ASSESSING SEASONAL DYNAMICS OF SOIL CO2 EFFLUX USING CONTINUOUS MEASUREMENTS IN A TEMPERATE PINE FOREST

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PREFACE

Assessing Seasonal Dynamics of Soil CO_2 Efflux Using Continuous Measurements in a Temperate Pine Forest is a thesis based on a field study where the primary author, Emily Nicholas has contributed in 70% of data collection and 90% of the data analysis and writing of the results. Other contributors include M. Altaf Arain, Jason J. Brodeur and Samantha L. MacKay.

Abstract

This study explores the seasonal dynamics of soil CO_2 efflux (Rs) in a temperate pine plantation forest located in Southern Ontario, Canada. Rs was continuously measured from June 15, 2008 to December 31, 2010 at this site using an automated soil CO_2 chamber system. The minimum Rs values ranged from 0.1 to 0.7 g C m^{-2} day^{-1} in the winter when the ground was covered with snow, while maximum values ranged from 8.3 to 11.0 g C m^{-2} day^{-1} in late summer when temperature was highest in the region. The total modeled annual Rs values for 2008 through 2010 were 1100±220, 1240±250 and 1150±230 g C m^{-2} $year^{-1}$, respectively. Annual values for 2008 were modeled from January 1 to June 15, 2008. Rs over the winter (January 1-March 31) was 150, 160 and 150 g C m^{-2}, accounting for about 13% of annual Rs. Component analysis of Rs conducted by making continuous measurements in a trenched plot where live roots were excised indicated that heterotrophic respiration (Rh) contributed approximately 72 and 80% (895 and 920 g C m^{-2} $year^{-1}$) of annual Rs in 2009 and 2010, respectively. Similarly, continuous Rs measurement in a litterless plot where the surface litter layer was removed contributed 65 and 57% (800 and 655 g C m^{-2} $year^{-1}$) of annual Rs in 2009 and 2010, respectively. Results of this study

suggested that overall soil temperature was the dominant control on Rs in this forest, except during the severe dry conditions.

In order to explore the impact of soil water limitations on Rs a through-fall exclusion experiment conducted from April 1 to July 3, 2009 - the spring and early summer season, when net carbon uptake is at a maximum at this site. Through-fall exclusion caused a large reduction in daily Rs. By the end of the exclusion period daily Rs in the through-fall exclusion area was 3.1 g C m^{-2} day^{-1} as compared to 8.4 g C m^{-2} day^{-1} in the reference area, indicating a strong soil water control on Rs during dry periods. This experiment further suggested that Rs became less sensitive to temperature and increasingly more sensitive to water as soil water content depleted due to the through-fall exclusion. Analysis of Rs versus temperature relationships indicated that the mean Q_{10} value during the through-fall exclusion period was 1.8, while during the non-exclusion period in 2009 the mean Q_{10} value was 2.8. This study helps to better understand the seasonal dynamics of Rs, and its components and controls in temperate conifer forests in Eastern North America. These forests are considered a large sink of carbon, and changes in Rs dynamics in this region may have implications for the global carbon cycle.

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Chapter 1: Literature Review

1.1 Soil CO_2 Efflux (Rs)

SoilCO_2 efflux from the forest floor is a product of decomposition of plant litter and soil organic matter (heterotrophic respiration) and from root respiration of both symbiotic microbes and mycorrhizae which feed on root exudates (autotrophic respiration) (Jassal and Black, 2006). Soil CO_2 efflux (Rs) is an important contributor to total ecosystem respiration as it can account for more than two-thirds of ecosystem respiration on an annual basis (Gaumont-Guay et al., 2006a). Rs is influenced by both the quantity and quality of soil C stored in both the forest floor and mineral soil layer. However, Rs in forest ecosystems is controlled by multiple factors including; soil temperature, soil water content (Saiz et al., 2007) and precipitation (Hui and Luo, 2004) as the primary ones. Other important factors are stand age, forest management activities, soil properties and carbon input rates into the soil (Saiz et al., 2007). Various models have been used to describe the main controlling factors on Rs (Joffre et al., 2003 and Richardson et al., 2007). Most models use both soil temperature and soil water content relationships to estimate Rs (Borken et al., 2006); Davidson et al., 1998; Drewitt et al., 2002 and Gaumont-Guay et al., 2006a). Further advancement in models and understanding of the dynamics of Rs is a vital step to estimating the future global C budget under current and future climate changes (Joffre et al., 2003 and Xu and Qi, 2001).

1.2 Soil CO_2 Efflux Components and Contributions

Litter Layer Contributions to Rs

The litter layer of a forest is said to be a major contributor to soil CO_2 efflux.. Zimmerman et al., 2009 discovered that the litter layer of a tropical montane forest contributed 37% of all the soil CO_2 efflux and surface temperature explained 92% of the diurnal variation of the litter layer. A litter layer field study conducted by DeForest in 2009 in an oak dominated forest found that soil temperature and moisture explained 85% of the variation in the mineral soil, but only 60% in the litter layer. The contrasting results provided by these two studies can be attributed to the thickness of the litter layer, soil temperature and soil moisture, therefore it is evident that additional studies that include a litter layer component will be crucial to the further understanding of soil CO_2 efflux in all environments.

Heterotrophic Contributions to Rs

Heterotrophic respiration is defined as the respiration of soil microbes and fungi which are a function of how much available soil carbon is present (Unger et al., 2009). In a drought simulation study conducted by Unger (2009) it was determined that the heterotrophic respiration contributed 60% of the total 70% soil CO_2. It was also determined that the heterotrophic respiration decreases as drought is induced (from 2 μmol CO_2 m^{-2} s^{-1} to 1 μmol CO_2 m^{-2} s^{-1}). Interestingly, even though heterotrophic respiration decreased its contribution to the total soil CO_2 efflux increased by 12%. Unger (2009) speculated that this was due to a decrease in understory respiration as the autotrophic respiration did not fluctuate. In a natural drought study conducted by Nikolova and colleagues (2009) both a beech and spruce stand were studied. For both the beech and spruce forest, heterotrophic respiration was strongly correlated with soil temperature, however during the drought year the beech forest had a significantly lower correlation with soil temperature while the spruce forest showed no changes with this relationship (Nikolova et al., 2009). The available soil water was not significantly correlated to the heterotrophic respiration in the spruce forest while the beech forest showed a positive relationship for heterotrophic respiration and available soil water until a threshold (100 mm). These studies highlight the difficulty in assuming that all forest and soil types will respond equally to drought conditions, therefore more studies will improve our knowledge on this important topic.

Autotrophic Contributions to Soil CO_2 Efflux

Autotrophic respiration is known to contribute between 10 and 90% to total soil respiration depending on vegetation type and season (Tang et al., 2005). The autotrophic component can be described as respiration from the understory vegetation and tree roots (Tang et al., 2005). Unger et al., (2009) used metal rings to cut off root respiration and allowed them to decompose for one year. They found that autotrophic respiration had little variation (0.1- 0.2 μmol CO_2 m^{-2} s^{-1}) and only contributed 10% of total soil CO_2 efflux (Unger et al., 2009). This low contribution can be explained by the low productivity of this forest compared to others. In another study, conducted in a temperate forest, Borken et al., (2006) found that root respiration was only slightly affected by low soil moisture due to the fact that roots are able to uptake water from deeper soils. In order to determine conclusive results and to fill the knowledge gaps more studies in differing forest types are required to not only quantify autotrophic respiration, but also heterotrophic respiration and litter layer respiration.

1.3 Winter Rs

Soil CO_2 efflux, in the dormant season can contribute from 10-50% of the total annual soil CO_2 efflux and therefore it can play an important role in the carbon cycle (Schindlbacher et al., $_2$2007). Many studies conducted on measuring soil CO_2 efflux are concentrated on the growing season, due to the ease of taking measurements and the misconception that it is the most important time to measure due to its large contribution to total soil CO_2 efflux. There may be important information that lies within the winter soil efflux measurements and they should not be overlooked. In fact, in an rainfall exclusion study conducted by Borken et al., (2006) noted that during the winter enhanced respiration potentially could have occurred in the rainfall exclusion plot during wet periods. An extensive study (Schindlbacher et al., 2007) on winter soil CO_2 efflux, in an Austrian mountain forest, showed winter efflux contributed 12% of the total soil CO_2 efflux (62 g C m^{-2}). As noted by Schindlbacher (2007) the snow cover acts as a physical barrier which disrupts the diffusion of CO_2 from the soil to the atmosphere and it also insulates the soil to allow for potential microbial activity as temperatures will remain above freezing in the soil. For both of these reasons winter soil CO_2 efflux is misunderstood and further studies will only enhance the limited knowledge in this topic.

1.4 Impact of Droughts on Rs

During a drought period, soil moisture is the primary limiting factor to decomposition of SOM. As drought conditions increase, solutes rich in carbon and nitrogen accumulate in the cytoplasm of the microbes and fungi. This process occurs to allow the cells of the microbes to resist dehydration during water limiting periods (Jarvis et al., 2007). In Mediterranean climates, droughts occur frequently, therefore, microbes in the soil have adapted to support these times of limiting soil moisture. Eventually rewetting occurs and microbes take up the water, increase in volume and release some of the accumulated cytoplasmic solutes into the soil resulting in increased soil carbon release to the atmosphere (Jarvis et al., 2007 and Reichstein et al., 2002). Therefore, as there are increases in soil moisture after a drought, soil CO_2 efflux increases due to increased heterotrophic respiration, as a result of the stimulation of soil microbial activity (Jarvis et al., 2007). Jarvis and colleagues discuss the "Birch Effect" which is when soil becomes dry in either a natural or lab experiment and when rewetting occurs there is a sudden increase in mineralization, decomposition, and the release of inorganic carbon dioxide. Jarvis (2007) conducted a Mediterranean forest drought experiment when the soil CO_2 efflux was 0.26 μmol CO_2 m^{-2} s^{-1}, after a rainfall event the efflux increased to 4.1 µmol CO_2 m^{-2} s^{-1}. A lab experiment conducted with the same soil concluded that 1 hour after rewetting the soil CO_2 efflux increased the most substantial compared to 24 hours later. This burst of soil CO_2 efflux can be a substantial contributor on an annual basis. In contrast, a study by Fierer and colleagues (2003) found that in a Mediterranean climate the additional carbon in SOM, after rewetting, is not highly liable and was not found to contribute to soil CO_2 efflux. Muhr (2008) and colleagues completed a similar lab study as to Jarvis and colleagues (2007) with soil columns from a Norway spruce forest. Soil CO_2 efflux during a drying period was measured followed by measurements during rewetting periods. The soil CO_2 efflux decreased as the drying period progressed (average decrease was 20%) and after rewetting occurred the upper soil layer showed an increase in soil CO_2 efflux levels (unlike the mineral soil layer). The total regeneration of efflux took several days and this was attributed to the majority of soil microbes dying off with a population re-growth of a few days after rewetting.

In a study, which modeled drought effects on decomposition dynamics, results stressed the importance on belowground processes for ecosystem carbon balances. The model used by Reichstein and colleagues (2002), predicted that soil microbial respiration most likely contributes the largest amount of carbon to ecosystem respiration, as microbial regrowth is substantial after rewetting dry soil. When the dynamic soil organic matter decomposition sub-model was applied, the liable carbon pool size varied by 7%, despite the drastic changes in litter fall each month. Therefore, it was found that these litter inputs would not significantly influence the overall carbon pool for decomposition throughout the year. These litter inputs only influenced soil microbial respiration by 5%, which was found to be insignificant (Reichstein et al., 2002).

Soil moisture affects the microbial decay of SOM in temperate forest ecosystems, which will in turn affect the root or rhizosphere respiration. The soil moisture is affected by the changes in precipitation, evaporation, and soil water content (Borken et al., 2006). In temperate forest ecosystems, the soil microbes are known to have a soil moisture threshold where their productivity levels of decay, are influenced by optimum soil moisture contents. This threshold of soil moisture may limit or inhibit decay if moisture is too high, or too low (Borken et al., 2006 and Risk et al., 2008). Risk and colleagues (2008) conducted a study where the decomposition-temperature response was studied at different depths. The results illustrated that surface soil had much higher SOM decomposition rates compared to a 35 cm depth, where every gram of soil carbon was 100 times less active in decomposition. It was also noted that soil temperature and moisture were strongly coupled and seasonal changes in both parameters influenced SOM decomposition. In the early season, saturation of the soil strongly inhibited soil CO_2 efflux, but as the season progressed temperatures increased, the soil dried, the pores became aerobic and high soil gas diffusivities replenished the oxygen content. As these temperature intervals occur, the SOM decomposition rates have small boosts (Risk et al., 2008). However, in general, during a drought the decomposition of SOM is known to decrease (Borken et al., 2006 and Risk et al., 2008).

It is well known that in a temperate forest ecosystem a summer drought will decrease the total soil CO_2 efflux, however the amount of reduction varies depending on contributions from the litter layer, heterotrophic and autotrophic respiration (Borken et al., 2006, Davidson et al., 1998, Irvine et al., 2002 and Muhr et al., 2008). In a through-fall exclusion experiment of 84 days for two sequential years soil CO_2 efflux decreased by 53 mg C m^{-2} h^{-1} and 68 mg C m^{-2} h^{-1}, which is a 10-30% annual reduction in soil CO_2 efflux (Borken et al., 2006). However, even though these results show that soil CO_2 decreases with summer droughts it does not prove if this CO_2 will be released at a later time. In a natural drought during August/ September, in a mixed hardwood forest, the forest experienced rapid declines in soil CO_2 efflux which was correlated exponentially with a declining soil matric potential (Davidson et al., 1998). Irvine (2002) similarly conducted a natural drought study in a ponderosa pine plantation which found both root and microbial respiration to decline. In these temperate ecosystems, it was found that the types of soil microbes have different thresholds of soil moisture. During a drought fungal decomposition dominates, as they are more resistant to limited water compared to heterotrophic bacteria (Borken et al., 2006 and Swift et al., 1979). Borken and colleagues (2006), suggest that further research is required to evaluate the function of fungi and their role in SOM decomposition and soil CO_2 efflux. The preliminary results indicate that fruiting fungus respired relatively large amounts of old SOM under drought conditions. However, there are still many uncertainties with respect to the extent to which fungi can store carbon to use for rapid growth of fruiting bodies, therefore limiting the knowledge of fungal decomposition rates (Borken et al., 2006).

In a dry tropical forest located in northern Ethiopia, the combined effects of seasonal drought and limited fresh litter quality account for slow decomposition rates of SOM. Therefore, litter inputs are important for decomposition rates (Descheemaeker et al., 2009). Decomposition is necessary for nutrient cycling and soil formation, and is controlled by climate, topography, parent material, forest age and density, chemical composition of the litter, soil chemical and physical characteristics and soil organisms (Descheemaeker et al., 2009).

Studies on the effects of drought, in tropical forests, are becoming increasingly important as severe droughts are becoming more common in the future (Brando et al., 2008). In tropical climates, decomposition of soil organic matter is greatly reduced during droughts (Bonal et al., 2008; Brando et al., 2008 and Meir et al., 2008), which will ultimately lead to a decrease in soil CO_2 efflux. Drought experiments are especially important in tropical forest ecosystems as it is known that, on both seasonal and inter-annual time scales, effects of variation of soil moisture availability on soil CO_2 efflux are much larger than soil temperature (Davidson et al., 2008 and Meir et al., 2008). Through-fall exclusions have been known to provoke changes in the carbon cycling processes, such as reduced litter fall and substrate limitation for heterotrophic microbes, which would result in a decline in decomposition of SOM. Thereby, reducing the amount of heterotrophic respiration within the litter layer and mineral soil layer (Davidson et al., 2008). During droughts, some carbon is not released in the form of heterotrophic respiration due to the moisture limitations; therefore, this carbon is stored in the soil as liable organic matter. This soil organic matter will eventually decompose and be released when moisture content of the decomposing tissue increases (Meir et al., 2008).

1.5 Temporal and Spatial Dynamics of Rs

High spatial and temporal variability in Rs have been reported in many forest types (Law et al., 2001 and Raich and Tufekciouglu, 2000) due to: species composition, stand age, management practices, and climatic conditions (Xu et al., 2001). The development of realistic carbon emission models is hindered by the poorly understood variability of soil CO_2 efflux, in both space and time, (Khomik et al., 2006) therefore; larger sample size experiments are required to identify how the above parameters affect soil CO_2 efflux.

