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Soil respiration fluxes and carbon sequestration of two mountain forests in Switzerland

presented by

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Summary

The major source of CO_2 from forest ecosystems, often referred to as soil respiration, is a component flux of root-rhizosphere respiration and microbial decomposition of litter and soil organic matter. Thus, to estimate the CO_2 balance of soils both respiration fluxes have to be accounted for separately, and in addition, information on soil C stocks as well as on above- and belowground litter input are needed. Therefore, we combined measurements of soil CO_2 efflux with a soil carbon model (Yasso07) using site-specific litter input and climate data to estimate the CO_2 balance of two Swiss mountain forests over several years.

We found soil respiration rates at both study sites to be strongly related to soil temperature if not limited by soil water availability. Inter-annual differences in soil respiration were found to be small, since the studied years were similar in mean annual temperature and precipitation. However, the three studied years were different in winter temperatures, affecting soil respiration at Lägeren. During the mild winter (Jan, Feb, March) in 2007, the cumulative soil respiration flux was nearly doubled compared to the harsh winter in 2006. Moreover, SR was found to be dominated by microbial respiration (MR) during winter, and in addition, MR was found to be highly temperature sensitive. During winter MR is not limited by substrate supply after autumnal leaf litter fall but rather by temperature. During the entire study period microbial and root-rhizosphere respiration were found to contribute each about half to soil respiration at both study sites, well within the range of other partitioning studies.

Simulated soil C stocks were found to be slightly lower than measured/interpolated soil C stocks, while simulated MR was comparable to measurement results. During the study period (1989–2008), the soils at Davos were found to be a significant C sink with 21 g C $m^{-2}y^{-1}$ (95% confidence interval of [5.8, 36.2]), while the soils at Lägeren were neither a significant C sink nor a significant C source with 3.4 g C $m^{-2}y^{-1}$ (95% confidence interval of [-16.0, 22.7]) on average. These numbers agreed very well to estimates of tree biomass C storage and net ecosystem productivity (NEP). The difference between NEP and tree biomass C storage does most likely represent the C sink of soils, estimated at Davos to be about 20–30 g C $m^{-2}y^{-1}$ and at Lägeren to be about 0 g C $m^{-2}y^{-1}$ (see BAFU report by Zweifel et al. 2009).

Higher temperatures, as measured during the past 20 years (mean temperature during 1989–2008 was about 1°C higher than during 1958–1998), were found to affect the soil C sink strength. Excluding this temperature increase from the simulation enlarged soil C storage rates. Thus, the higher temperatures during the past 20 years have probably dampened the soil C sink strength at both study sites. In addition, we found simulated microbial respiration and soil C storage rates to be highly variable during the study period caused by variations in temperature and precipitation. In general, warm and moist years increased decomposition and decreased soil C storage, while exceptionally dry years decreased decomposition and increased soil C storage.

Thus, by using the simple soil carbon model Yasso07 and comparing it to measurement results, we could show that the soils of our study sites are most likely a sink or at least not a clear source of C to the atmosphere under the current climate conditions. However, we are not able to make predictions on soil C storage rates in the future, since the effect of climate change on productivity (C-input) and on decomposition rates (C-output) is still far from clear.

Chapter 1

Introduction

In the frame of the Kyoto protocol, Switzerland can account for its national forest ecosystem carbon sinks to contribute towards carbon emission targets. To account for the C sink of forest ecosystems, the CO_2 balance of living and dead biomass as well as for soils has to be quantified separately. However, if a country can continuously show that forest soils are not a net source of CO_2, then the CO_2 balance of soils can be excluded from the national greenhouse gas accounting.

The major source of CO_2 from forest ecosystems, often referred to as soil respiration, is a component flux of root-rhizosphere respiration and microbial decomposition of litter and soil organic matter. While organisms of the root-rhizosphere (roots, microbes, incl. mycorrhizae) are supplied with carbon that was assimilated hours to years ago, soil microbes of the bulk soil receive their nutrients from decomposition of fresh plant litter and older soil organic matter. Whereas higher soil microbial decomposition rates may reduce carbon sequestration, increases in root and rhizosphere respiration (e.g., caused by increasing photosynthesis and/or C allocation to roots) may also reflect higher carbon inputs from plants to the belowground system (Högberg and Read 2006). Thus, to estimate the CO_2 balance of soils both respiration fluxes have to be accounted for separately, and in addition, information on soil C stocks as well as on above- and belowground litter inputs are needed.

To address the question how CO_2 losses from Swiss forest soils respond to inter annual variation in weather conditions that could affect the annual totals of CO_2 emission, soil respiratory fluxes were measured and partitioned into microbial respiration and root-rhizosphere respiration in two case studies at the Lägeren mixed mountain forest (during 3.5 years) and at the Davos subalpine Norway spruce forest (during 1.5 years). The effect of seasonality as well as of temperature and soil moisture on soil respiration and its component fluxes was assessed, and the contribution of soil respiration to total ecosystem respiration estimated. To model soil organic C stock and the change in this C stock of our two study sites, the Yasso07 soil carbon model (Liski et al. 2009), an improved version of an earlier Yasso model (Liski et al. 2005) was used. Yasso has already been successfully applied to simulate the effects of wind-throw on soil C stocks of forests in Switzerland (Thürig et al. 2005). The model requires only basic information on annual mean temperature and precipitation, as well as on litter quantity and quality. Changes of the soil C stock at Lägern and Davos were simulated over a 20-year period (1989–2008) using site-specific annual litter input, annual air temperature and precipitation data if available. To validate the quality of modelling results, simulated data were compared to measured soil C stocks and microbial respiration rates as well as to literature results.

Chapter 2

The research sites: Lägeren & Davos

2.1 Lägeren

The CarboEurope forest flux site Lägeren (CH-LAE, 47°28'42.0" N; 8°21'51.8"E) is situated 20 km North-West of Zurich, Switzerland, at a mean altitude of about 700 m a.s.l. on the South-facing slope of the Lägeren mountain (with a peak elevation of 866 m a.s.l.), which belongs to the Swiss Jura mountain range (Tab. 2.1). The study site with an altitudinal gradient of about 100 m and an average slope of 24° (45%), ranging between 10° to 45°, extends 200 m West to East, and 150 m North to South (Fig. 3.1) of the Lägeren Eddy Covariance (EC) tower and thus covers a representative area of the EC footprint. The upper slope of the study site is a nature reserve and comprises a mixed beech forest, unmanaged since 1998, while the lower slope is still an extensively managed forest according to FSC (Forest Stewardship Council) rules. The vegetation of the whole study site is typical for a highly diverse mixed mountain forest. The overstory vegetation consists mainly of beech, ash, fir, lime and spruce trees (*Fagus sylvatica* L., *Fraxinus excelsior* L., *Abies alba* Mill., *Tilia cordata* Mill., *Picea abies* (L.) Karst., respectively). These species represent over 80% of the basal area with *Quercus robur* L., *Acer pseudoplatanus* L., *Acer platanoides* L., *Carpinus betulus* L. and *Ulmus glabra* Huds. interspersed. The maximum leaf area index (LAI) of the overstory vegetation varied in the study site from 1.7–5.5 m^2 m^{-2} over the growing seasons of the two years 2006 and 2007. Generally, the understory vegetation is scarce and consists mainly of *Allium ursinum* L. flowering in early spring, except for those areas that were strongly affected by a winter storm in 1999, having an often dense understory of blackberry and raspberry as well as of juvenile beech and ash trees (about 15% of the study site; Fig. 3.1). The main bedrocks of the study site are limestone, marl and sandstone, with transition zones between marl and limestone (loamy debris) and marl mixed with sandstone (loam). The main soil types are rendzic leptosols (or rendzinas) and haplic cambisols according to the World Reference Base of Soil Resources (IUSS Working Group WRB 2007). The organic layer is thin, since leaf litter decomposes almost completely within one year.

Table 2.1: Comparison of site characteristics for the Lägeren mixed forest and the Davos Norway spruce forest.

	Lägeren	Davos
Altitude [m a.s.l.]	700	1640
Latitude	47°28’42.0”N	46°48’59”N
Longitude	8°21’51.8”E	9°51’25”E
Air temperature[$] [°C]	8.5	4.0
Precipitation[$] [mm y^{-1}]	970	1060
Dominat tree species	*Fagus sylvatica, Fraxinus excelsior, Picea abies, Abies alba*	*Picea abies*
Tree age [y]	50-180[a]	120-370[a]
Mean tree height [m]	c. 30[a]	c. 25[a]
Soil types[b]	rendzic leptosols, haplic cambisols	chromic cambisols, rustic podzols
pH	4.0–7.5	3.5–4.5
C[#] [kg m^{-2}] (0–20 cm)	8.4–9.6[c]	9.2–11[e]
N[#] [kg m^{-2}] (0–10 cm)	0.5[d]	0.3[e]

[$] 20-year long-term annual average calculated from NABEL and MeteoSwiss data

[#] including organic layers

[a] Stark et al. (1991), [b] after IUSS Working Group WRB (2007), [c] Heim et al. (2009)

[d] Wehrli (2006), [e] Jörg (2008)

2.2 Davos Seehornwald

The study site Davos Seehornwald is located near Davos, Switzerland (46°48’59”N, 9°51’25” E) at 1639 m a.s.l. (Tab. 2.1). The vegetation of the study site is typical for a subalpine forest, dominated by Norway spruce (*Picea abies* (L.) Karst.). The sustainable plenter management of the forest since at least 1876 lead to a broad range of tree ages (120–370 years, Stark et al. 1991). The understory vegetation is patchy, mainly composed of dwarf shrubs (*Vaccinium myrtillus* L., *Vaccinium gaultherioides* L.) and mosses. The main soil types are rustic podzols and chromic cambisols according to the World Reference Base of Soil Resources (IUSS Working Group WRB 2007). The organic layer is thick (4–10 cm) and contains about 4.2 kg C m^{-2} and 0.15 kg N m^{-2} (Jörg 2008).

