in litter quality of Scots pine and Norway spruce the dominant tree species can exert an effect on the soil emission of greenhouse gases, this is because it is very difficult to find this in Norunda forest due to the overlapping effect of different tree species, even trees might be grouped in species the mixture of needles on the ground is very complicate.

It has been reported by *Gärdenäs, (1998)* that Swedish forests under Norway spruce stands contain a significantly higher amount of soil organic matter in the forest floor than stands of Scots pine under the same conditions and site.

In contrast, a study established in Norway found lower levels of accumulated soil organic matter under Norway spruce stands than Scots pine stands *(De Wit & Kvindesland, 1999). Johnson, (1992)* on the other hand, found that the effect of tree species on soil organic carbon (SOC) accumulation is often significant but inconsistent. The effect of tree species on carbon accumulation in the soil can be attributed to differences in biomass production, and to the degree of the biomass turnover rate. The biomass turnover rate is greater in Norway spruce than Scots pine since higher biomass production and lower biomass decomposition rates result in rising above and below-ground litter production *(Albrektsson 1988, Berg et al. 1999a, b; Ågren & Hyvönen 2003).*

A negative correlation has been found between ground vegetation developments, which contribute to the litter on the forest floor and the canopy cover of the tree *(Persson & Hytteborn 1975)*. It is expected that there will be more dense vegetation cover under Scots pine stands (more favorable condition e.g. light) than under Norway spruce stands (more shade). We think that the higher biomass production, low density in ground vegetation and slower decomposition rate of litter under Norway spruce in comparison to the lower biomass production, more dense ground vegetation and rapid decomposition rate of litter under Scots pine, will make a kind of spatial homogeneity in soil CO_2 efflux. Another reason may be that the points we measured soil CO_2 efflux was about 2-3 m away from the tree trunk, where there is overlapping in roots distribution, homogeneity in ground vegetation cover and litter distribution.

Chapter 5: Conclusion and suggestions

5.1 Conclusion

The mean average soil CO_2 efflux R_{10} in the Norunda site was 2.09 ± 1.36 µmol m^{-2} s^{-1}, which is the sum of the total soil respiration mainly originating from autotrophic and heterotrophic respiration in additions to the respiration from the forest floor vegetation which was not removed from the surface of the soil layer during measurements of soil CO_2 efflux.

The spatial heterogeneity of soil CO_2 efflux expressed by coefficient of variation (CV) in Norunda was 65%, which reflects high spatial heterogeneity of soil CO_2 efflux among the collars in the study area.

Our results indicate that depth of the top soil layer above boulders 0-25 cm explains the greatest amount of variance in soil CO_2 efflux among collars by representing about 48% of the spatial heterogeneity, is been suggested that mainly is due to the root biomass distribution in the topsoil. The second explanation is the thickness of the humus layer which represented about 21% of the variance in soil CO_2 efflux among collars.

Micro-topography also had a significant effect on soil CO_2 efflux variation among collars, which is attributed to the variation in soil layer depth and humus thickness. A significant correlation was found between humus thickness and depth of the soil layer with the $R^2=0.24$, which means higher biomass production with deeper topsoil layer. A weak negative significant relationship was found between soil CO_2 efflux R_{10} and dry weight of the mosses with $R^2=0.06$.

A non-significant relationship was found between soil CO_2 efflux R_{10} and distance, diameter and species of the nearest three trees to each collar. We believe that the overlapping effect on these variables is the main reason for these unexpected results. In general the conclusion is that the variables that measured in the field represent about 50% the reasons behind spatial variation in soil CO_2 efflux. Therefore, others variables which have a stronger influence on the variation of soil CO_2 efflux are suggested to investigate for the future studies.

5.2 Suggestions

Due to the variety of factors and the interconnection between these factors affecting spatial and temporal variation of soil CO_2 efflux, particularly in forest ecosystems, we suggest some ideas that could better explain the reasons behind spatial variability in soil CO_2 efflux in the ADVEX site in Norunda, based on a variety of previous studies.

We suggest that root biomass distribution and uneven distribution of organic materials could be the main reasons behind spatial heterogeneity of soil CO_2 efflux. Therefore to be more sure about the effect of the root biomass on soil respiration, soil samples up to 30 cm deep must be evacuated from each soil collar using a core around 10 cm diameter after taking the soil respiration measurements. Each sample must be washed very well by a 0.2 mm mesh steel screen and live roots picked by hand. The stored roots should then be weighed after drying at 70 ^{o}C for 24h to a constant mass. It has been reported by *Widen & Majdi, (2001)* in a study established in Norunda, Sweden that most of the root densities and root activity of the fine-roots of Scots pine *(Pinus sylvestris L.)* and Norway spruce *(Picea abies L.)* exist at depths of 9-25 cm. This is very important information about root density and distribution, and its effect on soil CO_2 efflux. Also as a suggestion it's very important to measure soil humidity (moisture content) together with soil temperature during soil CO_2 efflux measurements, which might give a clear insight to the spatial variation in CO_2 efflux.

6. References

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7. Appendix

Figures of microtopographical classification of randomly selected points in the study area.

a. Elevated point on the stone

b. Normal point on the surface

c. Deepened point

7. Acknowledgment

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