Temporal variation in soil CO_2 effluxes are generally less than the spatial variation (Khomik et al., 2006; Law et al., 2001 and Xu et al., 2001), averaging 22% over the summer months (Law et al., 2001). In a mixed wood boreal forest, Khomik and colleagues (2006), measured soil respiration to have similar variation patterns over the years, with decreasing variation values towards the winter and increasing though the spring and summer. The minimum value for soil CO_2 efflux was reached in March for both years, with values of 0.5 ± 0.1 μmol CO_2 m^{-2} s^{-1} in year 1 and 0.4 ± 0.2 μmol CO_2 m^{-2} s^{-1} in year 2. Overall, it was concluded that a strong, positive, exponential relationship existed between seasonal variability of manually measured soil temperature and soil respiration (Khomik et al, 2006). Temporal variations are mainly explained by changes in soil temperature and soil moisture (Khomik et al., 2006 and Xu et al., 2001), where 76-95% of all the temporal variability was explained by soil temperature and moisture in a ponderosa pine plantation (Xu et al., 2001). The seasonal trend of soil CO_2 efflux, for the Mediterranean pine plantation, followed the same trend as soil moisture during the summer, when soil water content was low. When soil moisture was high, in October 1998 to May 1999, soil CO_2 efflux followed the same trend as soil temperature (Xu et al., 2001).

Khomik and colleagues (2006) discovered a significant spatial variability in soil respiration along a measured transect, observed at a mixed wood boreal forest, with the largest variability during the summer and the least amount of variability during the winter. The coefficient of variation between summer and winter months were 74% and 4%, respectively. These results were seen due to a decrease in root respiration during the winter, which limits the spatial variability in the distribution of tree roots. Heterotrophic respiration also decreased in the winter due to a decline in soil temperatures, and therefore beyond the capability of the instrument to detect a significant amount of soil respiration (Khomik et al., 2006). Other studies have reported that spatial variability of soil nitrogen, phosphorus, magnesium and organic matter could individually explain 44-55% of the spatial variability in soil respiration, within a ponderosa pine plantation (Xu et al., 2001). However, Khomik and colleagues (2006) found that this was not valid for the mixed wood boreal forest, where only the C:N ratio in the LFH layer correlated with soil respiration. Xu and colleagues (2001) also discovered a large spatial variation among the 18 sample points, in a ponderosa pine plantation, which had statistically different soil CO_2 efflux values ($P<0.01$). Law and colleagues (2001) also noted statistically different values for bare soil ($P<0.01$). The value reported for coefficient of variation is approximately 30%, however larger variations were seen in the non-growing season compared to the growing season. The majority (84%) of the spatial variation can be explained by fine root biomass, microbial biomass, and soil physical and chemical properties as well as the changes in soil temperature and soil moisture. There variables accounted for less than 34% of the total spatial variation (Xu et al., 2001).

Spatial variability may also occur in forests with differing species, which may result from significant variability within leaf area index. Therefore, shading in some areas, would cause a decrease in soil temperature or interception of precipitation in other places, which would decrease soil moisture (Khomik et al., 2006). As soil temperature and soil moisture are the primary constraining factors of soil CO_2 efflux, variability would be seen on the forest floor.

Spatial variability may also be attributed to changes in species. Deciduous broadleaf trees are known to have higher soil CO_2 efflux compared to coniferous trees (Khomik et al., 2006 and Raich and Tufekciouglu, 2000). Broadleaf tree species would have higher soil CO_2 efflux rates due to their larger amount of liable carbon which is available for decomposition during the leaf fall period (Khomik et al, 2006). The needles from conifers contain large amounts of lignin which is more difficult to decompose (Schlesinger, 1997). The deciduous species also contain less leaf area during the spring, allowing for increased amounts of radiation to penetrate to the soil, therefore warming the soil and increasing the soil CO_2 efflux.

Chapter 2: Introduction

Release of carbon dioxide (CO_2) to the atmosphere from decomposing soil carbon (C) and root respiration is referred to as soil CO_2 efflux (Rs) (Joffre et al., 2003). Rs is a product of both biological and physical processes which can be broken down into autotrophic (Ra; root respiration) and heterotrophic (Rh; microbial respiration) components (Gaumont-Guay et al., 2006b; Irvine et al., 2008). It has been known for some time that ecosystem respiration is most often dominated by the CO_2 efflux from the soil (Irvine et al., 2008). It has also been determined that reduced soil water may constrain both root and microbial respiration (Unger et al., 2009). Microbial respiration may decrease due to microbes dying off (Muhr et al. 2008), while root growth respiration may decrease due to decreased photosynthesis and the reduced water availability. In forest ecosystems, which store a large amount of C (Dixon et al., 1994; Turner et al., 1995), it is also important to consider the forest floor litter layer because changes in its thickness and organic matter content can impact its contribution to Rs (Gaumont-Guay et al., 2006; Jassal et al., 2005). Recently, there is an increased interest in partitioning Rs into its components along with emphasizing the physiological connections between above- and below- ground processes (Irvine et al., 2008).

Severe weather events, such as droughts, may significantly influence the seasonal dynamics of Rs in forest ecosystems. Many studies have explored the impact of drought on Rs (Borken et al., 2006; Breda et al, 2006; Davidson et al., 1998; Granier et al., 2007; Hanson et al., 2003; Krishnan et al., 2006; Reichstein et al., 2002; Unger et al., 2009), however, to our knowledge, none have focused on the impact of early growing season droughts on Rs in forests, in particular in eastern North America. Although it is not uncommon for summer droughts to occur in eastern North America (Hanson and Weltzin, 2000), over the last few decades this region has experienced large changes in precipitation patterns, where despite an overall increase in annual precipitation, frequency and severity of drought events have increased (Sheffield and Wood, 2008). As the early growing season is the most critical period for net C uptake in the forest ecosystems in this region (Peichl et al., 2010a, their figure 7), a severe drought event during this period may severely impact the C balance of forests growing in the region (Noormets et al., 2008). In particular, changes in soil C pools would be critical, because they account for 50–60% of the C stored in temperate forest ecosystems (Turner et al., 1995). Changes in soil C dynamics in this region may have implications for the global C cycle because eastern North American forests are considered a large sink of C and as a result of forest regeneration on former agricultural lands and fire suppression efforts (Rhemtulla et al., 2009).

In this study, we explored the dynamics of soil CO2 efflux (Rs) in a temperate pine forest in Southern Ontario, Canada. We continuously measured Rs in a mature (planted in 1939) white pine forest, from June 15, 2008 to December 31, 2010 using an automated soil CO_2 chamber system. The main advantage of the automated chamber systems is their ability to take continuous long-term measurements of Rs, thereby enhancing knowledge of diurnal and seasonal variations and environmental controls on CO_2 production and Rs (Cai et al., 2010; Drewitt et al., 2002; Gaumont-Guay et al., 2006a, b; Janssens et al., 2000; Jassal et al., 2005; Tang et al., 2005). This approach has the potential to provide much more reliable estimates of seasonal and annual Rs as compared to conventional manual chambers that have low temporal resolution (Bolstad et al., 2004; Khomik et al., 2010). Eddy covariance flux and meteorological data were also measured at this site since 1939. Further details of eddy covariance flux and meteorological measurements and its gap-filling are given in Arain and Restrepo-Coupe (2005) and Peichl et al. (2010a, b). In the past manual soil CO_2 efflux measurements were made at this site on bi-weekly to monthly intervals using a portable soil chamber unit from 2004 to 2006 (Khomik et al., 2010). However, these periodic manual Rs measurements were unable to capture the fluctuations in soil CO_2 efflux due to warm/cold or dry/wet weather events which frequently occurs in this region, in particular during spring and autumn seasons.

In order to further explore and quantity the impact of dry soil conditions on Rs, we continuously measured soil CO_2 efflux during a through-fall exclusion experiment conducted at this site in the spring and early summer of 2009. Further details of through-fall exclusion set-up are given in MacKay et al. (2011).

The main objectives of this study are; (i) to examine and quantify the seasonal dynamics of Rs and its components, (ii) to determine how Rs might be influenced by changes in soil temperature and soil water content and (iii) to investigate the effect of an induced early growing season through- fall exclusion or soil water stress on Rs.

Chapter 3: Methodology

3.1. Site Description

This study was conducted at the mature (70-year old in 2009) forest site of the Turkey Point Flux Station, located near the northernshore of Lake Erie, in southern Ontario, Canada (42° 42′ 35.20″ N, 80° 21′ 26.64″ W) (Arain and Restrepo-Coupe, 2006; Peichl et al., 2010a, b). The Turkey Point Flux Station is part of the Canadian Carbon Program (CCP), formerly known as the Fluxnet Canada Research Network (FCRN). The forest is dominated (>82%) by eastern white pine (*Pinus strobus L.*), which was planted on cleared Oak savannah land in 1939 to stabilize sandy soil. Other tree species include 11% balsam fir (*Abies balsamea L. Mill*) and native Carolinian species, including 4% Oak (*Quercus velutina* L., *Q. alba* L.), 2 % Red maple (*Acer rubrum L.*) and some wild black cherry trees (*Prunus serotina Ehrh*). The understory consists of ferns (*Pteridium* *aquilinum L.*), mosses (*Polytrichum spp*.), poison ivy (*Rhus radicans L.ssp*.) and Rubus species. The leaf area index is 8 (Chen et al., 2006). The 30-year mean annual temperature is 7.8 °C and the mean annual precipitation is 1010 mm, of which 438 mm falls between May and September, and 133 mm falls in winter as snow (Environment Canada climate records at Delhi, Ontario from 1970-2000). The soil at this site is sandy (>98% sand) and well drained, with low to moderate water holding capacity. The water table resides approximately 7 meters below ground level. Further site details are given in Peichl et al., (2010a, b).

3.2. Through-fall Exclusion Setup

The through-fall exclusion setup consisted of a 20 m × 20 m area that was covered by flat-bottomed aluminum troughs (0.61 m x 3.05 m), mounted on wooden stands at a 2° slope from a height of 1.37 to 0.84 m, in order to exclude precipitation from the area beneath. The exclusion began on April 1, 2009 and ended on July 3, 2009, spanning a total of 93 days. It excluded more than 90% of precipitation falling on this area (MacKay et al., 2011). Stem flow was not excluded; however it has minimal impact on soil water content in the vicinity of trees, as shown by periodic manual measurements following the precipitation events (MacKay et al., 2011). McLaren et al., (2008) also suggested that stem flow was negligible at this site. Troughs were removed at the end of exclusion period and rainfall occurred on July 5, effectively ending the rainfall-free period in the exclusion area. Litter SWC was not measured during this time, however manual measurement of SWC were made of the root zone (0-20 cm). Further details of the through-fall exclusion setup are given in MacKay et al. (2011).

3.3. Rs Measurements using an Automated Soil CO_2 Chamber System

Rs was continuously measured from June 2008 to December 2010 by automated non-steady state chambers (Drewitt et al., 2002; Jassal et al., 2005). The chambers consisted of a hemispherical dome that opened and closed above a cylindrical body. The chamber cylinders have an internal diameter of approximately 52.5 cm, a height of 13 cm, and a thickness of 1 cm. Each cylinder was mounted on a chamber collar that was installed on fairly level ground and inserted approximately 2 to 4 cm into the soil. The hemispherical dome has a headspace height of approximately 20.5 cm. A foam gasket seals the dome around the cylinder when the chamber closes for each measurement, providing an air-tight seal for proper measurements. The chambers contain a small fan that circulates the air inside, preventing stagnation zones and microclimate formation. To maintain consistent pressure within the chamber during its closing and operation, a 30 cm coiled tube was installed on the top of the chamber lid to allow pressure equalization.

From June 2008 to May 2009, three chambers were used as reference (control) chambers, while one measured heterotrophic respiration. In order to measure heterotrophic respiration root exclusion was achieved by severing live tree roots in the area surrounding the chamber. In May 2009, two additional chambers were installed, one in the through-fall exclusion area and one in the reference area, while the LFH layer was removed in an existing chamber to measure litterless respiration. In May 2010, two additional chambers were installed, one as a reference and the other measuring heterotrophic respiration in the through-fall exclusion area. See further details of chamber installation in Table 1. Throughout the growing season, vegetation was removed from inside the collars to eliminate any potential photosynthesis effects. In this analysis, we use April 1 through November 30 to represent the growing season (8 months).

During the winter, Rs data was occasionally lost when snowfall completely filled the collars, and when heavy ice and snow on the dome forced the chamber to remain shut for extended periods of time. On site visits, snow was removed from the top of the dome and the collar rim to ensure a continued tight seal for measurements. The chamber volume was corrected for snow accumulation in the chambers during the winter months, using snow depth measurements conducted at the site using a sonic ranger (CR50, Campbell Scientific Inc.), as well as occasional manual measurements in each collar during site visits. During this process, we assumed that although the porosity of snow will change, its effect on the volume of the chamber and resulting efflux is minimal.

3.4. Meteorological Measurements

Soil temperature (2, 5, 10, 20, 50 and 100 cm depth) and soil moisture (5, 10, 20, 50, 100 cm depth) were measured continuously alongside the eddy covariance flux and meteorological measurements. Soil temperature and soil moisture were also measured at 5, 10, 20 and 50 cm depths in both reference and through-fall exclusion areas in 2009 and 2010. Manual soil moisture measurements were made in the root zone (top 0-20 cm) at 54 locations in both through-fall exclusion and reference areas at bi-weekly intervals using a manual soil moisture probe (CS620, Campbell Scientific Inc.).

Precipitation was measured about 1.5 km northeast of the site by a weighed accumulation rain gauge, (T200B, Geonor Inc.). Additional tipping bucket rain gauges, one installed alongside the accumulation gauge (TE525, Texas Instruments) and on the top of the eddy covariance tower (CS700; Campbell Scientific Inc.), were used to cross-check and gap-fill the precipitation data.

3.5. Soil CO_2 Efflux Data Processing

Rs data were quality-controlled using a MATLAB (The MathWorks Inc.) program that estimated the slope of time versus high-frequency (1 Hz) CO_2 efflux for each half-hourly measurement interval. Data spikes within the continuous half-hourly fluxes were detected and removed by applying season-specific maximum and minimum thresholds to the data. Gaps also resulted from data loss during chamber malfunctions, calibrations, and winter snow and ice problems. On a few occasions, compressed air ran out earlier than expected due to air leaks, causing data gaps. Over the entire year, gaps represented approximately 19% of half-hourly data in each chamber, with the highest occurrence during the winter. However, we were able to capture much (73%) of the Rs data in winter (January 1-March 31). Gaps extending less than four consecutive half hours were filled using linear interpolation. Longer gaps were filled using modeled Rs values as described in the following section.

3.6. Soil CO_2 Efflux Model

To investigate the impact of soil temperature (Ts) and soil water content on Rs, two separate empirical models were fit to the data. Rs was first modeled as a function of Ts only, for which the Q_{10} model (Black et al., 1996; van't Hoff, 1884) was used:

$$Rs = a * b^{((Ts-10/10)} \qquad (1)$$

Where R_s is the soil CO_2 efflux (μmol CO_2 m^{-2} s^{-1}) and Ts is the soil temperature at 5 cm depth (°C), both measured half hourly. Fitted parameter "a" is Rs at 10 °C (μmol CO_2 m^{-2} s^{-1}). The parameter "b" (Q_{10} coefficient b) is the relative increase in the respiration rate for a 10 °C increase in temperature.

Soil water control was included in the model by multiplying equation 1 by a logistic function, following Richardson et al. (2007). Thus, Rs was modeled as a function of both Ts and soil water content as:

$$Rs = a * b^{((Ts-10)/10)} * \frac{1}{1+\exp(c-d*SWC)} \qquad (2)$$

Where Rs, Ts, a and b are described above, SWC is the soil water content within the 0-20 cm root zone(m^3 m^{-3}), and fitted parameters "c" and "d" control the shape of the logistic SWC function, which scales between 0 and 1.

We conducted our modeling analysis on seasonal basis for all chambers, including Rs from reference, exclusion, heterotrophic and litterless chambers for 2008, 2009 and 2010. The seasons analyzed included winter/spring (1 January - 30 June), summer (1 July -30 September) and autumn (1 October-31 December). Winter and spring season were combined together so that there is enough data points to allow spread in Rs values to fit the model. Error estimates were calculated for the modeled data using a Monte Carlo simulation where at a minimum of 100 runs were performed for each year of data. Error outputs were small due to the large data set, few data gaps and a well-defined area (footprint) for each soil CO_2 efflux measurement. Correlation co-efficient were also calculated among chambers to capture spatial heterogeneity. On average the spatial variability among chambers which measured the same Rs components was 20%.

Chapter 4: Results

4.1. Climate

The daily mean air temperature (T_a) ranged from -13.3, -16.3 and -19 °C in winter to 27.4, 25.3 and 23.8 °C in summer in 2008, 2009 and 2010, respectively. The annual mean values for T_a were 8.8, 7.7 and 7.9 °C (2008, 2009 and 2010 respectively), which were similar to the regional 30-year mean value of 7.8 °C. In March, T_a rose above 0 °C and continued to increase until mid August. From this point it gradually declined throughout the rest of the year, falling below 0 °C in mid December (Figure 1a). Soil temperature at 5 cm depth (T_s) closely followed the seasonal dynamics of T_a, however, it remained consistently near 0 °C in the winter (Figure 1b). The minimum T_s values of -2.2, -1.7 and -1.2 °C were observed in January 2008, February 2009 and February 2010, respectively. The maximum T_s was observed in July 2008, August 2009 and August 2010 with values reaching 21.6, 22.0 and 21.9 °C, respectively.