Chapter 3

Soil respiratory fluxes & environmental drivers

3.1 Summary

The main findings of this chapter are:

- Soil respiration rates were strongly related to soil temperature if not limited by soil water availability.
- Soil respiration vs. temperature relationships were comparable among the study years but differed between the study sites.
- Annual soil respiration estimates were similar for Lägeren and Davos.
- Microbial and root-rhizosphere respiration contributed each about half to annual SR estimates.
- The contribution of root-rhizosphere respiration was higher during the summer season caused by plant activity and carbon supply (Lägeren).
- The contribution of microbial respiration to soil respiration and its temperature sensitivity was increased during winter seasons (Lägeren).
- Higher temperatures during the winter season of the three studied years increased soil CO_2 loss (Lägeren).

3.2 Methods

3.2.1 Experimental set-up

Since the Lägeren study site is rather heterogeneous, 17 plots (10 m x 10 m, at least 25 m apart from each other) were established in 2005, accounting for the two main soil types and associated vegetation characteristics, to ensure representativeness of the plots in the EC footprint area (Fig. 3.1). At the Davos study site, being quite homogeneous, four plots were established in the EC footprint area in 2008 (one further plot was added in 2009; Fig. 3.2).

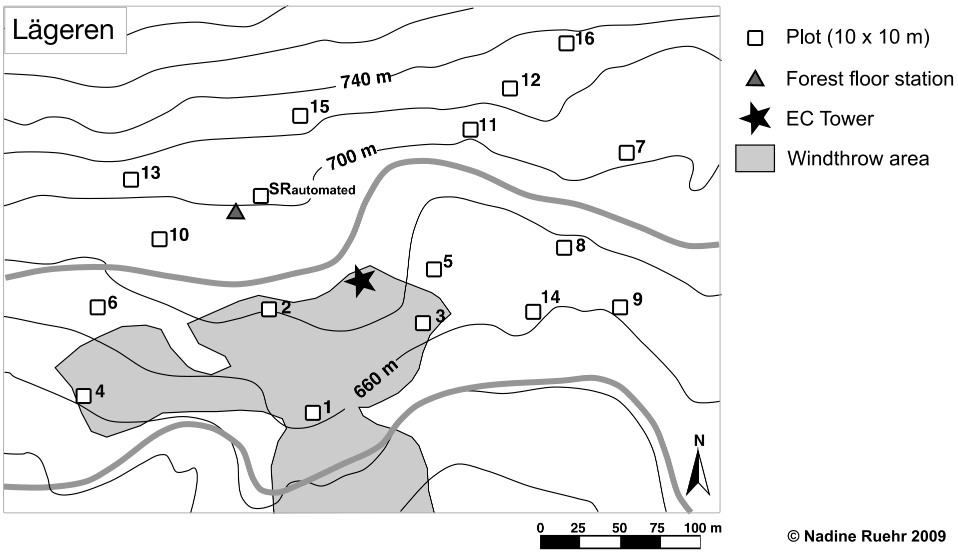

Figure 3.1: Map of the Lägeren study site fully covered by forest. The locations of the plots are shown where SR_{manual} was measured bi-weekly. Plots can be identified by their numbers (see also Tab. 3). Continuous soil moisture was measured at the forest floor station. Air temperature and precipitation were measured at the EC tower. Unpaved forest roads are represented by the thick grey lines. The grey shaded area shows the part of the study site most affected by the Lothar winter storm in 1999 (80% of the trees were thrown).

3.2.2 Soil respiration measurements

Soil respiration was measured with a portable device in a campaign mode (SR_{manual}) to cover the spatial heterogeneity of the study area (in the footprint of the EC tower), and continuously each 30 min ($SR_{automated}$) in one of the plots, to achieve high temporal resolution of soil respiration measurements at each study site. All soil respiration measurements were accompanied by measurements of soil temperature and soil moisture.

To measure soil respiration rates, one collar was installed at each plot at a location without vegetation (vegetation within the collars was removed regularly), two weeks prior to measurements. The PVC collars (inside diameter of about 20 cm) were inserted about 1.5 cm in the soil and additionally clamped with 10 cm long tent pegs to guarantee stability also at steep slopes. SR_{manual} was measured campaign-wise at Lägeren every two to three weeks at 16 plots during 2006 and 2007 and every four to six weeks at five to ten plots during 2008 and 2009. At Davos SR_{manual} was measured every four to six weeks at three plots during 2008 and four plots during 2009. To measure SR_{manual} a closed chamber system with a portable, non-dispersive infrared gas analyzer (LI-8100 with LI-8100-103 chamber, Li-Cor inc, Lincoln, NE, USA; except for measurements in January and February 2006 that were conducted with a LI-6400 with soil collars that were 10 cm in diameter and 10 cm high) was used. All SR_{manual} measurements were accompanied by periodical soil temperature and volumetric soil moisture measurements (ML2X Theta Probe, Delta-T Devices, Cambridge, UK). At the Lägeren site additional soil temperature sensors (HOBO Pendant Temperature Data Logger, Onset Computer Corporation, Bourne, MA, USA) were installed in each plot next to the collar for SR measurements in 5 cm depth, logging soil temperature every 30 min.

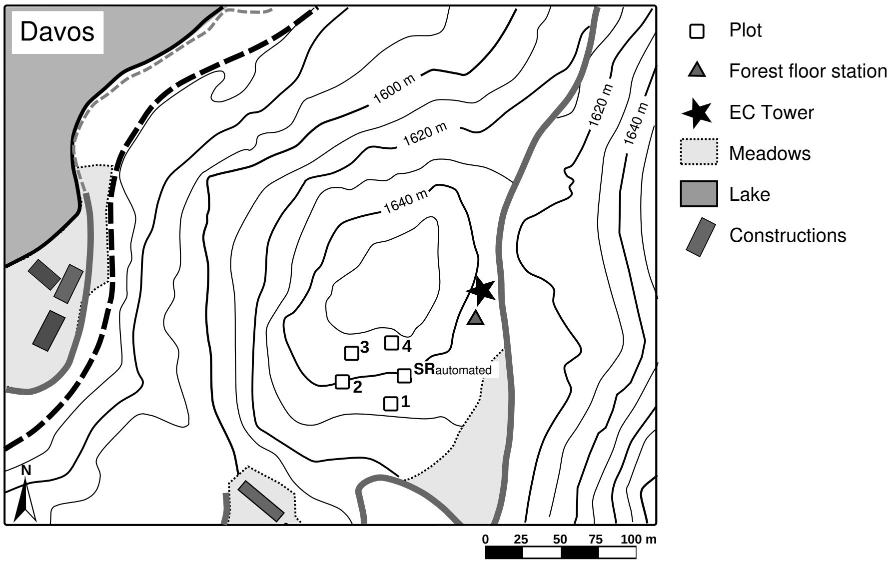

Figure 3.2: Map of the Davos Seehornwald study site including surroundings, fully covered by Norway spruce forest if not otherwise stated. The locations of the plots are shown where SR_{manual} was measured. Plots can be identified by their numbers. Roads are represented by the thick grey lines.

The same type of closed system (LI-8100, Li-Cor Inc, Lincoln, NE, USA) was used for $SR_{automated}$ measurements at both study sites, permanently connected to a chamber (Li-8100-101, Li-Cor Inc, Lincoln, NE, USA), opening in a 180° vertical arc to allow the soil to be exposed most of the time to ambient environmental conditions. The length of one measurement varied over the seasons: for high CO_2 efflux rates, measurement time was set to 60 s, for low CO_2 efflux rates, measurement time was expanded to 120 s. Soil temperatures (HTT thermocouple, OMEGA Engineering, Inc., Stamford, CT, USA) at 1 cm, 5 cm and 10 cm depth, as well as soil moisture at 10 cm depth (EC-20, Decagon Devices Inc., Pullman, WA, USA) were logged at the same time intervals. Data gaps occurred mostly due to equipment or power failure and after heavy snowfall when snow cover was > 10 cm (lid of the LI-8100-103 did not close).