Total annual precipitation at the site was 1140, 995 and 890 mm (2008, 2009 and 2010 respectively), which was comparable to the 30-year regional mean value of 1010 mm. The area received approximately 500, 400 and 450 mm (2008, 2009 and 2010 respectively) of precipitation during the growing season (April through November), with a notable dry period from August 29 to September 25 in 2009, where only 13 mm of precipitation was observed (Figure 1c). Maximum snow depth on the forest floor was about 20 cm in late February 2009 and about 19 cm in late January/early February, 2010. Snow depth declined at a rate of approximately 0.5 cm per day until no snow was present in early April (Figure 5d).

SWC in the root zone (0-20 cm) peaked in late winter/early spring with maximum values of 0.36, 0.25 and 0.22 m^3m^{-3}, in April 2008, February 2009 and March 2010, respectively. Generally, after peaking, SWC gradually decreased over the remainder of the growing season (Figure 1d). Minimum SWC values in the reference area were 0.05, 0.06 and 0.06 m^3m^{-3} during September in 2008, 2009 and 2010, respectively.

4.2 Seasonal and Inter-annual Trends in Rs

The seasonal trend of daily mean Rs for each chamber is shown in Figure 2. Distinct highs and lows were observed in Rs throughout the growing season that closely followed the air temperature (Figure 2 and 1a). A maximum daily mean Rs of 8.3, 9.2 and 11.0 g C m^{-2} day^{-1} was recorded in August 2008, August 2009 and July 2010, while a minimum daily mean of about 0.7, 0.1 and 0.2 g C m^{-2}

day^{-1} was observed in December 2008 and January 2009 and 2010. Following a rapid rise in temperature in mid June in 2009, Rs increased from approximately 3.0 g C m^{-2} day^{-1} to about 7.0 g C m^{-2} day^{-1} in 16 days, while in 2010 Rs increased from 3.0 g C m^{-2} day^{-1} in mid-March to about 9.0 g C m^{-2} day^{-1} in early June in 17 days.

We observed a sudden increase in Rs during and immediately after precipitation events (Figure 4). For example, on June 28 in 2009 maximum Rs increased from about 6.5 to about 7.5 g C m^{-2} day^{-1} immediately following a 22 mm precipitation event (Figure 4), where Rs declined to previous levels within 6 hours after the rain event.

Figure 5 shows half-hourly winter Rs values for two selected periods: March 14-17, 2009 and January 12-15, 2010. These periods were chosen as good quality continuous winter Rs data was available. In 2009, Rs ranged from 0.1 to 1.6 μmol m^{-2} s^{-1} while in 2010, there was an increase in variability among individual chambers where Rs ranged from 0.2 to 1.7 μmol m^{-2} s^{-1} with low Rs values measured in the litterless and heterotrophic chambers (Figure 5a, b). Overall, half-hourly Rs trends in all other chambers in 2010 were similar to values observed in 2009, except reference chamber 1 where Rs was generally higher.

Seasonal dynamics of daily mean winter Rs is shown in Figure 6, along with seasonal dynamics of Ts, SWC and snow depth. Daily Rs values in the winter ranged from 0.1 to 1.7 g C m^{-2} day^{-1} (Figure 6a). In 2009, Rs decreased in January, reaching a minimum in late January and early February, likely due to colder Ts resulting from minimal snow depth during that period. Generally, high daily Rs values coincided with high SWC. For example, in mid-February, 2009 SWC increased to 0.2 m^3 m^{-3} while Rs values ranged from 0.5 to 1.2 g C m^{-2} day^{-1} (Figure 6a, c). In 2010, snow depth was generally high from January-February (7-19 cm) when Rs values were about 1.0 g C m^{-2} day^{-1}. In early/mid-March daily Rs started to increase regardless of snow status on the ground.

Overall, maximum carbon loss occurred in summer months in 2008, 2009 and 2010 (i.e. 591, 535 and 463 g C m^{-2} $season^{-1}$, respectively) (Table 2), while annual carbon emissions for 2008, 2009 and 2010 were 1355, 1243 and 1196 g C m^{-2} $year^{-1}$, respectively. Winter Rs contributed 150, 160 and 150 (approximately 13%) to the annual Rs in 2008, 2009 and 2010, respectively.

4.3 Impact of Through-fall Exclusion on Rs

Through-fall was excluded from April 1, 2009 to July 3, 2009, during which 270 mm of precipitation fell. Approximately 90% of the total through-fall exclusion area was covered and stem flow was considered negligible. As a result, annual precipitation in the through-fall exclusion plot was approximately 625 mm in 2009. Over the through-fall exclusion period, precipitation events caused variations in SWC in the reference area that were absent in the through-fall exclusion area (Figure 1d). SWC in the reference area decreased from 0.15 to 0.08 m^3m^{-3} over the through-fall exclusion period, while SWC in the exclusion area reached a minimum of 0.053 m^3m^{-3} on the last day of exclusion (Figure 1d). T_s was similar in both the reference and exclusion areas, except during the through-fall exclusion experiment, when it was approximately 1^{o}C lower than the reference area, and during May-July in 2010, when the exclusion area had slightly higher T_s.

SWC was slightly higher (0.2 m^3 m^{-3}) in the reference area as compared to the exclusion area (0.17 m^3 m^{-3}) in the early spring of 2009, before the start of through-fall exclusion. At the onset of the growing season in early April 2009, SWC declined in both areas, however, the decline in the exclusion area was more rapid than in the reference area. The SWC in the exclusion area reached a minimum value of 0.053 m^3 m^{-3} in early July 2009, at the time of the removal of exclusion troughs. During the post-through-fall exclusion period, continuous SWC measurements again indicated slightly higher values in the reference area as compared to the through-fall exclusion area. The difference in SWC in the reference and through-fall exclusion areas during the pre- and post-drought periods as indicated in the continuous measurements may be due spatial difference in SWC. However, bi-weekly manual SWC measurements conducted at 54 locations across each of the exclusion and reference areas showed similar SWC values in both areas during the post-through-fall exclusion periods (see Figure 1d). Similar trends in SWC were also observed in 2010.

The through-fall exclusion coincided with a large decrease in Rs in both exclusion chambers (Figure 3). Daily Rs in the exclusion area on the last day of the experiment was 2.2 g C m^{-2} day^{-1}, as compared to 7.0 g C m^{-2} day^{-1} in the reference area; a 68 % decrease, suggesting a strong soil moisture control on Rs at our site under dry conditions (Figure 3). Rainfall occurred on July 5, 2009, two days after the removal of troughs, causing a rapid increase in the exclusion area

Rs to approximately 8.0 g C m^{-2} day^{-1}, producing similar values to those measured in the reference area (Figure 3).

Over the through-fall exclusion period, there was a 36% reduction in cumulative Rs in the exclusion area as compared to the reference area (i.e. 205 g C m^{-2} vs. 320 g C m^{-2}, respectively) (see Figure 7). The largest decline in Rs was observed during the last 20 days of the exclusion period, when the soil was the driest. Annual total Rs value in the exclusion area in 2009 was 1010 g C m^{-2} $year^{-1}$ (Table 2).

4.4 Environmental Controls on Seasonal Dynamics of Rs

Overall, trends in Rs and Ts were highly correlated during all three study years. Our analyses indicated that variation in Ts best explained temporal variability in Rs, with mean coefficients of determination, R^2 values of 0.82 and 0.88 for all chambers using the Ts-only and Ts-SWC model, respectively. Table 3 shows the performance measures for the T_s-only and Ts-SWC models for individual chambers for each season. In general, the Ts-SWC model simulated Rs values more accurately than the Ts-only model, especially during the summer when R^2 values for Ts-SWC model ranged from 0.68 to 0.92 as compared to 0.38 to 0.90 for the T_s-only model. In the winter and spring, the Ts-SWC model always produced a better fit to observed Rs, with R^2 values ranging from 0.85 to 0.93, while the T_s-only model yielded R^2 values ranging from 0.38 to 0.91.

The heterotrophic and litterless Rs values were also best represented by the Ts-SWC model with R^2 values ranging from 0.42 to 0.67 and 0.40 to 0.50 for the heterotrophic and litterless chambers, respectively (Table 3).

Figure 8 displays the Q_{10} relationship of soil temperature and Rs for both the non-exclusion and exclusion periods. The Q_{10} value for the non-exclusion period is 2.4. However, the Q_{10} values for the chambers within the exclusion area produced much smaller values during the water limiting period (1.5). An analysis conducted using the residuals of the Rs-T_s relationship (δ_{Rs}) (Figure 9) indicated near zero values when SWC was greater than 0.12 m^3 m^{-3}. δ_{Rs} values were above zero when SWC was between 0.07 and 0.12 m^3 m^{-3} (Figure 9) and δ_{Rs} values became increasingly negative when SWC declined below 0.07 m^3 m^{-3}, suggesting strong soil water control on Rs in our forest during dry periods. This phenomenon was further corroborated by the difference in T_s-only model performance during the non through-fall exclusion (R^2= 0.82 to 0.85), and the through-fall exclusion (R^2 = 0.73 to 0.75) periods. When both Ts and SWC were considered in the model, R^2 values increased, particularly for the exclusion period, (i.e. R^2 value increased from 0.73 to 0.89.) Model improvement for the non through-fall exclusion period was much less where R^2 increased from 0.87 to 0.89.

Figure 10 displays the Q_{10} value (fitted parameter 'b') for individual chambers for each season from 2008 to 2010 using the Ts-SWC model. The Q_{10} values in the winter/spring ranged from 1.15 to 5.01, while they ranged from 2.0 to 6.3 in the autumn (Table 4). The maximum value of Q_{10s} in the summer reached up to 5.0 (Figure 10). Overall, the reference chambers yielded the largest Q_{10} values, followed by the through-fall exclusion, heterotrophic and litterless chambers.

In general, base respiration at 10 ^{o}C, R_{S10} (model parameter 'a') values were larger when the Ts-SWC model was used (Figure 11). During the winter/spring season, R_{s10} values ranged from 2.60 to 4.09 (μmol CO_2 m^{-2} s^{-1}) which is slightly lower than the autumn values that ranged from 2.23 to 5.21 μmol CO_2 m^{-2} s^{-1} (with a couple of outliers not included in this range). During the summer, however, the R_{s10} values were much smaller and ranged from 2.7 to 3.49 μmol CO_2 m^{-2} s^{-1} (Figure 10 and Table 4).

Both Ts-only and Ts-SWC models were used to evaluate the SWC and T_s controls on Rs during the through-fall exclusion period. The Q_{10} values in the reference area ranged from 3.6 to 3.7 using Ts-only model, while they ranged from 2.5 to 2.6 for the Ts-SWC model ($R^2 = 0.87$ to 0.88). Similarly, the Q_{10} values in the exclusion area during the non-exclusion period ranged from 2.5 to 3.1, with Rs_{10} values ranging from 2.6 to 3.0 μmol CO_2 m^{-2} s^{-1} ($R^2 = 0.85$ to 0.88). A separate curve was fitted to the Rs-T_s relationship for the exclusion period (see Figure 8, dark grey circles and solid line). The Q_{10} values over the through-fall exclusion period in the exclusion area were much lower and ranged from 1.5 to 2.0, with R_{s10} values ranging from 1.5 to 2.0 (μmol CO_2 m^{-2} s^{-1}).

Chapter 5: Discussion

5.1 Seasonal and Annual Rs

Annual Rs values have been investigated by many researchers; however, there is much variation among their methodologies (e.g., equipment type, measurement frequency, predictive models and parameters used in gap filling) and ecosystem characteristics (soils, vegetation types), from which these annual values are achieved. In 1992, Raich and Schlesinger reported that annual estimates of Rs ranged from 250 to 1255 g C m^{-2} $year^{-1}$ for all types of forests. Other pine forest studies have reported annual Rs ranging from 598 to 1330 g C m^{-2} $year^{-1}$ (Hui and Luo, 2004; Irvine et al., 2008; Law et a., 1999; Palmroth et al., 2005; Zha et al., 2007). Our Rs values for 2008, 2009 and 2010 are near the higher end of this range, with annual Rs of 1100, 1240 and 1150 g C m^{-2} $year^{-1}$. These values are comparable with a pine plantation forest in the Sierra Nevada, USA, which reported an annual Rs estimate of 1184 g C m^{-2} $year^{-1}$ (Tang et al., 2005).

Our annual Rs estimates using automatic chambers are higher than an earlier manual chamber study conducted in 2006 at our site by Khomik at al. (2010), who reported annual Rs of 671±33 g C m^{-2} $year^{-1}$. As mentioned earlier, Khomik et al. (2010) used a portable Li-6400 (Li-COR Inc.) soil chamber system at bi-weekly to monthly intervals, while our study used an automated chamber system, which was able to capture continuous (24-hour) fluxes throughout the year. A study conducted by Savage and Davidson (2003), reported that on daily basis manual (portable) chambers underestimate Rs by 2 to 30% as compared to the automated chambers. Our results further supported the finding of Savage and Davidson (2003), causing an underestimation of annual Rs values (Figure 12a). A linear regression relationship fitted to manual Rs data from Khomik et al., and our continuous Rs data (Figure 12b) indicated a 29% decrease in Rs values from manual chambers (R^2 value of 0.56). Because Li-6400 Rs measurements were not conducted continuously over the year, therefore they may have missed large fluctuations in Rs due to variable weather patterns and events. However, in contrast fine temporal resolution, continuous chambers captured much less spatial variability as compared to manual Rs measurements. Khomik et al. (2010) conducted manual Li-6400 measurements over a 100 m transect, while our automatic chambers were located in two 20 m x 20 m areas for the duration of the study. A comparative study using manual measurements by the Li-6400 in the vicinity of the automatic chambers showed that both types showed similar half hourly results (Figure 13). Discrepancies in seasonal and annual Rs may arise due to different temporal and spatial scales of the two measurement methodologies. For example, periods of augmented Rs that immediately follow precipitation events would not be measured by the portable chamber system, and thus, would not be estimated by models derived from this data.

Although winter Rs values are generally low in cold regions (Khomik et al., 2006), they may contribute between 10 to 50% of total annual soil respiration

(Schindlbacher et al., 2007). Most studies in the literature do not include measurements taken during the winter (Elberling, 2007). Thus, there is a need for continuously measured winter Rs data, because an over- or underestimation of the ecosystem's carbon sequestration potential could result if it is ignored (Schindlbacher et al., 2007). Because of relatively mild winter conditions of our site, we were able to measure much of the winter Rs at our forest. Winter (January 1 to March 31) Rs contributed 150, 160 and 150 g C m^{-2} (~13%) of annual Rs in 2008, 2009 and 2010, which is lower than winter Rs reported by other studies (Elberling, 2007; Lee et al., 2010).

5.2 Through-fall Exclusion Impacts on Rs

IPCC (2007) predictions of future climate change suggest an increase in the frequency and intensity of severe drought events in various regions, including eastern North America that may alter the soil carbon dynamic in forests growing in these regions, highlighting the need to evaluate and quantify the impact of severe droughts on Rs in forests. During the drought the lack of soil moisture inhibits soil CO_2 production because microbes do not decompose soil organic matter within the upper soil layers (Borken et al., 2006; Gaumont-Guay et al., 2006a; Palmroth et al., 2005; Reichstein et al., 2002; Risk et al., 2008). The through-fall exclusion experiment conducted at our temperate pine forest site, induced water limiting conditions and caused a 36% decrease in Rs during the exclusion period. This decrease was similar to results of past studies conducted in temperate forests. For example, a temperate forest in Massachusetts, USA saw a 10-30% decline in Rs during a drought, primarily due to reduction in heterotrophic respiration (Borken et al., 2006). It cannot be determined whether a decrease in heterotrophic respiration was the cause of the Rs reduction at the Turkey Point site during the through-fall exclusion in 2009, however further studies at the site can investigate this possibility by placing a chamber in the exclusion period above a trenched area (excluding all roots). In a cool temperate forest in central Korea, there was a significant suppression of Rs during both 2005 and 2006 early and late summer droughts (Lee et al., 2010). Similarly, a temperate pine forest that experienced water limiting conditions during the summer months in the Belgian Campine Region, recorded up to a 50% decline in Rs during these water-limiting periods (Curiel Yuste et al., 2003).

Soil temperature and soil moisture are the two major controls on Rs (Davidson et al., 1998; Lloyd and Taylor, 1994; Borken et al., 2006; Unger et al., 2009), which may have confounding effects on Rs (Joffre et al., 2003). We found that in our forest, the variation in Rs explained by T_s decreased during the through-fall exclusion period as indicted by our T_s-only model (R^2 = 0.82 to 0.85) during the non-exclusion period compared to (R^2 =0.73 to 0.75) the exclusion periods (Table 3). The Q_{10} values during the exclusion period averaged to 1.8, while during the non-exclusion period the Q_{10} values averaged to 2.8 (Table 3). Without consideration of SWC condition, the larger Q_{10} values would suggest that there may be a major change in the ecosystem response to T_s. However, SWC may have a confounding effect on Rs. Our exclusion period Q_{10} value of 1.8 is very similar to Q_{10} values of 1.4 for volumetric soil moistures of < 14% reported by Xu and Qi (2001) in young ponderosa pine plantation forest in western USA. Our results are consistent with Borken et al. (2006) as well who found that during the exclusion period Rs was less correlated to Ts, while it was more correlated to soil water content. Similarly, in their experimental drought study, Joffre et al. (2003) found that the temperature sensitivity of soil respiration was strongly affected by soil water status and severe soil moisture limitations caused low Rs values in drought plots.