3.2.3 Partitioning of soil respiration

Lägeren

Next to the collars for soil respiration measurements (within 50 cm; Plot 1–10), small root exclusions were installed in March 2006, using mesh bags (25 cm high and 35 cm in diameter) constructed from 38 μm monofilament PET mesh by heat sealing the seams (PETEX; Sefar Holding Inc., Freibach, Switzerland). With a mesh size of 38 μm and an open area of 27%, we were able to prevent roots from growing into the root exclusion treatment, but did still maintain a high permeability for soil water drainage. Thus, with this set-up, we were able to partition root-rhizosphere (i.e., roots, root associated microbes and mycorrhizal mantle) from microbial respiration (incl. mycelia respiration), but we were not successful to single out ecto-mycorrhizal mycelia respiration, which was shown in a recent study of Moyano et al. (2008) to contribute about 3% (beech) and 8% (spruce) to total soil respiration in two German forests stands.

For mesh bag installation, first, a circular area with the same diameter as the mesh bags was marked, the litter layer removed, and the soil removed in 5 cm thick layers to a depth of 20 cm. Then, the mesh bag was placed into the hole, refilled with soil, according to its layers and the litter layer was placed back. We inserted one PVC collar to measure soil microbial respiration (MR) in the center of these root exclusions. The area around the collar, within the mesh bag (about 7.5 cm), was used for soil climate measurements. MR fluxes and soil climate were measured as described above for SR_{manual}. Root-rhizosphere respiration (RR) was calulated for each plot as [RR = SR – MR].

Davos

Since root density and stone content was much higher at Davos, careful soil removal would have been problematic, therefore, a slightly different root exclusion approach was applied. Within 3 m next to the collars for soil respiration (Plot 2, 3 and 4), small root exclusions were installed in May 2009 as follows. A small trench was established by removing soil to a depth of 30 cm around a 50 x 50 cm intact soil area. Inside the trenched area all roots were cut, and the sides of the trenched soil area covered by a plastic foil, preventing roots from growing into the root exclusion treatment. We inserted one PVC collar to measure soil microbial respiration (MR) in the center of these root exclusions. The area around the collar, within the trenched area, was used for soil climate measurements. MR fluxes and soil climate were measured as described above for SR_{manual}. Root-rhizosphere respiration (RR) was calulated for each plot as [RR = SR – MR].

3.2.4 Soil respiration models

Soil respiratory fluxes were related to soil temperature using a non-linear least squares model (model$SR_{m,1}$) after Lloyd and Taylor (1994):

$$SR_{m,1} = R_{ref}\, e^{E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T_{soil}-T_0}\right)} \tag{3.1}$$

where R_{ref} is soil respiration (μmol CO_2 m^{-2}s^{-1}) under standard conditions (at T_{ref} = 10 °C; about equal to mean annual soil temperature in 5 cm depth), E_0 (K^{-1}) is the parameter for the activation energy, T_0 = –46.02°C, as in the original Lloyd and Taylor model and T_{soil} is the measured soil temperature at a given depth.

When SR was limited by water availability, as in summer 2006, the temperature sensitivity of SR depended on soil moisture and, therefore, a second model ($SR_{m,2}$) was used, in which E_0 was defined as a linear function of soil moisture (Reichstein et al. 2003):

$$SR_{m,2} = R_{ref}\, e^{(a\ SM+b)\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T_{soil}-T_0}\right)} \tag{3.2}$$

with *SM* being the measured volumetric soil moisture at a given depth, and *a* and *b* are the parameters of the linear function.

3.2.5 Annual estimates and uncertainties

All soil respiratory fluxes (SR, MR, RR) were fitted separately for each plot and year to Lloyd-Taylor models (Eqs. 3.1 or 3.2). To estimate seasonal or annual soil CO_2 efflux, modelled parameters and continuous half-hourly soil temperature measurements (5 cm depth) from each plot (Lägeren) or from the forest floor station (Davos) were used. In addition, to estimate also the uncertainties of annual and seasonal sums (Lägeren only), caused by temporal and spatial integration, Monte Carlo simulations (parametric bootstrapping) were applied (for details see Knohl et al. 2008).

At Davos, each year was divided into a summer season starting after snow-melt (15 May–14 Nov), and a winter season when the soils were covered with snow (1 Jan–14 May and 15 Nov–31 Dec) and soil respiration measurements were impossible. For the summer season, we calculated the parameters of the models (Eqs. 3.1) using $SR_{automated}$ and SR_{manual} with synchronized soil temperature measurements (5 cm depth, forest floor station). Soil respiration rates during the winter season under a closed snow-cover were estimated to be 0.5 μmol CO_2 $m^{-2}s^{-1}$ by studies of winter soil respiration fluxes in coniferous mountain forests (see McDowell et al. 2000; Monson et al. 2006; Schindlbacher et al. 2007; Liptzin et al. 2009).

To gain annual or seasonal estimates for $SR_{automated}$ at Lägeren, we had to gap-fill the data. Gaps in data occurred mostly due to equipment or power failure and after heavy snow fall, when the snow cover > 10 cm (lid of the LI-8100-103 did not close). First, we divided each year into a growing season (Lägeren: 1 April – 31 Oct) and a dormant season (1 Jan – 31 March and 1 Nov – 31 Dec), because parameters of the Lloyd and Taylor model may change between seasons (Janssens and Pilegaard 2003). Then, we calculated the parameters of the models (Eqs. 3.1 and 3.2) with their respective standard deviations using $SR_{automated}$ with synchronized soil temperature (5 cm depth) and, if Eq. (3.2) was used, soil moisture measurements (10 cm depth). To estimate annual and seasonal sums as well as their uncertainties, we used Monte Carlo simulations (for details see Knohl et al. 2008). However, uncertainties were estimated only when missing data were replaced by modeled data. All statistical calculations were performed using R version 2.8 (R Development Core Team 2007), extended by the MASS package for parametric bootstrapping (Venables and Ripley 2002).

3.3 Results

3.3.1 Seasonal course of soil climate and soil respiratory fluxes

The seasonal course of soil climate was pronounced at the Lägeren mixed forest during the study years (2006 to 2009). Lowest soil temperatures were generally measured in January and highest soil temperatures in July, while soil moisture content reached its maximum during the winter seasons (Fig. 3.3). In general, soil respiration rates were found to follow the changes in soil temperature (Fig. 3.3). Using the manual approach of measuring soil respiration (SR_{manual}) to characterize the spatial heterogeneity within the study site, resulted in a minimum campaign-average of 0.41 μmol CO_2 $m^{-2}s^{-1}$ on 1 February 2006 and a maximum campaign-average of 4.74 μmol CO_2 $m^{-2}s^{-1}$ on 17 July 2007. In addition, using the automated approach to capture the temporal variation at one location ($SR_{automated}$), showed a minimum daily average of 0.30 μmol CO_2 $m^{-2}s^{-1}$ on 21 January 2006 and a maximum daily average of 5.71 μmol CO_2 $m^{-2}s^{-1}$ on 5 September 2006.

The CO_2 efflux in the root exclusion treatment (MR) was about half the background SR between September 2006 and May 2008. The differences between SR and MR rates resulted from root-rhizopshere respiration (RR) rates, which showed a very pronounced seasonal course ranging from 0.32 to 3.09 μmol CO_2 $m^{-2}s^{-1}$. The seasonal course of MR was less pronounced with respiration rates ranging from 0.55 and 2.67 μmol CO_2 $m^{-2}s^{-1}$. Highest contributions of RR were found in July 2007 (59%) and in May 2008 (58%), and lowest contributions in January 2007 (31%) and in April 2008 (29%). Comparing the growing season (16 April 2007–24 Oct 2007) with the dormant season (3 Nov 2006–15 April 2007, 25 Oct 2007–28 April 2007), RR fluxes contributed on average about 10% more to SR during the growing season of 2007 than during the dormant seasons, most likely caused by increased plant activity and C supply to roots (phenological data by Ahrends et al. 2008).

At Davos Norway spruce forest, the seasonal course of soil temperature was pronounced during the study year in 2008, while soil moisture content showed only small seasonal variations. During the entire winter season (15 Nov 2007 to 15 May 2008), soils were hardly frozen, caused by thermal insulation from a distinct snow cover. Soil temperature (5 cm depth) reached its maximum at the end of June with about 13.5°C (Fig. 3.3k). Using the manual approach of measuring soil respiration (SR_{manual}) resulted in a maximum campaign-average of 6.47 μmol CO_2 $m^{-2}s^{-1}$ on 6 August 2008, and using the automated approach showed a maximum daily average of 7.22 μmol CO_2 $m^{-2}s^{-1}$ on 1 September 2008. To estimate the contribution of microbial and root-rhizosphere respiration to SR only measurement during June to Aug 2009 were available. During this period MR rates ranged between 2.00 and 2.87 μmol CO_2 $m^{-2}s^{-1}$ and contributed 48% to SR, while RR rates ranged between 1.81 to 3.37 μmol CO_2 $m^{-2}s^{-1}$ and contributed 52% to soil respiration (Fig. 3.3j).

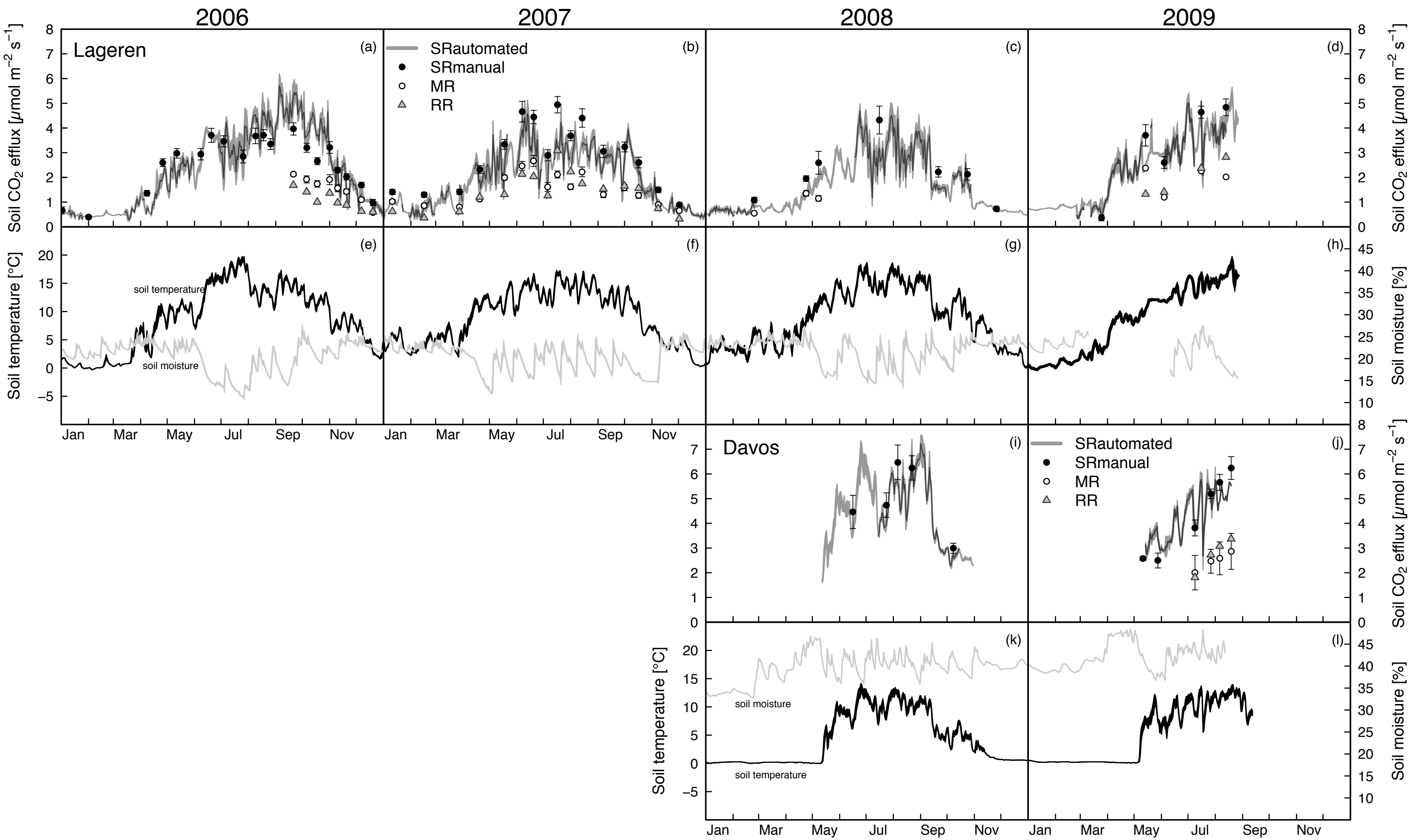

Figure 3.3: Time-series of soil respiratory fluxes, soil temperature and soil moisture for the Lägeren mixed forest (a–h) and the Davos Norway spruce forest (i–l). a–d, i–j: Daily means of $SR_{automated}$ with standard deviation and campaign-averages of SR_{manual}, as well as microbial (MR) and root-rhizosphere respiration (RR) are shown. e–h, k–l: Daily means of soil temperature (5 cm depth) and soil moisture (10 cm depth) are given. Error bars represent ±1 SE.

3.3.2 Soil respiratory fluxes and abiotic drivers

Soil respiratory fluxes (daily and campaign averages) of both study sites were typically very strongly related to soil temperature at 5 cm depth (Fig. 3.4). However, low precipitation (only 82.4 mm in June and July 2006; data not shown) and a decline of soil moisture to a minimum of about 11% (about 40% relative soil water content, Reichstein et al. 2003) caused a strong water limitation on soil respiration (Fig. 3.4a and b). The threshold for this water limitation was found to be about 15% soil moisture content (about 55% relative soil water content; Fig. 3.4a and b). Inter-annual differences of temperature response curves of soil respiration were generally small. Differences can probably be related to methodological errors caused by differences in measurement frequency (e.g., 16 measurement campaigns in 2007 vs. 6 in 2008). The temperature response curve for $SR_{automated}$ during 2006 (Fig. 3.4a; soil moisture < 15% excluded) was much steeper compared to other years, probably caused by respiration pulses after rain events following the drought period in July 2006 (for details see Ruehr et al. 2009). It can be noted, that SR rates at 10°C doubled those at Davos ($SR_{automated}$: R_{ref}= 4.55, SR_{manual}: R_{ref}= 4.81) than at Lägeren ($SR_{automated}$: R_{ref}=1.72, SR_{manual}: R_{ref}=2.23).

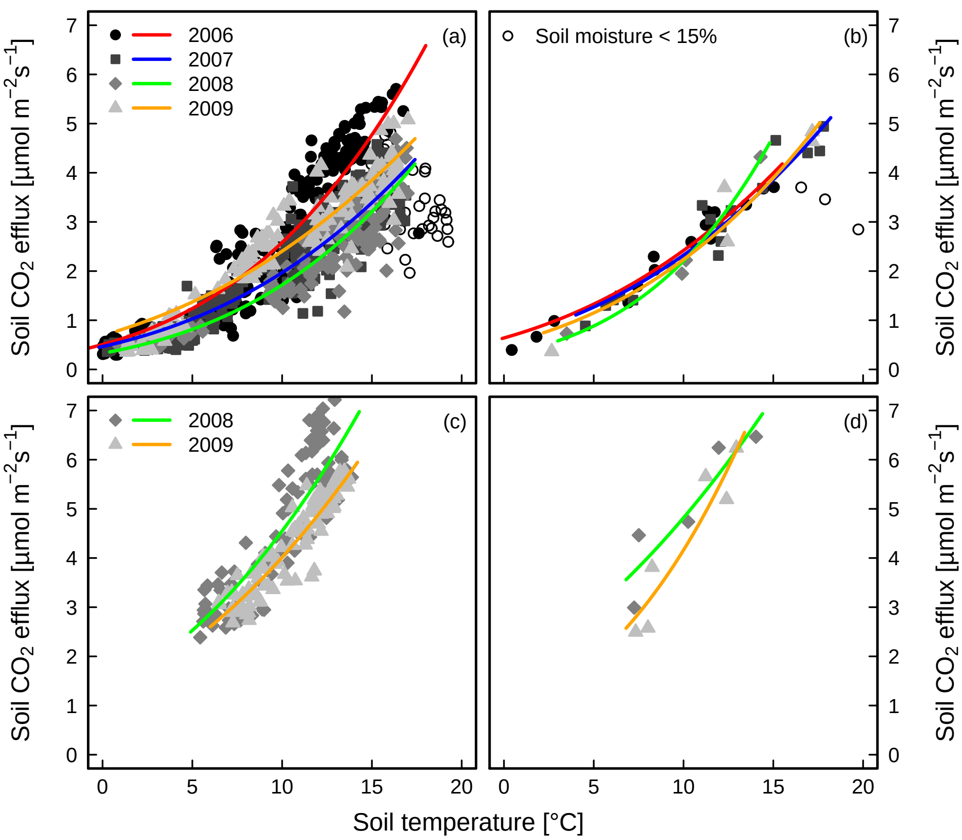

Figure 3.4: Soil respiration vs. soil temperature at the Lägeren between 2006 and 2009 (a–b) and Davos Seehornwald between 2008 and 2009 (c–d). Shown are daily-averages of $SR_{automated}$ and SR_{manual}.