After the troughs were removed on July 3, a 12 mm precipitation event occurred on July 5 that caused an increase in R_s from 2.0 to 4.5 g C m^{-2} day^{-1}. This rain event rewetted the upper soil layer, and we infer that soil microbial populations increased and rapidly began to decompose carbon compounds within the litter and upper soil layers (Borken et al., 2006). Many studies in forests have reported increased Rs after precipitation events. For example, in a boreal aspen stand, Rs increased rapidly from 3.6 to 9.0 μmol m^{-2} s^{-1} after a large rain event in August that ended a dry spell (Gaumont-Guay et al., 2006a). These results suggest the importance of considering soil water content when modeling Rs as it can have a confounding effect on Rs-T_s relationship when SWC values are low.

5.3 Comparison of Rs to Ecosystem Respiration, Re

Over the three years of study, the annual Rs value at our forest site was approximately 92% of the annual ecosystem respiration (Re) measured by the eddy covariance system. Such a large ratio of Rs/Re is a common occurrence in the literature, as chamber-based methods have shown as much as a 25% overestimation of eddy-covariance derived Re (Gaumont-Guay et al., 2006). Some studies have even reported overestimation of chamber-based Re values that include leaf and wood respiration in addition to Rs (e.g. Griffis et al., 2004, Khomik et al, 2010; Lavigne et al., 1999 and Law et al., 1999, who have reported

20-37%, 18%, 20-40% and 50% overestimation, respectively). Some of the possible explanations for this phenomenon may be the differences between spatial coverages of the automatic chamber systems and eddy covariance flux footprint (Law et al, 2001; Drewitt et al, 2002). Also, there are difficulties involved in estimating nighttime Re with eddy covariance systems during stable atmospheric conditions, and subsequently, in applying methods to gap-fill the flux data (Baldocchi, 2008). At such small scales, forest floor heterogeneity may lead to challenges in up-scaling chamber-based measurements (Xu and Qi, 2001). Even with these challenges, automatic chamber-based measurements still provide valuable information about soil CO_2 efflux contributions to ecosystem respiration. Though manual chamber measurements (e.g. Bolstad et al., 2004; Khomik et al., 2010) may account for more spatial variability, automated chambers are important, as they capture Rs at a greater temporal frequency. The automated chambers are able to reveal rapid responses of Rs to drying and wetting events and to the passing of weather fronts -- understanding that is necessary for investigating seasonal changes in model parameters. Improved understanding of Rs dynamics and availability of continuous data is essential to develop, improve and validate soil respiration models. In particular, availability of measured Rs data during extreme weather, such as water limiting events, would help to better constrain these models.

Chapter 6:

Conclusions

Rs was continuously measured from June 15, 2008 to December 31, 2010 in a temperate pine plantation forest located in Southern Ontario, Canada using an automated soil CO_2 chamber system. The total annual Rs values for the reference area for 2008 through 2010 were 1100±220, 1240±250 and 1150±230 g C m^{-2} $year^{-1}$. The winter months contributed about 160 g C m^{-2}, which was approximately 13% of annual Rs. Heterotrophic respiration contributed about 895 (72%) and 920 (80%) g C m^{-2} $year^{-1}$ of the annual Rs, while soil without a litter layer contributed 800 (65%) and 655 g C m^{-2} $year^{-1}$ (57%) of the annual total Rs in 2009 and 2010, respectively. Rs was simulated using models that considered soil temperature only (Q_{10} model), as well as soil temperature and soil moisture relationships (Q_{10} and logistic model). In general, the model that included both soil temperature and soil water content estimated Rs more accuracy with seasonal R^2 values ranging from 0.68 to 0.92 as compared to 0.38 to 0.90 for the soil temperature only model.

An early growing season through-fall exclusion study conducted to induce a water limiting period (April 1 to July 3) suggested that although soil temperature was the dominant control on Rs, Rs became less sensitive to temperature and increasingly more sensitive to soil water content as the soil dried due to the through-fall exclusion. The mean Q_{10} value during the exclusion period was 1.5 and 2.7, while during the non-exclusion period the mean Q_{10} value was 3.6 and 3.7 for the Ts-only model and Ts-SWC model, respectively. This study provides information about Rs dynamics during the winter season when soil CO_2 efflux measurements are difficult make, therefore giving improved estimates for annual values. It also helps to better understand the impact of early growing season water limitation on Rs, where as SWC decreases the dependence on this control increases. This study provides insight into the soil CO_2 efflux seasonal dynamics in temperate forests in eastern North America.

7. References

Arain, M.A. and Restrepo-Couple, N., 2005. Net ecosystem production in a temperate pine plantation in southeastern Canada. Agricultural and Forest Meteorology, 128, 223-241.

Arain, M.A., Yuan, F., and Black, A., 2006. Soil- plant nitrogen cycling modulated carbon exchanges in a western temperate conifer forest in Canada. Agricultural and Forest Meteorology, 140, 171-192.

Baldocchi, D.D., 2008. Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurements systems. Australian Journal of Botany, 56, 1-26.

Borken, W., Savage, K., Davidson, E.A., and Trumbore, S.E., 2006. Effects of experimental drought on soil respiration and radiocarbon efflux from a temperate forest soil. Global Change Biology, 12, 177-193.

Black, T.A., Den Hartog, G., Neumann, H.H., Blanken, P.D., Yang, P.C., Russell, C., Nesic, Z., Lee, X., Chen, S.G., Staebler, R. and Novak, M.D., 1996. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest. Global Change Biology 2, 219-229.

Breda, N., Huc, R., Granier, A., Dreyer, E., 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long term consequences. Annals of Forest Science 63, 625-644.

Bolstad, P.V., K.J. Davis, J.M. Martin, B.D. Cook, and W. Wang, 2004. Component and whole-system respiration fluxes in northern deciduous forests, Tree Physiology, 24, 493-504.

Bonal, D., Bosc, A., Ponton, S., Goret, J.Y., Burban, B., Gross, P., Bonnefond, J.M., Elbers, J., Longdoz, B., Epron, D., Guehl, J.M., and Granier, A., 2008. Impact of severe dry season on net ecosystem exchange in the Neotropical rainforest of French Guiana. Global Change Biology, 14, 1917-1933.

Brando, P.M., Nepstad, D.C., Davidson, E.A., Trumbore, S.E., Ray, D., and Camargo, P., 2008. Drought effects on litterfall, wood production and belowground carbon cycling in an Amazon forest: results of a throughfall reduction experiment. Biological Sciences, 363, 1839-1848.

Cai, T., Flanagan, L.B., and Syed, K.H., 2010. Warmer and drier conditions stimulate respiration more than photosynthesis in a boreal peatland ecosystem: Analysis of automatic chambers and eddy covariance measurements. Plant, Cell & Environment, 33, 394-407.

Chen, J.M., Govind, A., Sonnentag, O., Zhang, Y., Barr, A., and Amiro, B., 2006. Leaf area index measurements at Fluxnet-Canada forest sites. Agricultural and Forest Meteorology, 140, 257-268.

Christensen, T.R., Jonasson, S., Callaghan, T.V. and Havstrom, M., 1999. On the potential CO2 release from tundra soils in a changing climate. Applied Soil Ecology, 11, 127-134.

Curiel Yuste, L., Janssens, I.A., Carrara, A, Meiresonne, L., and Ceulemans, R., 2003. Interactive effects on temperature and precipitation on soil respiration in a temperate maritime pine forest. Tree Physiology, 23, 1263-1270.

Davidson, E.A., Belk, E., and Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Global Change Biology, 4, 217-227.

Davidson, E.A., Richardson, A.D., Savage, K.E. and Hollinger, D.Y., 2006. A distinct seasonal pattern in total ecosystem respirations in a spruce-dominated forest. Global Change Biology, 12, 230-239.

Deforest, J.L., Chen, J, and McNulty, S.G., 2009. Leaf litter is an important mediator of soil respiration in an oak- dominated forest. International Journal Biometeorology, 53, 127-134.

Descheemaeker, K., Muys, B., Nyssen, J., Sauwens, W., Haile, M., Poesens, J., Raes, D. and Deckers, J., 2009. Humus Form Development during Forest Restoration in Exclosures of the Tigray Highlands, Northern Ethiopia. Restoration Ecology, 17, 280-289.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. Science 263, 185–189.

Drewitt, G.B., Black, T.A., Nesic, Z., Humphreys, E.R., Jork, E.M., Swanson, R., Ethier, G.J., Griffis, T., and Mergenstern, K., 2002. Measuring forest floor

CO2 fluxes in a Douglas-fir forest. Agricultural and Forest Meteorology, 110, 299-317.

Elberling, B., 2007. Annual soil CO2 effluxes in the High Arctic: The role of snow thickness and vegetation type, Soil Biology and Biochemistry, 39, 646-654.

Fierer, N. and Schimel, J.P., 2003. A Proposed Mechanism for the Pulse in Carbon Dioxide Production Commonly Observed Following the Rapid Rewetting of a Dry Soil. Soil Biology and Biochemistry, 67, 798-805.

Gaumont- Guay, D.I., Black, A., Griffs, T.J., Barr, Morgenstern, K., Jassal, R.S., Nesic, Z., 2006a. Influence of temperature and drought on seasonal and interannual variations of soil, bole and ecosystem respiration in a boreal aspen stand. Agricultural and Forest Meteorology, 140, 203-219.

Gaumont- Guay, D.I., Black, A., Griffs, T.J., Barr, A.G., Jassal, R.S., and Nesic, Z., 2006b. Interpreting the dependence of soil respiration on soil temperature and water content in a boreal aspen stand. Agricultural and Forest Meteorology, 140, 220-235.

Griffis, T. J., T. A. Black, D. Gaumont-Guay, G. B. Drewitt, Z. Nesic, A. G. Barr, K. Morgenstern, and N. Kljun (2004), Seasonal variation and partitioning of ecosystem respiration in a southern boreal aspen forest. Agricultural and Forest Meteorology, 125, 207–223.

Granier, A., Reichstein, M., Breda, N., Janssens, I.A., et al., 2007. Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003. Agricultural and Forest Meteorology 143, 123-145.

Hanson, P.J. and Weltzin, J.F., 2000. Drought disturbance from climate change response of United States forests. Science of the Total Environment, 262, 205-220.

Hanson, P.J., O'Neill, E.G., Chambers, M.L.S., Riggs, J.S., Joslin, J.D., Wolfe, M.H., 2003. Soil respiration and litter decomposition. In: Hanson PJ, Wullschleger SD, Eds, *North American Temperate Deciduous Forest Responses to Changing Precipitation Regimes*. Springer, New York, pp. 163-189.

Hui, D. and Luo, Y., 2004. Evaluation of soil CO_2 production and transport in Duke Forest using a process-based modeling approach. Global Change Biology, 18, 1-10.

Irvine, J., Law, B.E., Martin, J.G. and Vickers, D., 2008. Interannual variation in soil CO_2 efflux and the response of root respiration to climate and canopy gas exchange in mature ponderosa pine. Global Change Biology, 14, 2848-2859.

IPCC (Intergovernmental Panel on Climate Change), (2007). Climate Change 2007: The physical science basis. Contribution of Working Group I to the fourth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers. IPCC secretariat, c/o WMO, Switzerland. (http://www.ipcc.ch, 12.03.2007).

Jarvis, P., Rey,. A, Petsikos, C., Wingate,L., Rayment, M., Pereia, J., Banza, J., David, J., Miglietta, F., Borghetti, M., Manca, G., and Valentini, R., 2007. Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emissions: the Birch effect. Tree Physiology, 27, 929-940.

Jassal, R., Black, A., Novak, M., Morgenstern, K., Nesic, Z., Gaumont-Guay, D., 2005. Relationship between soil CO_2 concentrations and forest-floor CO_2 effluxes. Agricultural and Forest Meteorology, 130, 176-192.

Jassal, R. and Black, A., 2006. Estimating heterotrophic and autotrophic respiration using small- area trenched plot technique: Theory and practice. Agricultural and Forest Meteorology, 140, 193-202.

Janssens, I.A., Kowalski, A.S., and Ceulemans, R., 2000. Forest floor CO2 fluxes estimated by eddy covariance and chamber-based model. Agricultural and Forest Meteorology, 106, 61-69.

Joffre, R., Ourcival, J.M., Rambal, S., Rocheteau, A., 2003. The key-role of topsoil moisture on CO2 efflux from a Mediterranean *Quercus ilex* forest. Annual Forest Sciences, 60, 519-526.

Kicklighter D.W., Melillo J.M., Peterjohn W.T., Rastetter E.B., McGuire D.A., Steudler P.A., Aber J.D., 1994. Aspects of spatial and temporal aggregation in estimating regional carbon dioxide fluxes from temperate forest soils, Journal of Geophysical Research, 99, 1305–1315.

Khomik, M., Arain, A. and McCaughey, J.H., 2006. Temporal and spatial variability of soil respiration in a boreal mixedwood forest. Agricultural and Forest Meteorology, 140, 244- 256.

Khomik, M., Arain, A., Liaw, K.L. and McCaughey J,H., 2009. Debut of a flexible model for simulation soil respiration – soil temperature relationship: Gamma model. Journal of Geophysical Research, 114, 1-11.

Khomik, M., Arain M.A., Brodeur, J.J, Peichl M., Restrepo-Coupé,N., and McLaren, J.D., 2010. Relative contributions of soil, foliar, and woody tissue respiration to total ecosystem respiration in four pine forests of different ages. Journal of Geophysical Research., 115, G03024, doi:10.1029/2009JG001089.

Krishnan, P., Black, T.A., Grant, N.J., Barr, A.G., Hogg, E.H., Jassal, R.S., Morgenstern, K., 2006. Impact of changing soil moisture distribution on net ecosystem productivity of a boreal aspen forest during and following drought. Agriculture and Forest Meteorology 139, 208-223.

Lavigne, M. B., Ryan, M.G., Anderson, D.E., Baldocchi, D.D., Crill, P.M., Fitzjarrald, D.R., Goulden, M.L, Gower, S.T., Massheder, J.M., McCaughey, J.H., Rayment, M., and Striegl, R.G., 1997, Comparing nocturnal eddy covariance measurements to estimates of ecosystem respiration made by scaling chamber measurements at six coniferous boreal sites. Journal of Geophysical Research, 102, 28 977–28 987.

Lavigne, M.B., Foster, R.J. and Goodine, G., 2004. Seasonal and annual changes in soil respiration in relation to soil temperature, water potential and trenching. Tree Physiology, 24, 415-424.

Law B.E., Kelliher F.M., Baldocchi D.D., Anthoni, P.M., Irvine, J., Moore D., Van Tuyl, S., 2001. Spatial and temporal variation in respiration in a young ponderosa pine forest during a summer drought. Agricultural and Forest Meteorology, 110, 27–43.

Law, B.E., Baldocchi, D.D. and Anthoni, P.M., 1999. Below- canopy and soil CO2 fluxes in a ponderosa pine forest. Agricultural and Forest Meteorology, 94, 171-188.

Lee, N.Y., Koo, J.W., Noh, N.J., Kim, J., and Son, Y., 2010. Seasonal variation in soil CO2 efflux in evergreen coniferous and broad-leaved deciduous forests in a cool-temperate forest, central Korea. Ecological Research, 25, 609-617.

Liski, J., Nissinen, A., Erhard, M. and Taskinens, O., 2003. Climate effects on litter decomposition from arctic tundra to tropical rainforest. Global Change Biology, 9, 575-584.

Lloyd, J. and Taylor, J. A.: On the temperature dependence of soil respiration, Functional Ecology, 8, 315–323, 1994.

Mackay S.L., Arain M.A., Brodeur J.J., 2011. The impact of induced drought on transpiration and growth in a temperate pine plantation forest. Agriculture and Forest Meteorology, School of Geography and Earth Sciences, Masters Thesis.

McLaren, J. D., Arain, M.A., Khomik, M., Peichl, M., and Brodeur, J., 2008. Water flux components and soil water-atmospheric controls in a temperate pine forest growing in a well-drained sandy soil. Journal of Geophysical Research, 113, 1-16.

Meir, P., Metcalfe, D.B., Costa, A.C.L and Fisher, R.A., 2008. The fate of assimilated carbon during drought: impacts on respiration in Amazon rainforests. Physiological Transactions of the Royal Society, 363, 1849-1855.

Moren, A.S. and Lindroth, A., 2000. CO_2 exchange at the floor of a boreal forest. Agricultural and Forest Meterorology, 101, 1-14.