3.3.3 Winter respiration

Comparing the coldest months (Jan, Feb, March) at the Lägeren study site of three consecutive years (2006, 2007 and 2008) offered the opportunity to study the effect of contrasting winter seasons on soil CO_2 efflux. While the harsh winter in 2006 was characterized by a distinct snow cover and air temperatures mostly below 0°C, the winter in 2007 was mild with hardly any snow cover and air temperatures mostly above freezing. The winter in 2008 was also rather mild, but colder than the winter in 2007 (mean air temperature –1.03°C in 2006, 3.96°C in 2007, 2.98°C in 2008; mean soil temperature at 5 cm depth 1.35°C in 2006 vs. 5.04°C in 2007, 3.80°C in 2008). SR and soil temperature (5 cm) measured during the dormant season of each year was used to

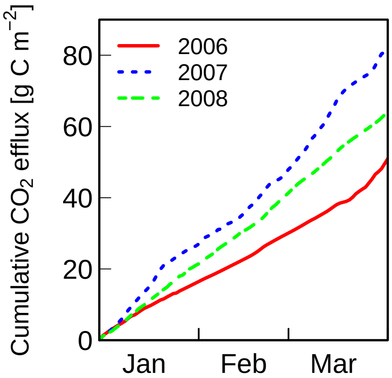

Figure 3.5: Cumulative $SR_{automated}$ flux during the coldest months at the Lägeren study site in 2006, 2007 and 2008.

calculate the soil CO_2 loss during these contrasting winter seasons using Eq. 3.1. The resulting cumulative flux of $SR_{automated}$ was highest during the warmest winter in 2007 with 80.8 g C m^{-2} (95% confidence interval of [75.3, 86.4]), followed by the winter in 2008 with 63.3 g C m^{-2} and much lower during the coldest winter in 2006 with 49.6 g C m^{-2} (95% confidence interval of [39.0 , 61.6]; Fig. 3.5). Thus, an increase in soil temperature of about 4°C in 2007 nearly doubled the cumulative CO_2 loss from soils compared to 2006 (Fig. 3.5) and increased the contribution of CO_2 efflux during winter months to the annual $SR_{automated}$ estimate from 6% in 2006 to 11% and 10% in 2007 and 2008 (see Tab. 3.1). Since we found SR to be dominated by MR during winter (contributing about 70% to SR during JFM in 2007) and MR to be very sensitive to temperature (Fig. 3.6), higher respiration rates during winter should mainly originate from decomposition of litter and soil organic carbon. Thus, an increase in winter temperatures at the Lägeren study site may mainly increase microbial decomposition rates, leading to increased soil CO_2 loss during winter.

3.3.4 Annual soil respiratory fluxes

Annual soil respiration estimates were calculated from Lloyd-Taylor functions including soil temperature and soil moisture (only 2006). Despite pronounced differences in temperature and precipitation during winter and summer seasons of the three study years at the Lägeren forest, mean

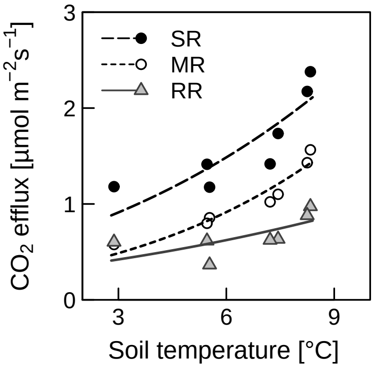

Figure 3.6: Relationship of soil respiratory fluxes with soil temperature (5 cm depth) during the dormant season 06/07 (6 Nov 2006 – 10 April 2007).

annual temperatures and amounts of precipitation as well as annual SR_{manual} rates were similar between the three study years (Tab 3.1). The Lägeren mixed forest lost on average about 880 g C $m^{-2}y^{-1}$ from soils (including roots) between 2006 and 2008 (Tab 3.1). However, annual estimates of $SR_{automated}$ were found to differ significantly between the years. These differences have probably a methodological reason, caused by a ”chamber installation effect“, since we did not change the location of the collar and the chamber since June 2006. The Li-8100-101 chamber is mounted on a frame above the soil surface. But this frame is still covering the soil surrounding the collar by about 5 cm wide just like a tiny roof. When the chamber is open (c. 90% of the time) another about 350 cm^2 of the adjacent soil is covered. This set-up might reduce precipitation and litter fall, and therefore, contributed to the lower estimates of $SR_{automated}$ in 2007 and 2008. We calculated annual estimates for MR and RR for 2007 and found that the C losses by respiration from the soils at Lägeren consisted about half of microbial (489 g C $m^{-2}y^{-1}$with a 95% confidence interval of [466, 514] g C $m^{-2}y^{-1}$) and half of root-rhizosphere respiration (428 g C $m^{-2}y^{-1}$ with a 95% confidence interval of [398, 467] g C $m^{-2}y^{-1}$).

Annual SR estimates for Davos were 866 g C $m^{-2}y^{-1}$ for SR_{manual} and 916 g C $m^{-2}y^{-1}$ for $SR_{automated}$ in 2008 (Tab 3.1), assuming that SR at 0°C under a closed snow cover is approx. 0.5 μmol CO_2 $m^{-2}s^{-1}$, estimated from winter soil respiration rates in Norway spruce (Schindlbacher et al. 2007) and sub-alpine forests (McDowell et al. 2000; Monson et al. 2006; Liptzin et al. 2009). If we assume a 50% contribution of MR to SR on an annual basis, then the CO_2 loss from soils via microbial decomposition should have been about 430 g C $m^{-2}y^{-1}$ in 2008. Despite pronounced differences in vegetation, altitude and mean annual air temperature between the study sites, annual SR estimates were similar for Lägeren and Davos in 2008.

3.3.5 Contribution of SR to ecosystem respiration

The contribution of annual SR to total ecosystem respiration (ER) at Lägeren was found to be very similar over the three study years with 77% in 2006 (1131 g C $m^{-2}y^{-1}$), 79% in 2007 (1146 g C $m^{-2}y^{-1}$) and 72% in 2008 (1185 g C $m^{-2}y^{-1}$). At Davos annual ER was estimated

Table 3.1: Annual soil respiration estimates of SR_{manual} and $SR_{automated}$ for the Lägeren mixed forest (700 m asl) and the Davos Norway spruce forest (1640 m asl). The 95% confidence intervals for the annual SR estimates received by parametric bootstrapping are given within squared brackets.

	Lägeren				Davos			
	AirTemp (°C)	Precip (mm)	SR_{manual} (g C $m^{-2}y^{-1}$)	$SR_{automated}$ (g C $m^{-2}y^{-1}$)	AirTemp (°C)	Precip (mm)	SR_{manual} (g C $m^{-2}y^{-1}$)	$SR_{automated}$ (g C $m^{-2}y^{-1}$)
2006	8.9	1032	869 [846, 890]	868 [837, 900]	4.5	789	–	–
2007	9.1	914	907 [871, 942]	729 [709, 748]	4.4	1006	–	–
2008	8.7	951	855 [811, 899]	623 [604, 643]	4.0	1164	866$	918$

$ Respiration under closed snow cover (1 Jan to 15 May and 15 Nov to 31 Dec) estimated to be 0.5 μmol CO_2 $m^{-2}s^{-1}$ (see McDowell et al. 2000; Monson et al. 2006; Schindlbacher et al. 2007; Liptzin et al. 2009).

to be 1307 g C $m^{-2}y^{-1}$ in 2008. Thus, if SR is estimated to be 866 g C $m^{-2}y^{-1}$, then SR contributed about 66% to ER at the Davos study site in 2008. This estimate is well in the range of results from other coniferous forests (Davidson et al. 2006; Gaumont-Guay et al. 2009). We investigated the contribution of SR to ER at Davos in more detail for the period from July to October 2008, when SR and ER measurements were both available. The contribution of SR to ER ranged between 71% to 125% with an average of 93% for $SR_{automated}$ and of 94% for modeled SR_{manual} rates (ER data are from Etzold, unpublished; for details on ER measurements see Zweifel et al. 2009).

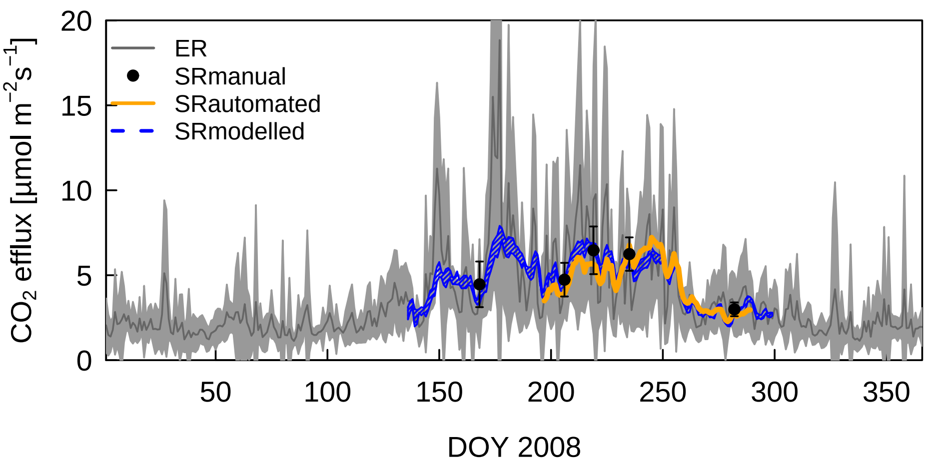

Figure 3.7: Ecosystem and soil respiration for the Davos Seehornwald in 2008. Shown are daily averages with standard deviation for ecosystem respiration, $SR_{automated}$ and modeled soil respiration rates as well as campaign-averages of SR_{manual}. Error bars are ±1 SE. ER data are from Etzold, unpublished. For details on ER measurements see the BAFU report byZweifel et al. (2009).