Muhr, J., Goldberg, S.D., Borken, W. and Gebauer, G., 2008. Repreated drying-rewetting cycles and their effects on the emissions of CO_2, N_2O, NO, and CH_4 in a forest soil. Journal of Plant Nutrient Soil Science, 171, 719-728.

Nikolova, P.S., Raspe, S., Anderson, C.P., Mainiero, R., Blaschke, H., Matyssek, R. and Haberle, K.H., 2009. Effects of the extreme drought in 2003 on soil respiration in a mixed forest. European Journal of Forest Respiration, 128, 87-98.

Noormets, A., McNulty, S.G., DeForest, J.L., Sun, G., Li, Q., and Chen, J., 2008. Drought during canopy development has lasting effect on annual carbon balance in a deciduous temperate forest. New Phytologist, 179, 818-828.

Palmroth, S., Maier, C.A., McCarthy, H.R., Oishi, A.C., Kim, H.S., Johnson, K.H., Katul, G.G. and Oren, R., 2005. Contrasting responses to drought of forest floor CO_2 efflux in a Loblolly pine plantation and a nearby Oak-Hickory forest. Global Change Biology, 11, 421-434.

Peichl M., Arain M.A., Brodeur J.J., 2010a. Age effects and climatic controls on carbon fluxes in pine forests. Agricultural and Forest Meteorology, 150, 1090–1101, doi:10.1016/j.agrformet. 2010.04.008.

Peichl M., Brodeur J.J., Khomik M., Arain M.A., 2010b. Biometric and eddy-covariance based estimates of carbon fluxes in an age-sequence of temperate pine forests. Agricultural and Forest Meteorology,150,952-965, doi:10.1016/j.agrformet.2010.03.002.

Peichl M., Arain M.A., Ullah S., Moore T., 2009. Carbon dioxide, methane, and nitrous oxide exchanges in an age-sequence of temperate pine forests. Global Change Biology, doi: 10.1111/j.1365-2486.2009.02066.x.

Presant, E.W. and Acton, C.J., 1984. The soils of the regional municipality of Haldimand-858 Norfolk, Vol.2. Report No.57 of the Institute of Pedology: Research Branch, Agriculture 859 Canada, Ministry of Agriculture and Food.

Raich, J.W. and Tufekciouglu, A., 2000. Vegetation and soil respiration: correlations and controls. Biogeochemistry, 48, 71-90.

Raich, J.W. and Schlesinger, W.S., 1992. The global carbon-dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus Series B-Chemical and Physical Meteorology, 44, 81-99.

Reay D, Sabine C, Smith P, Hymus G., 2007. Spring-time for sinks. Nature, 446: 727–728.

Reichstein, M., Tenhunen, J.D., Roupsard, O., Ourcival, J.M., Rambal, S., Miglietta, F., Persesottis, A., Pecchiaris, M., Tirone, G. and Valentini, R., 2002. Severe drought effects on ecosystem CO2 and H2O fluxes at three Mediterranean evergreen sites: revision of current hypotheses? Global Change Biology, 8, 999-1017.

Richardson, A., Hollinger, D., Aber, J., Ollinger, S. and Braswell, B., 2007. Environmental variation is directly responsible for short- but not long-term variation in forest-atmosphere carbon exchange. Global Change Biology, 13, 788-803.

Richardson, A.D. and Hollinger, D.Y. 2007. A method to estimate the additional uncertainty in gap-filled NEE resulting from long gaps in the CO_2 flux record. Agricultural and Forest Meteorology, 147, 199-208.

Risk, D., Kellman, L., Beltrami, H. and Diochon, A., 2008. In situ incubations highlight the environmental constraints on soil organic carbon decomposition. Environmental Research Letters, 3, 1-4.

Rhemtulla J.M., Mladenoff D.J., Clayton M.K., 2009. Historical forest baselines reveal potential for continued carbon sequestration**.** Proceedings of the National Academy of Sciences, 106, 6082–6087. DOI: 10.1073/pnas.0810076106.

Saiz, G., Black, K., Reidy, B., Lopez, S., and Farrell, E.P., 2007. Assessment of soil CO2 efflux and its components using a process- based model in a young temperate forest site. Geoderma, 139, 79-89.

Savage, K. and Davidson, E.A., A comparison of manual and automated systems for soil CO_2 flux measurements: trade-offs between spatial and temporal resolution. Journal of Experimental Botany, 54, 891-899.

Schindlbacher, A., Zechmeister-Boltenstern, S., Glatzel, G., and Jandl, R., 2007. Winter soil respiration from and Austrian mountain forest. Agricultural and Forest Meteorology, 146, 205-215.

Sheffield, J., Wood, E.F., 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Climate Dynamics 31, 79-105.

Tang, J., Misson, L., Gershenson, A., Cheng, W. and Goldstein, A.H., 2005. Continuous measurements of soil respiration with and without roots in a ponderosa pine plantation in the Sierra Nevada Mountains. Agricultural and Forest Meterorology, 132, 212-227.

Turner D.P., Koerper G.J., Harmon M.E., Lee J.J., 1995. A carbon budget for forests of the conterminous United States. Ecology Applied, 5,421–436.

Unger, S., Maguas, C., Pereira, J.S., Aires, L.M., David, T.S., and Werner, C., 2009. Partitioning carbon fluxes in a Mediterranean oak forest to disentangle changes in ecosystem sink strength during drought. Agricultural and Forest Meteorology, 149, 949- 961.

van't Hoff, J. H., 1884. Etudes de dynamique chemique, Frederrk Muller, Amsterdam.

Wickland, K.P. and Neff, J.C., 2008. Decomposition of soil organic matter from boreal black spruce forest: environmental and chemical controls. Biogeochemistry, 87, 29- 47.

Xu, M., and Qi Y., 2001. Soil surface CO2 efflux and its variation in a young ponderosa pine plantation in the Sierra Nevada Mountains, California. Global Change Biology, 7, 667-677.

Zimmermann, M., Meir, P., Bird, M., Malhi, Y. and Ccahuana, A., 2009. Litter contribution to diurnal and annual soil respiration in a tropical montane cloud forest. Soil Biology and Biochemistry, 41, 1338- 1340.

Zha, T., Xing, Z., Wang, K.Y., Kellomäki, S. and Barr, A., 2007. Total and Component Carbon Fluxes of a Scots Pine Ecosystem from Chamber Measurements and Eddy Covariance. Annuals of Botany, 99, 345-353.

Table 1: Automated chamber measurement dates and types of measurements from 2008 though 2010.

Chamber Identification	Measuring Dates	Type of Measurement
Reference 1	June 2008 through December 2010	Reference
Reference 2	June 2008 through December 2010	Reference
Reference 3	May 2010 through December 2010	Reference
Exclusion 1	June 2008 through March 2009	Reference
	April 2009 through December 2010	Exclusion
Exclusion 2	May 2009 through December 2010	Exclusion
Exclusion/Heterotrophic	May 2010 through December 2010	Exclusion/Heterotrophic
Litterless	June 2008 through April 2009	Reference
	May 2009 through December 2010	Litterless

Table 2: Seasonal total Rs values in g C m^{-2} $season^{-1}$ for 2008 through 2010. Error estimates represent error within the model only.

	Reference 1	Reference 2	Reference 3	Exclusion 1	Exclusion 2	Exclusion/ Heterotrophic	Heterotrophic	Litterless
Winter 2008	148.22	-	-	107.95	-	-	95.87	131.38
Winter 2009	100.71	123.84	-	63.93	110.57	-	61.49	72.16
Winter 2010	101.54	66.77	119.97	88.65	73.47	83.46	40.01	37.29
Spring 2008	372.76	-	-	312.61	-	-	268.06	326.18
Spring 2009	323.1	338.15	-	161.72	238.12	-	287.6	226.34
Spring 2010	388.61	397.47	521.2	302.68	351.04	251.11	189.38	216.42
Summer 2008	591.04	-	-	509.94	-	-	440.34	506.89
Summer 2009	562.81	539.84	-	467.37	531.32	-	419.77	360.71
Summer 2010	442.37	478.28	468.07	357.24	468.07	361.53	294.71	278.62
Fall 2008	243.81	-	-	192.16	-	-	166.26	215.24
Fall 2009	262.56	235.27	-	201.33	217.64	-	136.02	141.23
Fall 2010	212.84	205.89	188.61	172.89	188.61	143.15	110.8	122.18
Annual Total 2008	1355±3.47	-	-	1122±1.16	-	-	970 ±0.86	799±0.74
Annual Total 2009	1249±1.17	1237±1.52	-	894±1.01	1097±0.89	-	904±1.32	800±0.50
Annual Total 2010	1145±1.42	1148±1.06	1298±1.87	921±1.36	1081±1.01	839±1.74	635±1.02	655±0.94

Table 3: Average seasonal root mean squared error (RMSE) and average seasonal correlation coefficient (R^2) for each chamber using Rs-Ts relationship and Rs-Ts relationship that includes SWC; (-) represents insufficient data for modeling.

WINTER/SPRING	**Ts**	**Ts+SWC**	**Ts**	**TS+SWC**
	RMSE		**R2**	
Reference 1	0.64	0.56	0.90	0.92
Reference 2	0.85	0.61	0.83	0.91
Reference 3	1.42	-	0.38	-
Exclusion 1	0.44	0.41	0.83	0.85
Exclusion 2	0.60	0.55	0.91	0.93
Exclusion/Hetero	-	-	-	-
Heterotrophic	0.49	0.58	0.60	0.90
Litterless	0.51	0.47	0.83	0.85
SUMMER	**Ts**	**Ts+SWC**	**Ts**	**TS+SWC**
	RMSE		**R2**	
Reference 1	0.82	0.79	0.60	0.68
Reference 2	0.69	0.81	0.59	0.70
Reference 3	1.45	1.00	0.56	0.79
Exclusion 1	0.74	0.84	0.38	0.58
Exclusion 2	0.99	0.92	0.30	0.54
Exclusion/Hetero	0.71	0.63	0.48	0.59
Heterotrophic	0.65	0.84	0.42	0.67
Litterless	0.63	0.61	0.40	0.50
AUTUMN	**Ts**	**Ts+SWC**	**Ts**	**TS+SWC**
	RMSE		**R2**	
Reference 1	0.55	0.63	0.75	0.77
Reference 2	0.55	0.53	0.83	0.84
Reference 3	0.68	-	0.77	-
Exclusion 1	0.44	0.41	0.83	0.84
Exclusion 2	0.45	0.44	0.86	0.87
Exclusion/Hetero	0.45	-	0.74	-
Heterotrophic	0.42	0.40	0.73	0.75
Litterless	0.43	0.42	0.60	0.61

Table 4: (a) Model parameters for each chamber, where parameters a (Q_{10}), b (R_{s10}) c and d are fitted to observed Rs from each chamber using Rs-Ts relationship (parameter a and b only) and Rs-Ts relationship that includes SWC.. (b) Root mean squared error (RMSE), bias error (BE), and correlation coefficient (R^2) for each chamber and each model.

(a)

Model Parameters	**Rs-Ts Model**		**Rs-Ts Model with SWC**			
Chamber	**a**	**b**	**a**	**b**	**c**	**d**
Reference 1	3.2	2.4	3.6	2.6	1.0	29.0
Reference 2	3.8	2.3	3.7	2.5	1.0	26.0
Exclusion 1	1.4	2.7	2.5	3.0	6.0	115.0
Exclusion 2	1.6	2.5	3.1	2.6	6.0	119.0

(b)

	Rs-Ts model			**Rs-Ts model with SWC**		
Chamber	**RMSE**	**BE**	**R^2**	**RMSE**	**BE**	**R^2**
Reference 1	0.89	0.02	0.85	0.81	0.04	0.88
Reference 2	0.89	0.01	0.82	0.77	0.03	0.87
Exclusion 1	0.99	-0.01	0.73	0.74	0.03	0.85
Exclusion 2	1.03	-0.003	0.75	0.74	0.03	0.88

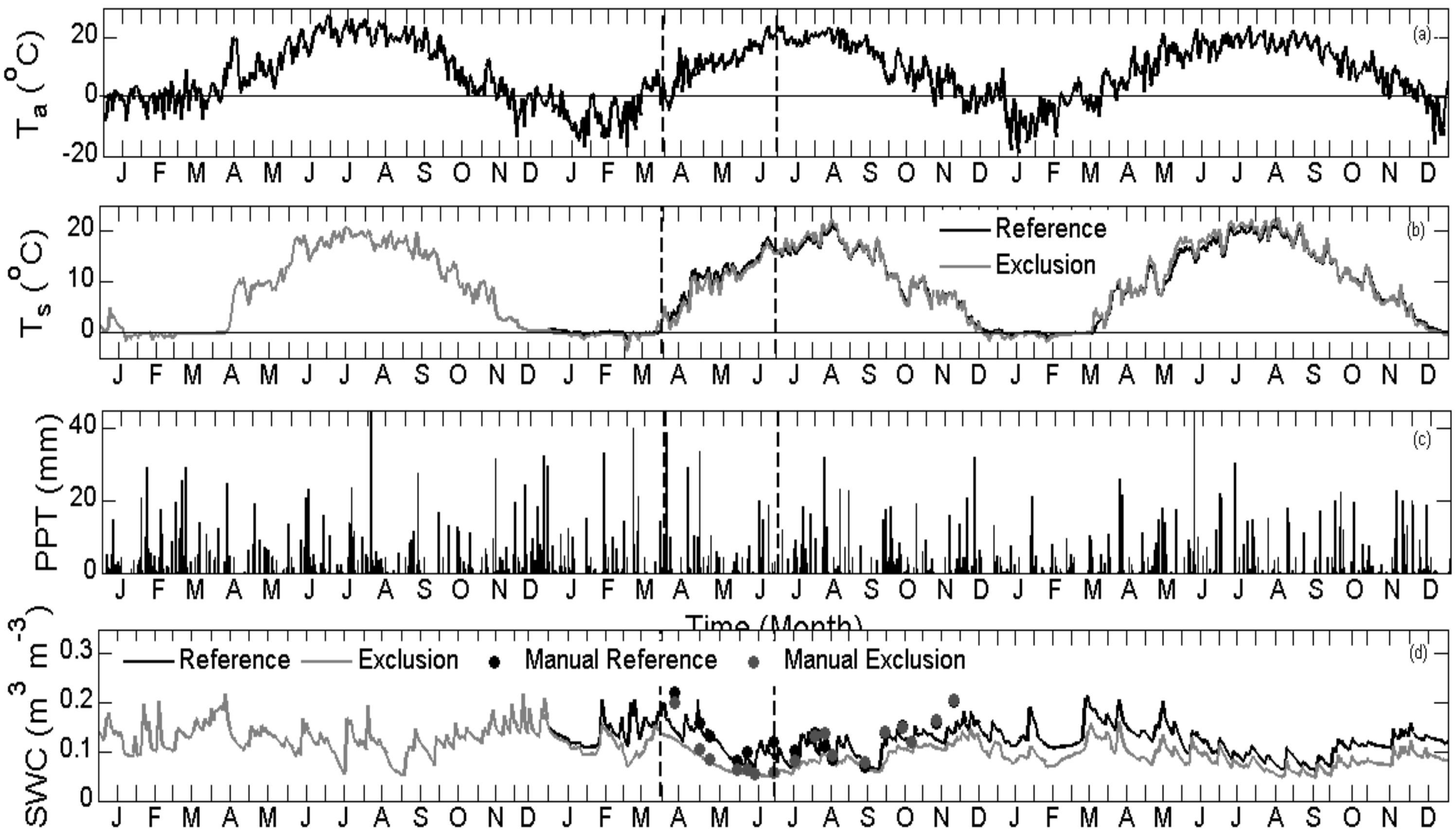


Figure 1: Daily mean environmental values for 2008, 2009 and 2010. (a) air temperature (T_a), (b) soil temperature (T_s) at 5 cm depth for the exclusion and reference areas, (c) daily totals of precipitation (PPT) and (d) soil water content (SWC) in 0- 20 cm layer, for both the reference and exclusion areas. Manual measurements are shown using

the dots in black (reference) and grey (exclusion). Vertical dash lines indicate exclusion period from April 1 to July 3, 2009.

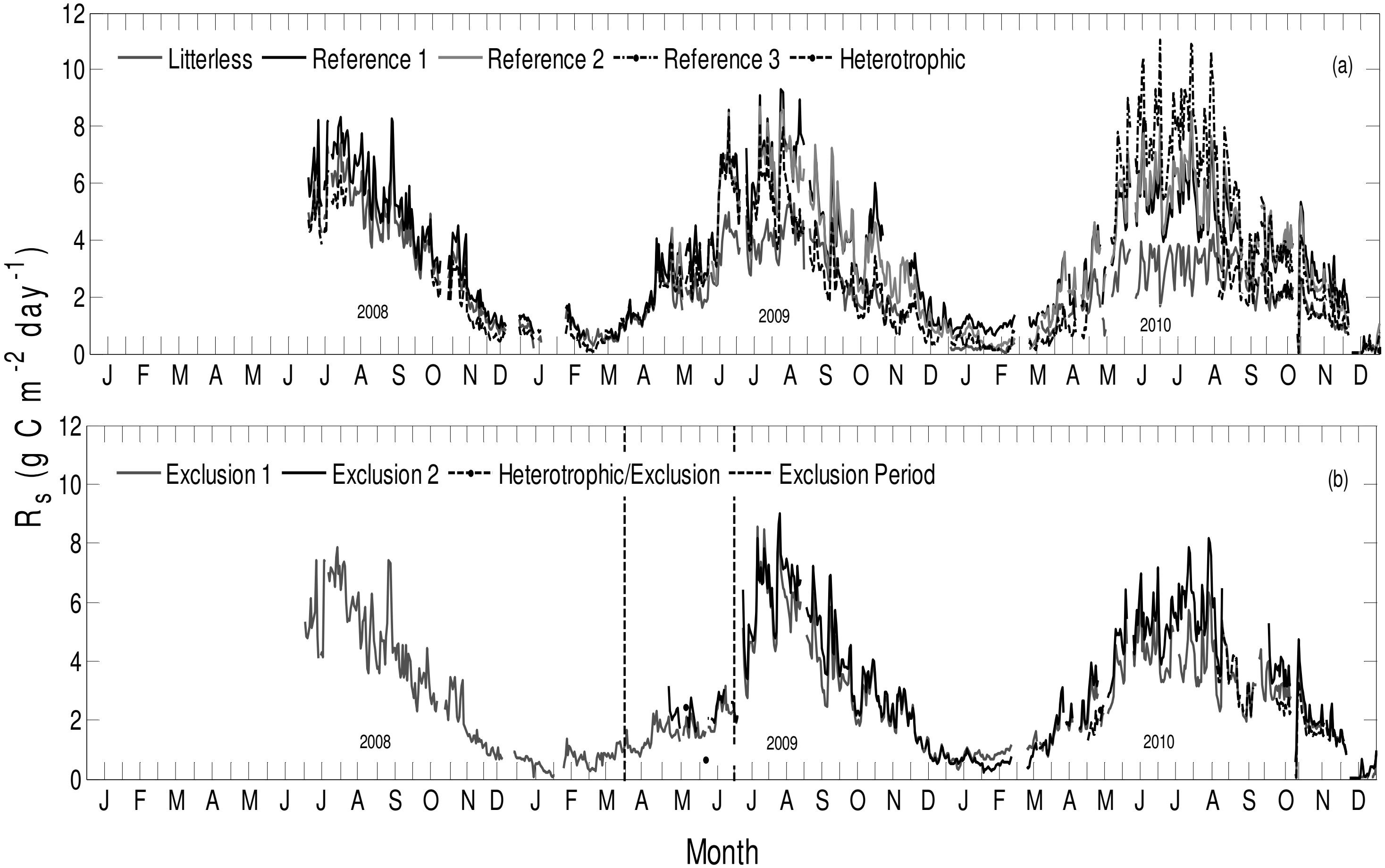


Figure 2: Daily mean Rs for 2008, 2009 and 2010 for all reference, exclusion, heterotrophic and litterless chambers.

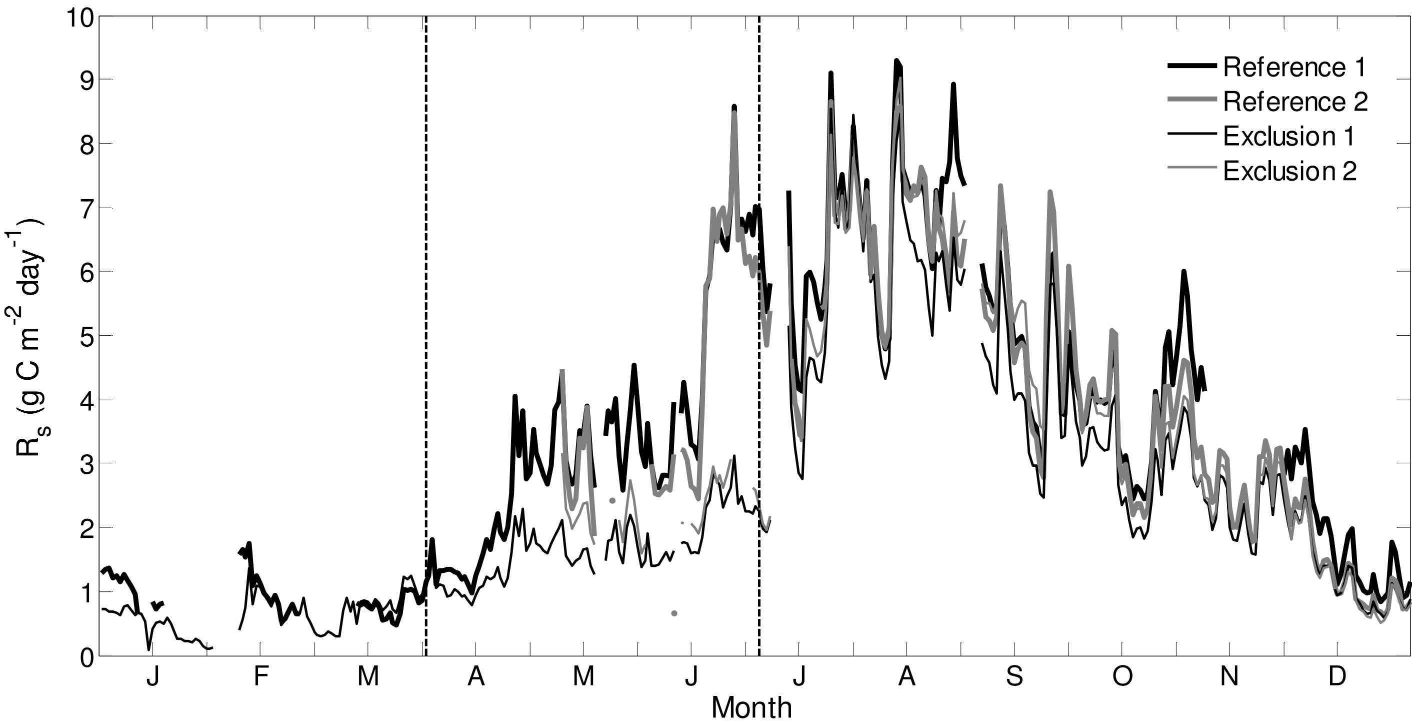


Figure 3: Comparison of daily mean Rs for reference and exclusion areas. Vertical dash lines indicate exclusion period from April 1 to July 3, 2009.

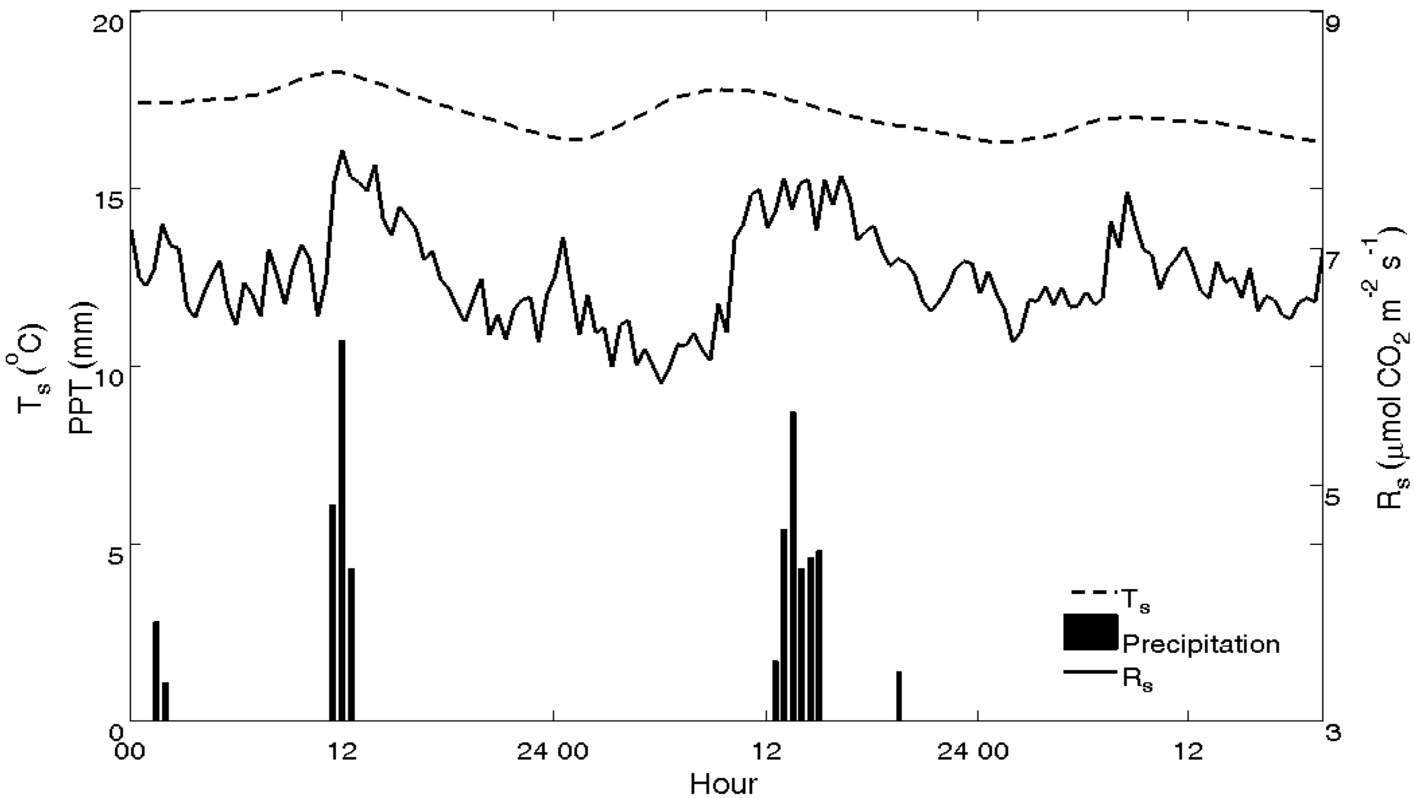


Figure 4: Half-hourly Rs during precipitation events on June 28 and 29, 2009. Soil temperature (Ts) at 5 cm depth is also shown.

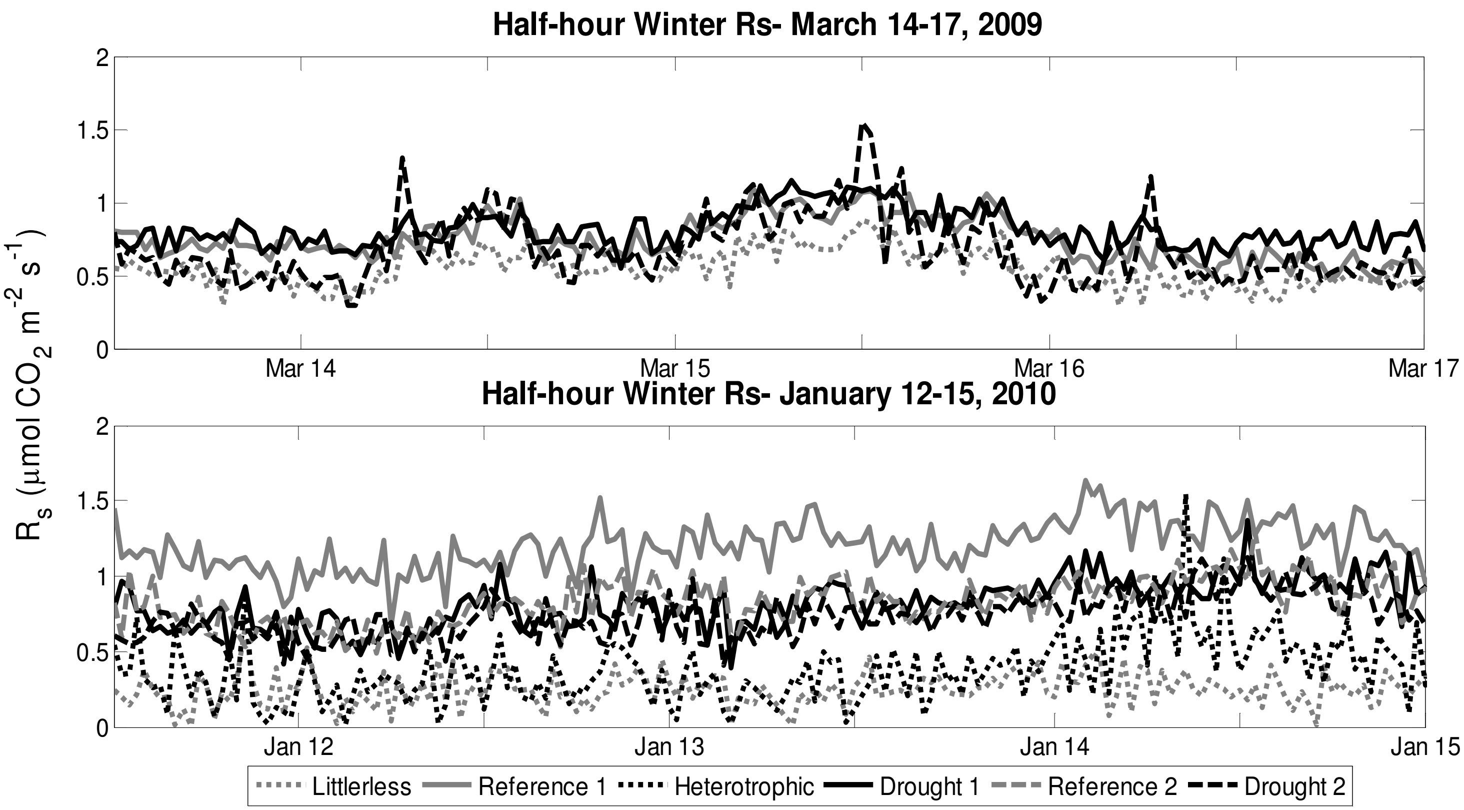


Figure 5: Continuous winter Rs data for two, three day periods in 2009 and 2010. (a) Continuous half hourly data for March 14 to March 17 2009 and (b) continuous half hourly data for January 12 to January 15, 2010.

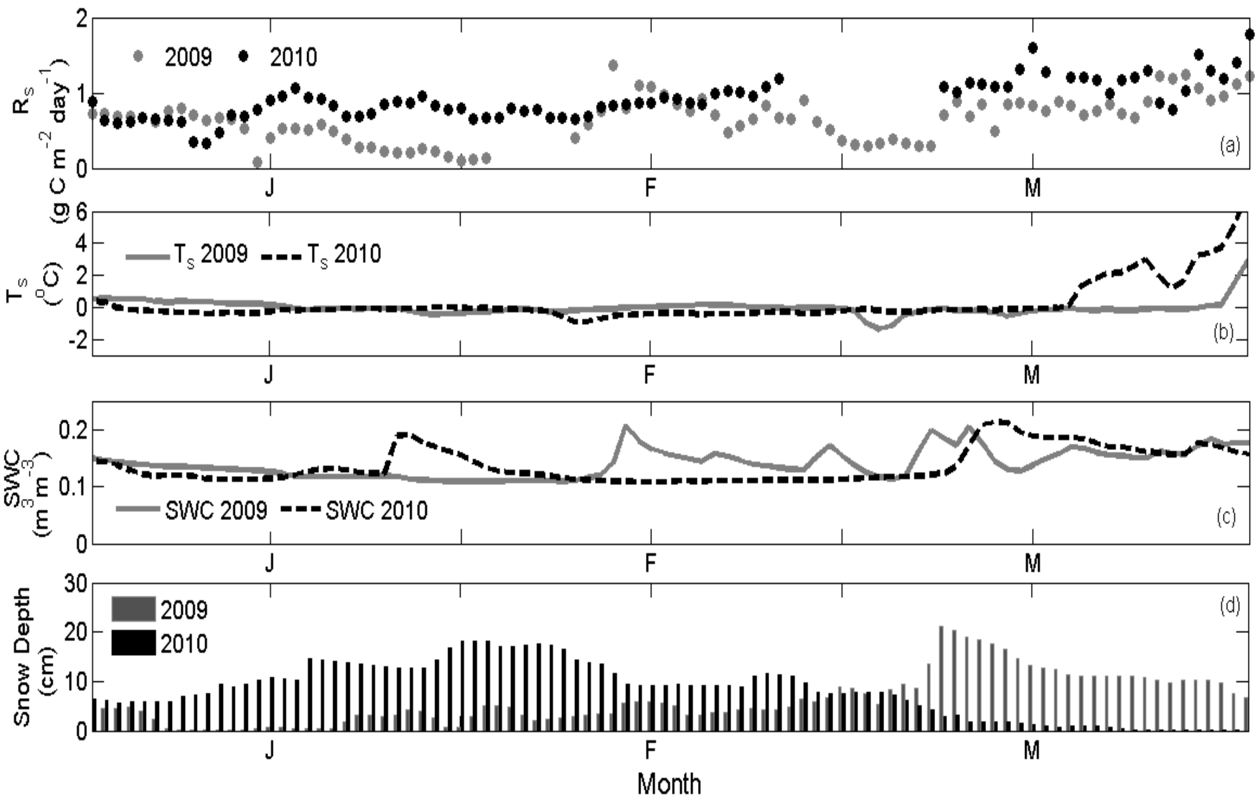


Figure 6: (a) Daily mean Rs averaged for all chambers for January through March 2009 (green) and 2010 (purple), (b) temperature (T_s) at 5 cm depth for January through March 2009 (solid line) and 2010 (dashed line), (c) soil water content (SWC) in 0-20cm layer soil for January through March 2009 (solid line) and 2010 (dashed line), and (d) daily totals of accumulated snow depth for January through March 2009 (green) and 2010 (purple).