3.4 Discussion

Despite pronounced differences in temperature and precipitation during winter and summer seasons of the three study years, mean annual temperatures and amounts of precipitation as well as total annual SR estimates were comparable between the three study years. The Lägeren forest lost on average about 880 g C $m^{-2}y^{-1}$ via soil respiration (Tab. 3.1; with an uncertainty <10% at the 95% confidence interval), well within the range of estimates of other beech-dominated forests in Europe (e.g., Knohl et al. 2008). The annual SR estimate at Davos in 2008 is with 870 g C $m^{-2}y^{-1}$ quite high compared to other soil respiration studies. For a 140-year old Norway spruce forest in Germany annual SR rates of 710 g C $m^{-2}y^{-1}$ were reported (Matteucci et al. 2000). However, since no data on winter soil respiration were available, our annual SR estimate could be either over- or underestimated. Assuming 0.5 g C $m^{-2}y^{-1}$ for soil respiration under a closed snow cover resulted in a contribution of about 25% to total ecosystem respiration. This is lower than the contribution of SR to ER (35%) reported from a sub-alpine forest in Colorado during winter (Monson et al. 2006). Nevertheless, our findings of similar annual SR estimates from Lägeren and Davos are in agreement with a study on soil respiration among European forests (Janssens et al. 2001). In the mentioned study, a positive relationship of SR rates with gross primary productivity (GPP) but not with temperature was found. In accordance with their findings, GPP at Lägeren was only slightly higher than GPP at Davos in 2008 (Etzold, pers. comm.). Thereby, explaining the similar SR rates among our two studied forests.

We successfully partitioned soil respiration in microbial and root-rhizosphere respiration using small root exclusions. However, since no partitioning method is perfect, several factors might have influenced our results. Excluding roots from soils may not only decrease respiration rates but may also influence soil moisture content (e.g., Irvine et al. 2008; Schindlbacher et al. 2008), soil temperature, and soil nutrient concentrations (e.g., Moyano et al. 2007). Higher soil moisture in the root exclusion treatment should be of concern mainly during drought periods, since microbial respiration rates can be easily overestimated (as observed during the drought spell in July 2006, see in Chapter 3 Ruehr 2009). On the other hand, higher mineral N concentrations (as measured in the root exclusion treatment; see Chapter 3 in Ruehr 2009) might suppress microbial activity and lead to a decrease in microbial decomposition (e.g., Thirukkumaran and Parkinson 2000; Burton et al. 2004), and thus to an overestimation of root-rhizosphere respiration. Since we did not account for decomposing fine roots and roots from deeper soil layers, the contribution of RR to SR could still be slightly underestimated (e.g., if 50% of the standing fine root biomass of c. 70 g C m^{-2} would decompose within one year, the contribution of MR to SR at Lägeren might increase by 4%). Nevertheless, our estimate of MR and RR to contribute each about half to SR, is in good accordance with other root exclusion studies from temperate forest ecosystems (see review by Subke et al. 2006).

Microbial respiration rates could be explained very well with soil temperature, showing the highest temperature sensitivity during the dormant season, when decomposition is not limited by substrate supply after autumnal litter fall, but rather by temperature. Moreover, the contribution of

MR to SR was highest during winter. In addition, winter respiration rates of the three study years were found to be highest during the mild winter in 2007. This clearly indicates, that higher winter temperatures as expected for the next decades will increase soil CO_2 loss during winter months and thus, increasing the importance of winter respiration at the Lägeren study site.

Chapter 4

Soil carbon modelling

4.1 Summary

The main findings of this chapter are:

- Simulated soil C stocks were slightly lower than measured/interpolated soil C stocks.
- Simulated annual microbial respiration rates were comparable to measurement results.
- Soils at Davos were a significant C sink averaged over the entire study period (1989–2008).
- Soils at Lägeren were neither a significant C sink nor a significant C source averaged over the entire study period (1989–2008).
- Climate variability had a large impact on annual microbial respiration and soil C storage.

4.2 Methods

4.2.1 Soil carbon model Yasso07

We used the soil organic carbon model Yasso07 (Liski et al. 2009), an improved version of an earlier Yasso model (Liski et al. 2005) to calculate the stock of soil organic C, changes in the stock of soil organic C and microbial soil respiration of our two study sites. The model requires only basic information on weather, litter quantity and quality. The underlying assumption of Yasso07 is that decomposition depends on litter input types (non-woody litter and woody litter), their chemical composition (i.e., waxes, sugars, cellulose, lignin) and on annual weather conditions (air temperature, temperature amplitude and precipitation). Decomposition of woody litter depends additionally on the size of the litter (e.g., coarse woody litter, fine woody litter). The effects of annual weather conditions are modelled by adjusting the decomposition rates of the compartments according their physical and chemical properties to air temperature and precipitation. We simulated changes in the soil C stock at Lägeren and Davos over a 20-year period (1989–2008) using annual litter input with two diameter classes for wood (2 cm and 10 cm; for details see below) and annual air temperature and precipitation data. The initial soil C stock at each study site was assumed to be in steady-state, calculated from the litter input at the beginning (1988) and averaged annual temperature and precipitation over the past 30 years (1958–1988). To estimate the uncertainties originating from the parameter estimates of the model, the mean and the 95% confidence interval (estimated from Monte-Carlo simulations by sampling 500 times from the parameter estimates) of the annual soil C stock, change in the soil C stock and microbial respiration rates are given.

4.2.2 Climate data

Climate data (air temperature and precipitation) for each study site were available from the Swiss National Air Pollution Monitoring Network (NABEL) as monthly means for the period from 1987 to 2008. To extrapolate missing climate data, linear relationships between monthly climate data from the study sites and MeteoSwiss stations close-by (data records until 1901) were used. Due to pronounced differences of precipitation measurements between the NABEL and MeteoSwiss station at Davos, only the precipitation data from the MeteoSwiss station were used.

4.2.3 Litter input

For the Lägeren mixed forest, data on above-ground litter input were available from 1985 to 1988 (over- and understory; see Lüscher 1991) and from 2006 to 2007 (only overstory, see Ruehr 2009). Between these periods, leaf litter input increased by 1.1 g C $m^{-2}y^{-1}$ (0.64% per year; Tab. 4.1). Based on this increment rate and assuming the carbon content of biomass to be 50%, yearly litter input (except for fine wood) was extrapolated. To estimate annual coarse root and stem woody litter, the average of coarse woody litter (including coarse roots > 5 mm) for the Swiss Jura/Plateau region as given in Thürig et al. (2005) was applied. Data on fine root litter (< 2 mm) were only available for 2006 and 2007. Fine root turnover was estimated from maximum fine root biomass (sequential coring) and annual fine root growth (ingrowth cores) to be 2.53 years, resulting in an average fine root litter input of 50 g C $m^{-2}y^{-1}$ (Ruehr, unpublished data). Since the coarse woody litter fraction (Thürig et al. 2005) included only coarse roots > 5 mm, fine root litter input (< 2 mm) was multiplied by 1.25 to cover all diameter classes.

Table 4.1: Litter input at Lägeren and Davos for the calculation of the steady-state (1988) and at the end (2008) of the Yasso07 simulation.

		Litter input (g C $m^{-2}y^{-1}$)					
	Year	Leaves$^{\$}$	Fine roots	Fine wood (incl. branches, seeds)	Coarse wood (incl. branches > 7 cm, coarse roots, stems)	Understory	Total
Lägeren	1988	163.3^{a}	66.4^{c,d}	105.2^{a}	90.8^{b,†}	39.7^{a}	465.3
	2008	185.6^{c,†}	75.5^{c,†}	112.4^{d,†}	103.3^{b,†}	45.1^{a,†}	521.9
Davos	1988	220.3$^{b,\#}$	—	90.2$^{b,\#}$	64.1$^{b,\#}$	23.7^{a}	398.3
	2008	291.1$^{b,\#}$	—	119.2 $^{b,\#}$	84.7$^{b,\#}$	31.3$^{a,\#}$	526.3

$ includes fine root litter for Davos

[a] Lüscher (1991), [b] Thürig et al. (2005),[c] Ruehr (2009), [d] Ruehr unpublished data

† calculated based on the annual increment of leaf litter (0.64%)

calculated based on the annual increment of stem volume (1.14%, M. Dobbertin, pers. comm.)

For the Davos Norway spruce forest, only data on understory litter were available from Lüscher (1991) for 1985 to 1988. Litter input of the overstory was estimated from the average litter input (1986–1996) as given by Thürig et al. (2005) for forests of the Alpine region (Tab 4.1). We further assumed, the annual increment rate of litter input (between 1988 and 2008) to be equal to the annual growth rate of stem volume, which was found to be 1.14% for Norway spruce trees at Davos between 1988 and 2006 (M. Dobbertin, pers. comm.).