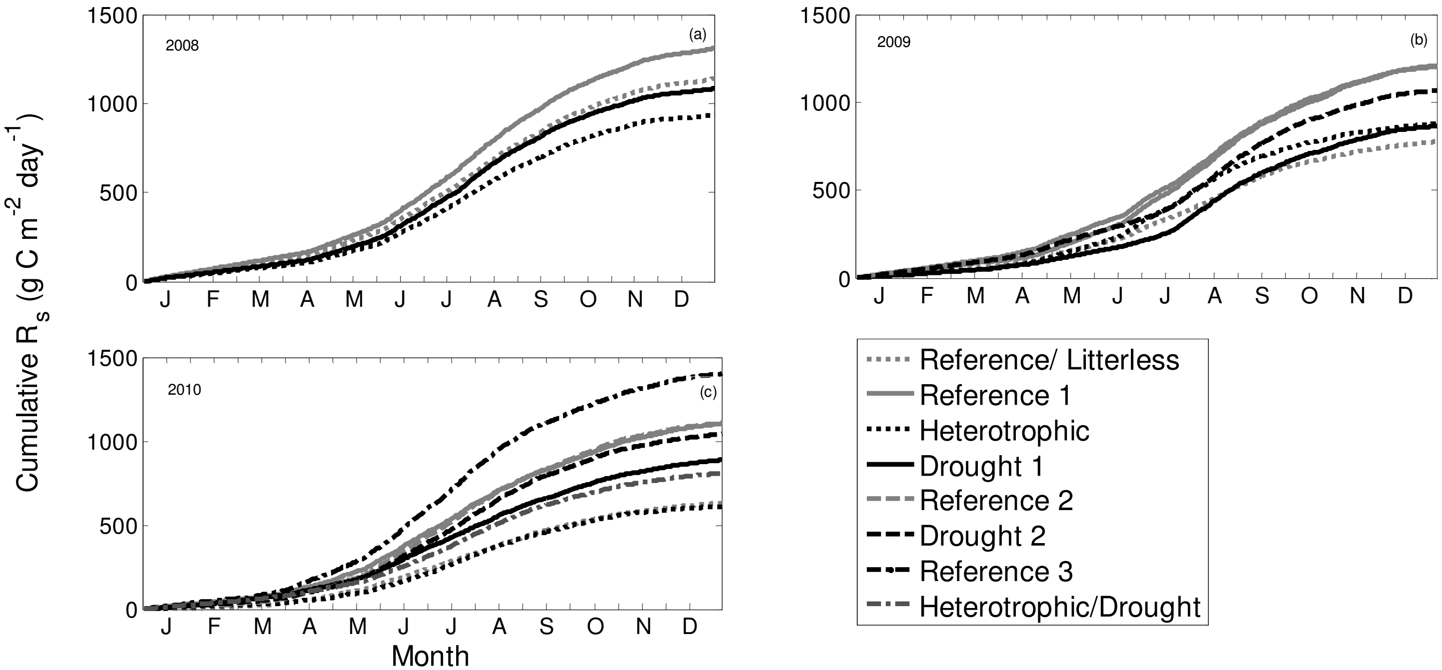


Figure 7: Cumulative Rs for all chambers during 2008, 2009 and 2010.

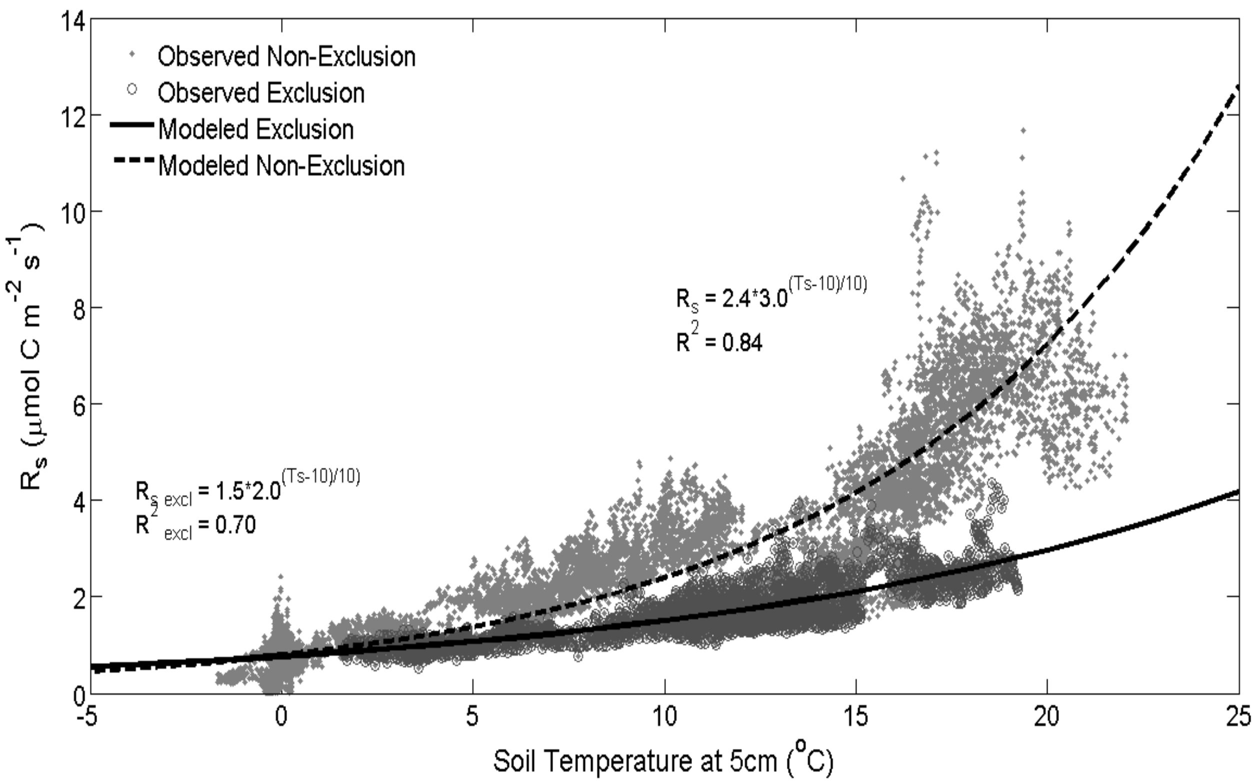


Figure 8: Relationship between half-hourly Rs vs soil temperature (Ts) at 5cm depth and fitted models for the exclusion and non-exclusion periods. The light grey dots illustrate the raw data during the non-exclusion period

while the dashed line represents the Q10 relationship for that time period. The darker grey open dots illustrate the raw data during the exclusion period while the solid line represents the Q10 relationship for that time period.

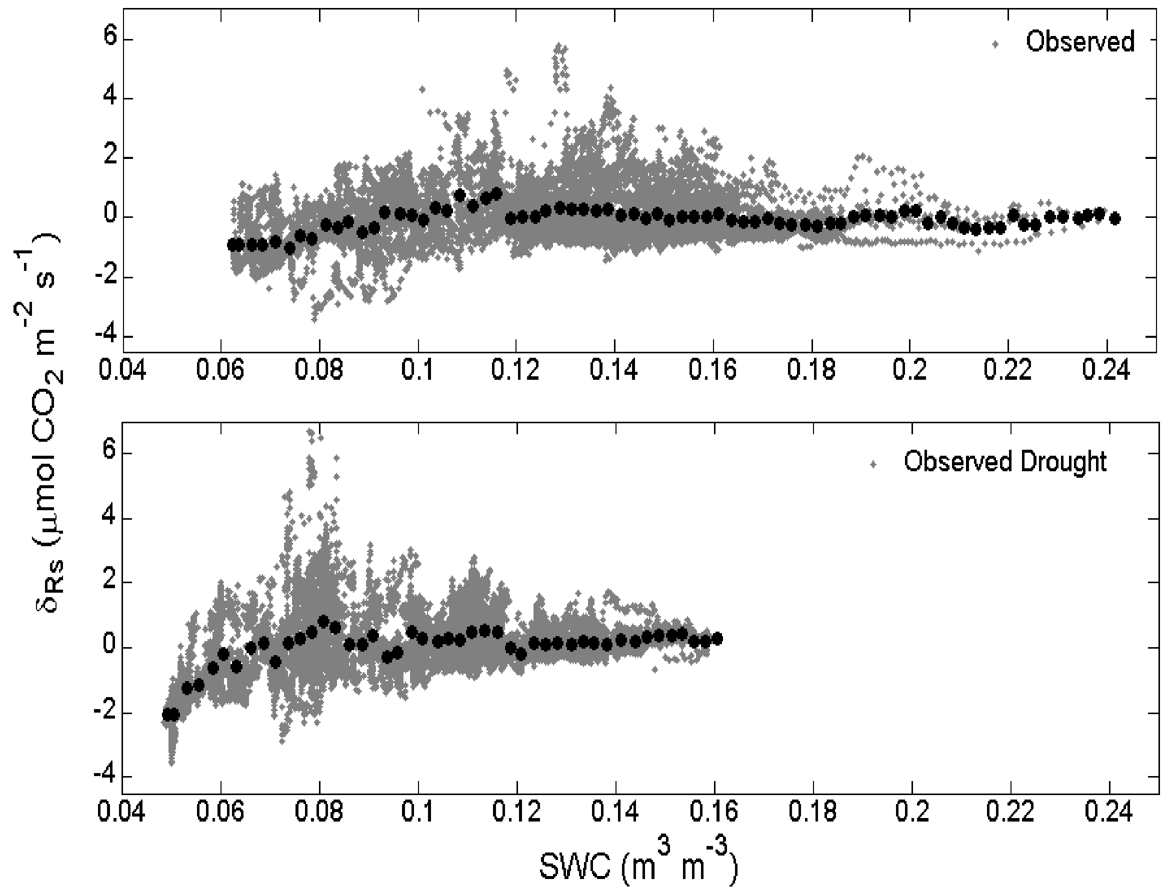


Figure 9: Relationship between half-hourly residuals of Rs and soil water content (SWC) for reference and exclusion areas. The dark circles indicate the bin averaged values of this relationship. Values above the zero line indicate a model overestimation while values below the zero line indicate a model for a given SWC value.

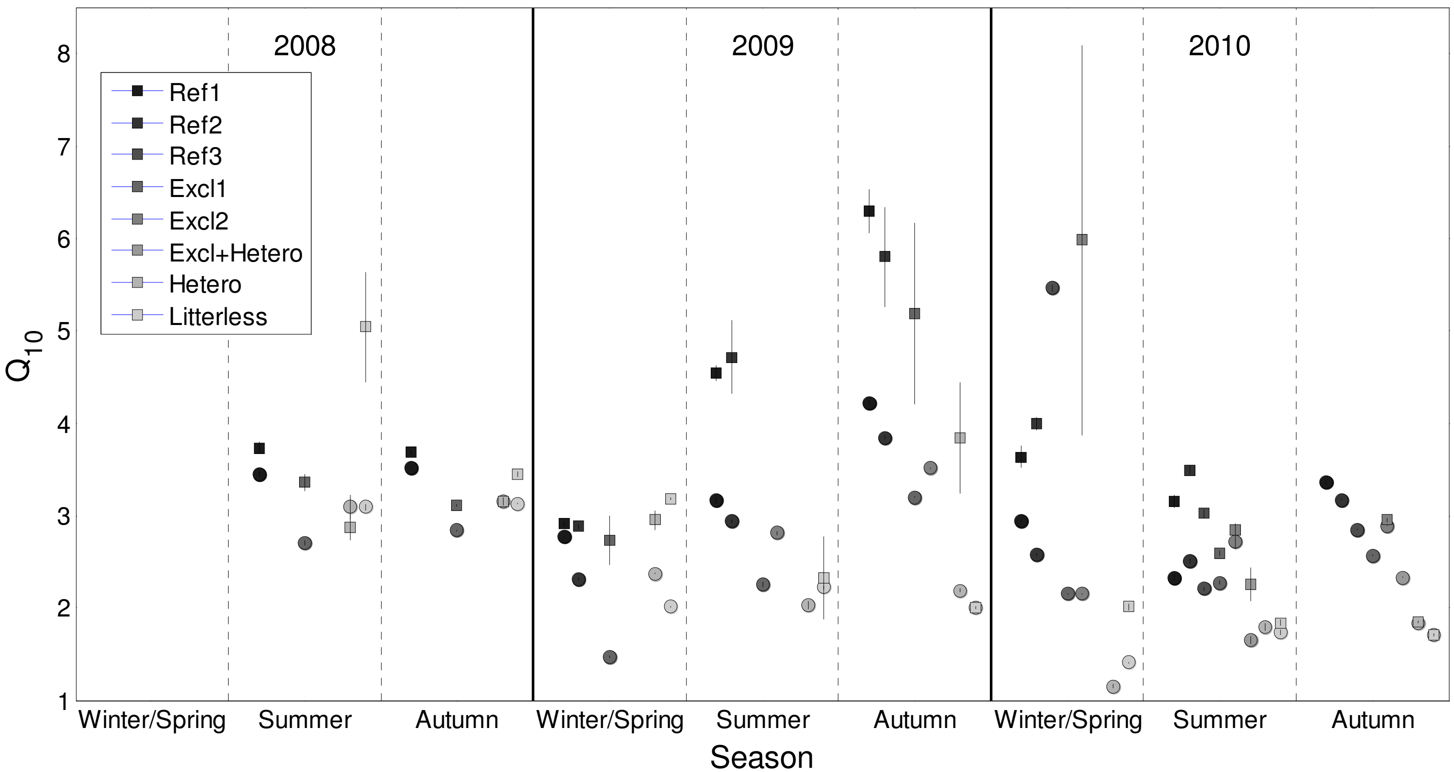


Figure 10: This figure compares the Q_{10} values for both the Ts only model (circles) and Ts+SWC model (squares) during each season for 2008, 2009 and 2010. Each chamber is represented by a different shade for inter-annual comparisons. The lines over the squares and circles represent the standard deviation of each model parameter.

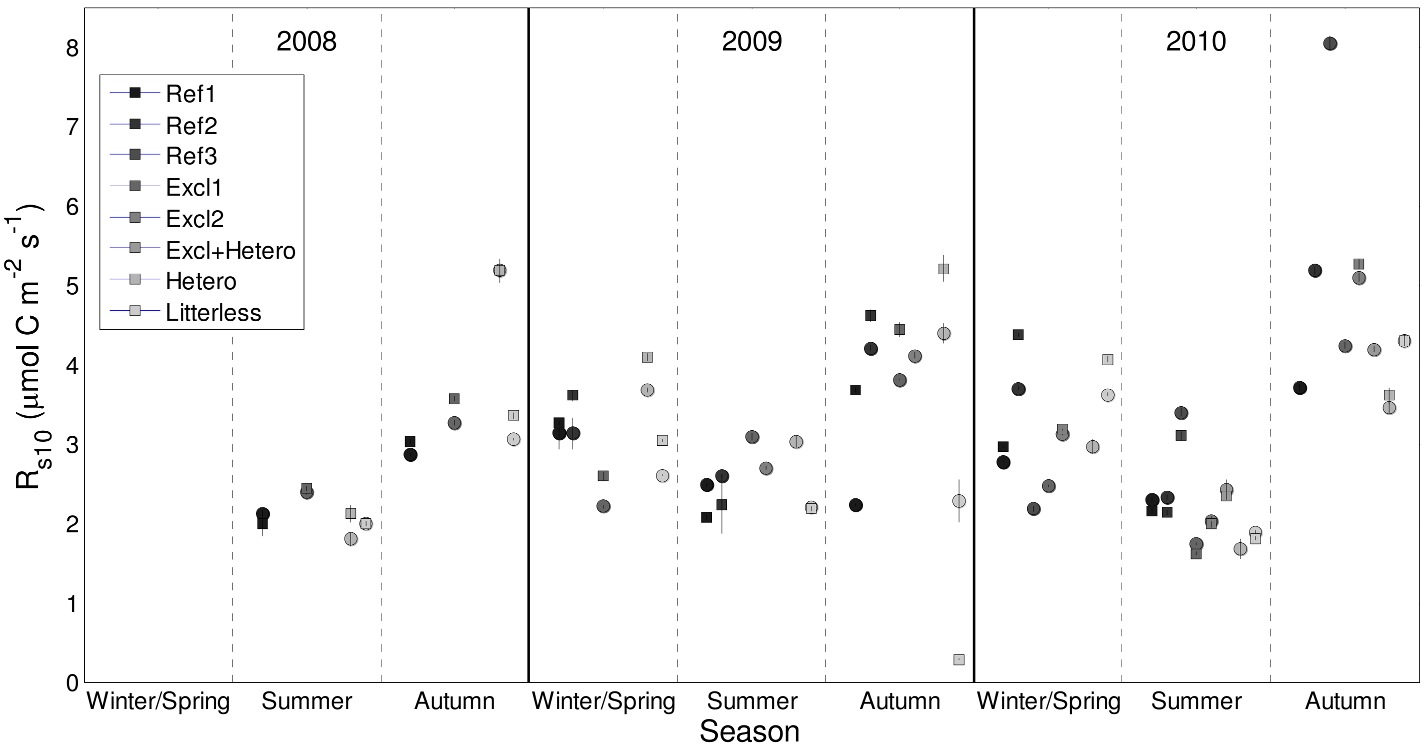


Figure 11: This figure compares the R_{s10} values for both the Ts only model (circles) and Ts+SWC model (squares) during each season for 2008, 2009 and 2010. Each chamber is represented by a different colour for inter-annual comparisons. The lines over the squares and circles represent the standard deviation of each model parameter.