The chemical composition of leaves, needles, fine roots and understory litter were based on findings by Heim and Frey (2004). The chemical compositions of coarse woody litter at Lägeren (average of the chemical composition of stem wood from several tree species) and at Davos (average of the chemical composition of stem wood from *Picea abies*) were estimated as given by Liski et al. (2009). In addition, the chemical composition of fine woody litter was estimated from measurements by Vavrova et al. (2009).

4.3 Results

The initial values for soil organic carbon stocks (including woody and non-woody litter), obtained with the assumption of steady state conditions, were 11.16 kg C m^{-2} for Lägeren (95% confidence interval of [10.92, 11.40] kg C m^{-2}) and 11.05 kg C m^{-2} for Davos (95% confidence interval of [10.83, 11.27] kg C m^{-2}; red lines in Fig. 4.1e and Fig. 4.2e). Since Yasso07 estimates the soil C stock to a depth of 1 m, including woody litter, the simulated soil C stocks were found to be higher than the measured soil C stocks (0–20 cm, including litter and organic layers) of the two study sites (see Tab 2.1). Annual soil C loss from simulated microbial respiration (MR) was at Lägeren

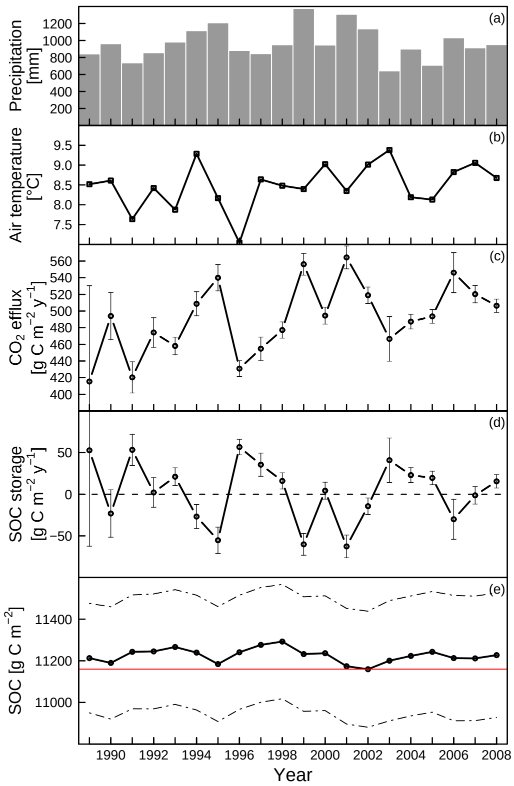

Figure 4.1: Lägeren mixed mountain forest (700 m asl). (a) Annual precipitation, (b) mean annual air temperature, (c) annual microbial respiration rates, (d) annual soil organic carbon (SOC) storage rates and (e) dynamics of the SOC stock are given. (e) The calculated steady-state SOC stock is shown by the red line and the 95% confidence intervals of the annual SOC stocks are given by the dashed lines. Error bars represent the 95% confidence interval.

491 g C m^{-2}y^{-1} (95% confidence interval of [472, 511] g C m^{-2}y^{-1}; Fig. 4.1c) and at Davos 442 g C m^{-2}y^{-1} (95% confidence interval of [426, 457] g C m^{-2}y^{-1}; Fig. 4.2c), averaged over the study period. Simulated MR was found to be in very good agreement with the annual estimate from root exclusions at the Lägeren study site in 2007 (simulated MR: 520 g C m^{-2}y^{-1} with 95% confidence interval of [510, 531] g C m^{-2}y^{-1}; MR from root exclusion: 489 g C m^{-2}y^{-1} with 95% confidence interval of [466, 514] g C m^{-2}y^{-1}). While at Davos, simulated MR was found to be slightly larger than estimated annual MR rates from root exclusion in 2008 (simulated MR: 495 g C m^{-2}y^{-1} with 95% confidence interval of [488, 502] g C m^{-2}y^{-1}; MR from root exclusion: ≈ 430 g C m^{-2}y^{-1}).

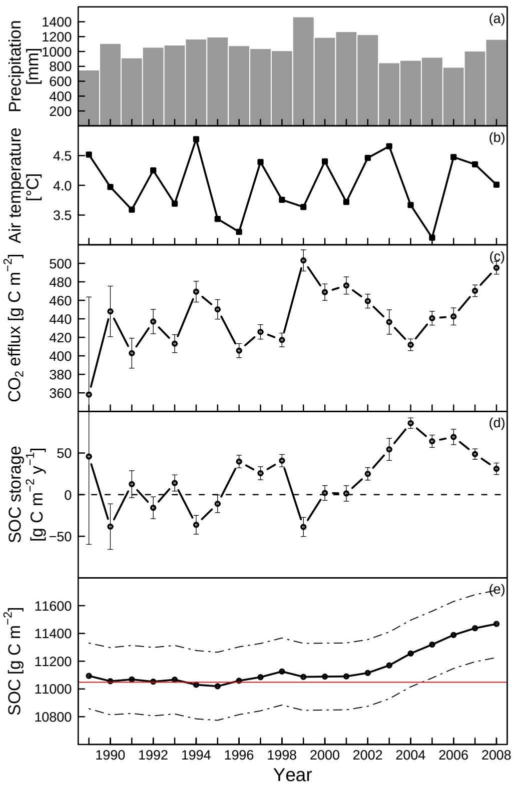

Figure 4.2: Davos Seehornwald subalpine Norway spruce forest (1640 m asl). Annual precipitation (a), mean annual air temperature (b), annual microbial respiration rates (c), annual soil organic carbon (SOC) storage rates (d) and dynamics of the SOC stock (e) are given. e: The calculated steady-state soil organic carbon stock is shown by the red line and the 95% confidence intervals of the annual SOC stocks are given by the dashed lines. Error bars represent the 95% confidence interval.

Variations in annual air temperature and precipitation were pronounced (Fig. 4.1a–b and Fig. 4.2a–b), affecting annual MR and soil organic C stocks. Despite pronounced variations in soil C storage rates caused by climatic variability, both study sites tended to be a C sink with 3.4 g C m^{-2}y^{-1} (95% confidence interval of [-16.0, 22.7] g C m^{-2}y^{-1}) at Lägeren and 21 g C m^{-2}y^{-1} (95% confidence interval of [5.8, 36.2] g C m^{-2}y^{-1}) at Davos (Fig. 4.1d and Fig. 4.2d). The largest increase in soil C was found at Davos between 2003 and 2006 (Fig. 4.2d), when precipitation was below the long-term average. At Lägeren, the picture was less clear. However, the strongest decrease in soil carbon was found between 1998 and 2002 (Fig. 4.1d), when both air temperature and precipitation were high, resulting in large MR rates. The small soil C storage rates at Lägeren can be explained by the small increment in litter input and by differences in air temperature. During the simulation of soil C change (1989 to 2008) mean air temperature (8.5°C) at the study site was 1°C higher than the mean air temperature between 1958 and 1988 (7.5°C), which was used for the calculation of the initial soil C stock. Indeed, soil C storage at Lägeren was more pronounced (11.8 g C $m^{-2}y^{-1}$ with 95% confidence interval of [−7.8, 38.1] g C $m^{-2}y^{-1}$), assuming the same temperatures for the calculation of the initial soil C stock as during the simulation of soil C change (Fig. 4.3). Thus, the higher temperatures during the past 20 years have probably reduced the soil C sink strength at the Lägeren study site.

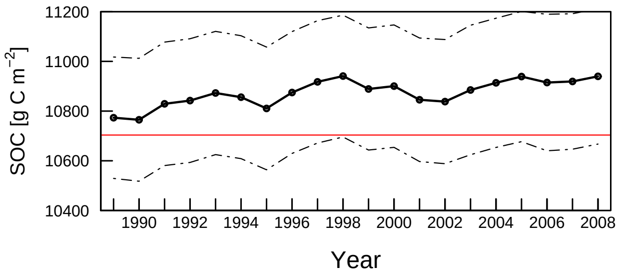

Figure 4.3: Dynamics of soil organic carbon stocks at Lägeren mixed mountain forest (700 m asl). The initial steady-state soil organic carbon stock (red line) was calculated by assuming the same climate as during the study period. The 95% confidence intervals of the SOC stocks are given by the dashed line.

To investigate the influence of annual climate variability (and climate warming) on soil C stocks in more detail, we repeated the simulation using constant climate data during both the calculation of the steady-state and the simulation of soil C change (average climate data from 1978–2008). This resulted in a step-wise increase of soil C storage rates during the study period reaching a maximum in 2008 with 22 g C $m^{-2}y^{-1}$ at Lägeren and 53 g C $m^{-2}y^{-1}$ at Davos. Thus, excluding climate variability and climate warming resulted in both study sites being a significant C sink.

4.4 Discussion

4.4.1 Uncertainties

Uncertainties in the estimates of soil carbon stocks and changes in the soil carbon stock as well as microbial respiration rates were given at a 95% confidence interval, originating from uncertainties in the parameter values of the Yasso07 model. Additional uncertainties resulted from the assumption of the initial soil C stock to be in steady state and from the litter input data per se. For the Lägeren study site, data on aboveground and on fine root litter were available from measurements (litter traps) between 1985 and 1988, and between 2006 and 2007. Uncertainties of these measurements are caused by spatial variability and should be about ±10%. Moreover, the observed increase in litter input between the two periods could also be affected by spatial variability (litter traps were not at the same locations between the two periods). The annual increase in leaf litter (0.64%) was only slightly lower than stem wood increase calculated from Swiss national forest inventories between 1985 and 1995 (≈ 0.9%). This comparatively smaller increase can be explained by the Lothar winter storm in 1999, affecting about 30% of the study area in which about 80% of the trees were thrown (Fig. 3.1).

Since sufficient litter input data were unfortunately not available for the Davos Norway spruce forest, litter estimates based on a Swiss national forest inventory as given by Thürig et al. (2005)

were used (also for coarse woody litter at Lägeren). These estimates underlie several uncertainties, as for example, the assumed proportion of fine root biomass being 5% of coarse root biomass or the fixed fine root turnover rate of 1.5 years (for details see Thürig et al. 2005). In addition, further uncertainty might originate from the assumption of a constant linear increase in litter input, independent from the actual climate variability. Indeed, this assumption seems to be highly criticisable, since annual litter input depends also on annual productivity, which depends on climate conditions as shown by EC measurements at Davos (see the BAFU report by Zweifel et al. 2009).

The simulated soil C stocks were found to be higher than measured soil C stocks (0–20 cm), since Yasso07 simulates the C stock to a depth of 1 m. However, when the simulated soil C stocks were compared with measured/interpolated soil C stocks including deeper soil horizons (Lägeren: 0–40 cm, Davos: 0–60 cm), the simulated soil C stocks (Lägeren: 11.2 kg C m^{-2}, Davos: 11.1 kg C m^{-2}) underestimated the measured/interpolated soil C stocks [Lägeren: 13.9 kg m^{-2} (Heim et al. 2009), Davos: 14.2 kg m^{-2} (Jörg 2008)]. This could probably result from an overestimation of the soil C stock caused by interpolation of the measured data or from an underestimation of the simulated soil C stocks caused by soil properties, not accounted for in the model. For example, the rustic podzols at Davos are rich in iron, causing strong metal-binding of organic substances.

Nevertheless, despite differences in soil C stocks between simulation and measurement, the annual soil C losses via microbial respiration estimated from measurements and from simulation were found to be in good agreement. Therefore, simulated soil C storage rates can be assumed to be at least in the correct order of magnitude.

4.4.2 Soil carbon sink

Estimates of the soil C sink in Swiss forests are high compared to forests in Northern Europe (Liski et al. 2002). The higher C sink simulated for Swiss forest soils results mainly from the high growing stock (366 m^3 stemwood ha^{-1}) and the large annual increase of this growing stock (3.2 m^3 stemwood $ha^{-1}y^{-1}$; Brassel and Brändli 1999). Perruchoud et al. (1999) estimated a carbon stock increase of 33 g C $m^{-2}y^{-1}$ (uncertainty ranged from 10 to 55 g C $m^{-2}y^{-1}$) for Swiss forest soils in 1985 using national forest biomass inventory data and the ForClim-D model. While Liski et al. (2002) gave even a higher estimate of the C sink of Swiss forest soils with 43 g C $m^{-2}y^{-1}$ in 1990 using the same model. However, in contrast to our simulation of soil C storage, none of the above mentioned studies accounted for the effect of climate variability, which we found to strongly affect simulated annual soil C storage rates. Excluding any climate variability from the simulation resulted in larger soil C storage rates at our study sites, comparable to those of Perruchoud et al. (1999) and Liski et al. (2002). In contrast, including climate variability decreased soil C storage rates, mainly because of an increase in temperature between the calculation of the initial C stock (average temperature between 1958 and 1988) and the simulation of soil C change (average temperature between 1989 and 2008). Nevertheless, the soils at Davos were found to be a significant C sink during the study period, assuming a constant increase in litter input. Whereas the soil C sink was mainly caused by the high increment in litter input and by exceptional dry years

(2003–2006) and cool temperatures in 2004 and 2005. In contrast, the soils at Lägeren were found to be neither a significant C sink, nor a significant C source. Whereas the lower soil C storage at Lägeren compared to Davos seems to be mainly caused by the lower increment in litter input (probably caused by the Lothar winter storm in 1999) and the higher increase in air temperature (1°C at Lägeren vs. 0.7°C at Davos) between the calculation of the steady state (1958–1988) and the simulation of soil C change (1989–2008). However, it should be noted, that calculating the soil C sink at Lägeren from MR measurements and litter input data in 2007 resulted in higher soil C storage (4–53 g C $m^{-2}y^{-1}$) compared to the simulation results.

Nevertheless, comparing the soil C storage rates from Yasso07 (including climate variability) to tree biomass and forest ecosystem C sink estimates of our two study sites revealed a surprisingly good agreement. The simulated soil C sink at Davos with about 21 g C $m^{-2}y^{-1}$ fitted well to the tree C sink with 120–130 g C $m^{-2}y^{-1}$ estimated from forest inventories (1988–2008; M. Dobbertin pers. comm.) and to net ecosystem productivity (NEP; measured with Eddy Covariance, see BAFU report by Zweifel et al. 2009), estimating the whole forest ecosystem (including soils) to be a C sink of about 150 g C $m^{-2}y^{-1}$ (1997–2008). At Lägeren, small soil C storage rates are contrasted by high annual NEP. It is likely that tree growth could be the single explaining factor causing high C storage at Lägeren (for more details see BAFU report by Zweifel et al. 2009), additionally affected by forest re-growth on wind-throw areas.

Thus, by using the simple soil carbon model Yasso07, we could show that the soils of our study sites, under current climate conditions, are most likely a sink or at least not a clear source of carbon to the atmosphere. Moreover, when we excluded the temperature increase during the past 20 years from the simulation, annual soil C storage rates were even larger. Thus, the higher temperatures during the past 20 years have probably dampened the soil C sink strength. Nevertheless, the effect of future climate conditions on soil C storage is unclear, since the effect of climate change on productivity (C-input) and on decomposition rates (C-output) are still uncertain.

Chapter 5

Synthesis

We could show that soil respiration rates at each study site increased with temperature within each study year, if not limited by water availability. However, we were not able to evaluate the effect of different annual temperatures and precipitation on SR rates, since mean annual temperature and precipitation were comparable between the studied years. Nevertheless, by comparing three contrasting winter seasons, we found higher winter temperatures to increase soil microbial decomposition at Lägeren. Higher air temperatures at Davos during winter, should be of minor concern, since the soil is isolated by snow, leading to constant winter soil temperatures (5 cm depth) of about 0°C.

The dynamic soil carbon model Yasso07 allowed us to simulate soil C stocks and their changes using site-specific litter and climate data over a 20 year period (1989–2008). Despite several uncertainties, simulated MR and changes in soil C storage were comparable to measurement results. During the entire study period (1989–2008), the soils at Davos were found to be a significant C sink, while the soils at Lägeren were neither a significant C sink nor a significant C source. In addition, we found the warmer climate during the past 20 years to reduce the soil C sink strength at both study sites.

However, the estimates of soil C stocks and fluxes given in this study are moderately to highly uncertain and underlie several assumptions. Often the uncertainty might be higher than the actual change of the annual estimates and therefore missed (Falloon and Smith 2003). Especially the detection of changes in soil C stocks is difficult, since annual soil C storage is a very small number among huge C pools and large C fluxes, and it can not be measured directly.

To reduce uncertainty about soil C storage, also in the context of global warming, long-term studies including above- and belowground pools and fluxes are needed. Those studies will provide a better process understanding and the possibility to validate carbon models, towards a more reliable estimate of soil carbon sequestration. Such long-term studies should be carried out at representative forest sites, including briefly the following measurements:

- Standardised C stock measurements every 5 to 10 years, including above- (tree and understory) and below-ground biomass as well as soil organic carbon.
- Litter input from above-ground with litter traps (monthly) and from below-ground with ingrowth cores and sequential coring to estimate fine root turnover (yearly), as well as litter

quality measurements.

- Continuous, year-round C-flux measurements of the whole ecosystem with Eddy Covariance and of soil respiration with chambers, including partitioning in microbial and root-rhizosphere respiration.
- Additional experiments, such as decomposition studies.

These measurements should be combined with dynamic soil carbon and vegetation models such as Yasso07 or LPJ-Guess, to improve models and to validate modelling results, and thereby, reducing uncertainties of soil C storage estimates. These models could then be applied nation wide to assess the CO_2 balance of forest ecosystems, and therefore, provide more accurate annual soil C storage estimates as needed for Kyoto accounting.

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