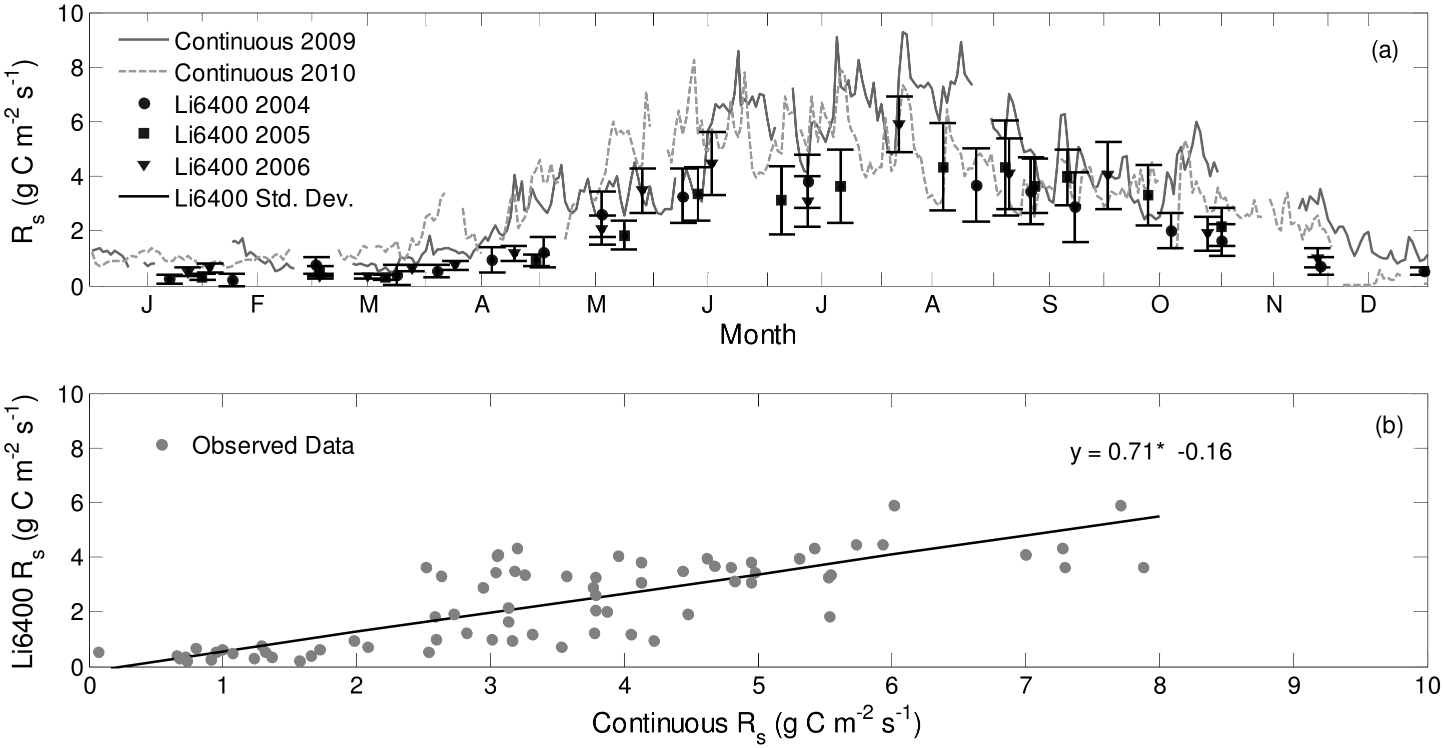


Figure 12: (a)Daily averaged continuous Rs from reference area for 2009 (black) and 2010 (grey). Daily averaged manual measurements from the Li-6400 which were measured in 2004- 2006 for Khomik et al., 2010. Error bars

represent standard deviation of each measurement and (b) scatterplot between Li6400 Rs and Continuous Rs where the lines represent the linear relationship between the two measurement types.

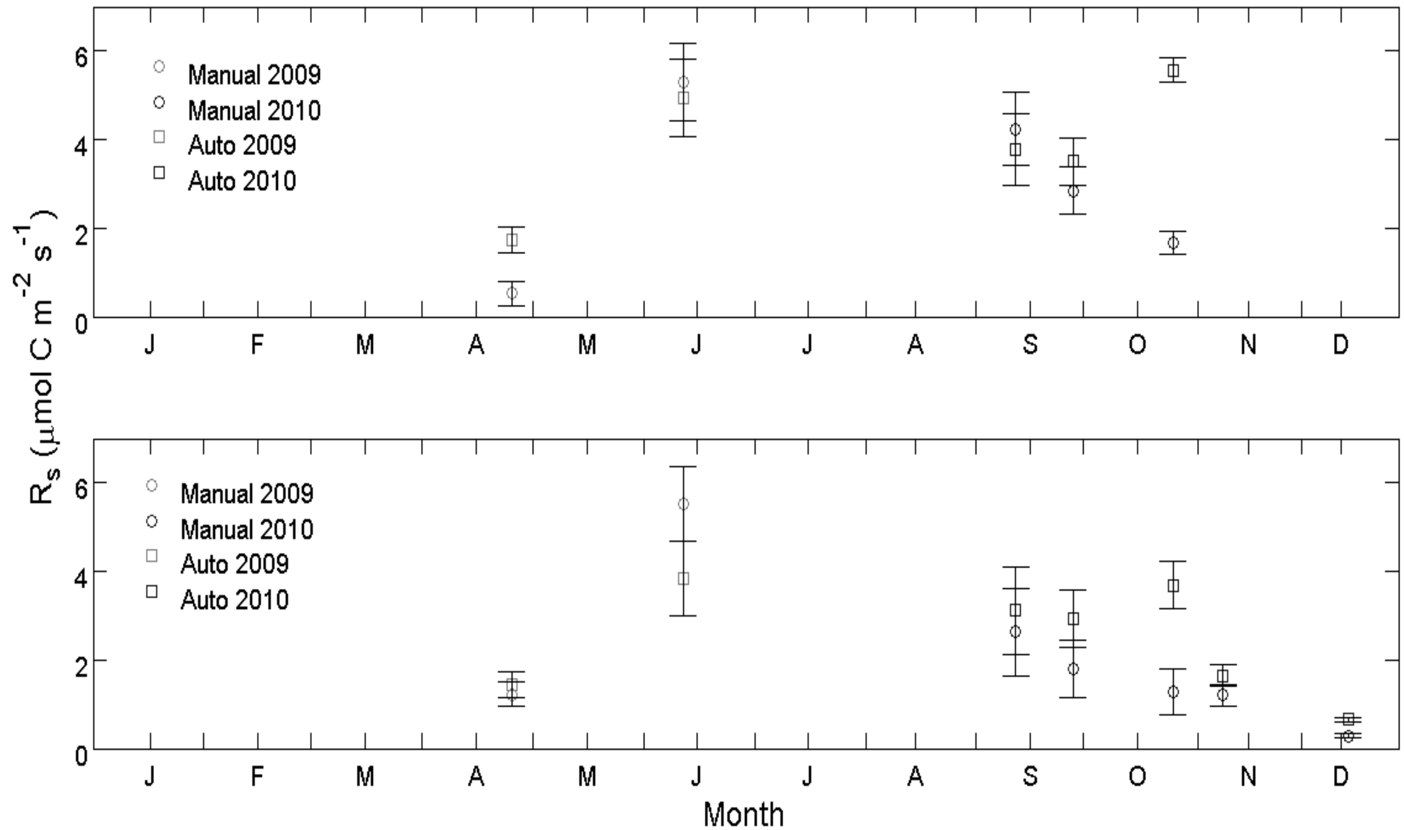


Figure 13: Comparison of half-hour measurements from both the Li-6400 (circles) and the automated chambers (squares) in 2009 and 2010. (a) represents data from the non-through-fall exclusion area, while (b) represents data from the through-fall exclusion area. The error bars represent standard deviation from each measurement.

Appendix

McMaster University – Hamilton, Ontario

Hydrometeorology and Climatology Lab Group

User Manual for the Automated Soil Chambers

(Updated from the UBC Chamber Manual prepared by Zoran Nesic)

Overview

Each chamber is constructed with a PVC cylinder and covered by a transparent plastic (Polymethyl methacrylate) dome that connects to the cylinder's aluminum frame. A torsion spring provides force to close the chamber dome during measurement, while a chamber-mounted, two-way pneumatic cylinder (model BFT-173-DN, Bimba Manufacturing Co.), opens the dome when compressed air is pushed through the tubing. The opening and closing of the chamber dome is controlled by a solenoid valve (model 45A-AA1-DAA-1BA, Mac Valves Inc.), which controls the supply of compressed air to the pneumatic cylinder. The main control unit, consisting of a CO_2 sampling system, infrared gas analyzer (Li-840, LiCOR Inc.) and a data logging computer was housed in an insulated box. An AC linear pump is used to supply air to the IRGA, and electronic relays switch the chambers and the pump on and off. Industrial air cylinders were used to operate these chambers.

The chamber domes are closed for 1-minute intervals, during which, CO_2 concentration is measured within the headspace of the chamber. Measurements are cycled through the chambers for a total of three cycles per half hour period. Thus, each half hour consists of three, minute-long CO_2 concentration measurements per chamber. Concentrations measured during the 15 seconds following dome closure are discarded to ensure the sampling tubes are free from air from the previous sampled chamber.

The soil CO_2 efflux, Rs (μmol CO_2 m^{-2} s^{-1}) is calculated as:

$$Rs = \rho_a \frac{Ve}{A} \frac{dSc}{dt} \qquad (3)$$

where ρ_a is air density in the chamber headspace (μmol m^{-3}), Ve is the effective volume of the chamber (m^3), A is the area (m^2) of the soil surface covered by the chamber, and dSc/dt is the time rate of change of CO_2 mixing ratio in the chamber headspace (μmol CO_2 mol^{-1} dry air s^{-1}). One half-hourly value was produced by the average of 3 measurements at each collar for computation and analysis purposes.

The mean Ve value was calculated using the following equations by injecting CO_2 through the top of the chamber domes for one minute and recording the CO_2 concentration change (in ppm):

$$Ve = \frac{IRT}{PV(S_c - S_m)} \qquad (4)$$

Where S_c (μmol CO_2 μmol^{-1} dry air s^{-1}) is the rate of CO_2 concentration increase during the calibration period, I (μmol CO_2 s^{-1}) is the rate of injection of CO_2 during the calibration period, S_m (μmol CO_2 μmol^{-1} dry air s^{-1}) is the rate of change of CO_2 concentration, P is the atmospheric pressure (Pa), V is the volume of the chamber (m^3), T is the chamber air temperature (K), and R is the universal gas constant, (8.314 J μmol^{-1} K^{-1}). The mean value of the effective chamber volume calculated using above procedure was 0.069 m^3. See further details in Drewitt et al. (2002) and Jassal et al. (2005).

1. Automated chamber system

The automated chamber system is comprised of the following major units;

- the control unit which houses the computer, PDQ56, the pump, the LI840 (see attached manual) and sampling tubes
- the chamber itself, with the clear dome which is hinged onto the collar
- the chamber pneumatic system for opening and closing the chamber lid
- cables for sampling air, returning air to the chamber and Dekeron tubing for compressed air
- thermocouples on the bottom for air temperature measurements (not installed at the moment)
- crossover cable and data software for operation
- dual regulator to have multiple compressed air tanks (see manual attached for regulator)

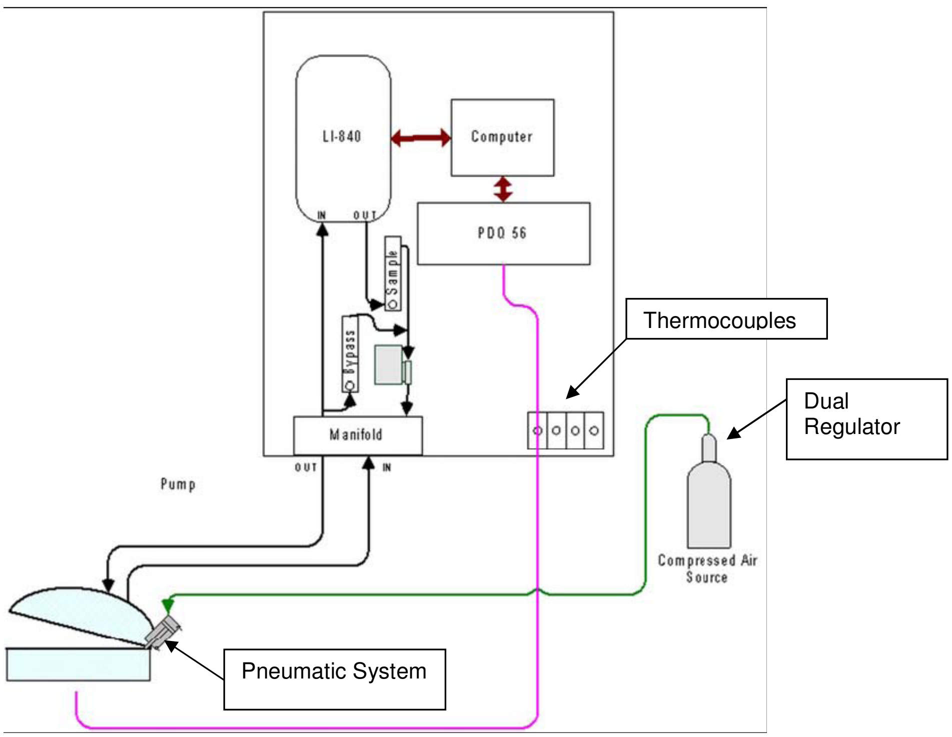
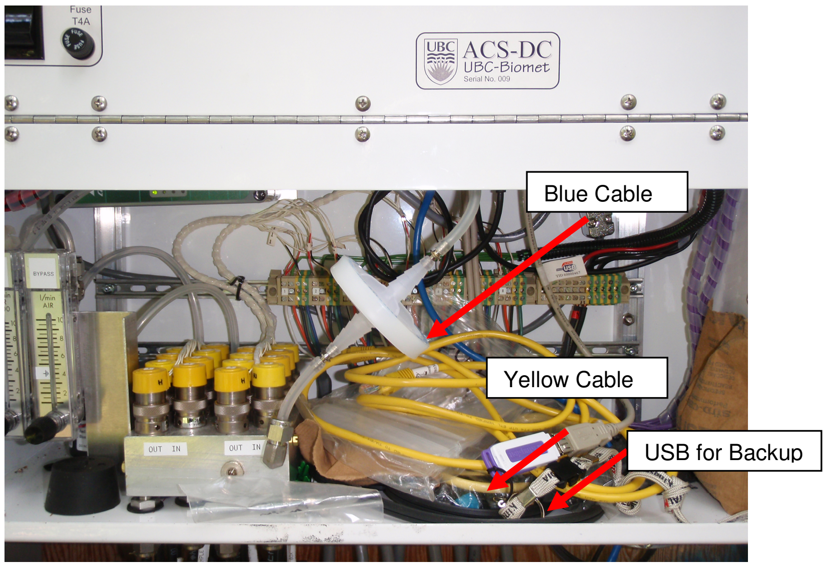


Figure 1: Set Up of Automated Chamber System

2. Data 2.1 Field Data Collection

- data is stored in the computer which is housed in the main unit
- this computer can be logged onto by connecting the laptop to the chamber computer using the yellow crossover cable (see picture)
- The yellow cable and blue cable plug into the same outlet. Keep the blue crossover cable connected at all times so you are able to connect into the chambers from the lab.

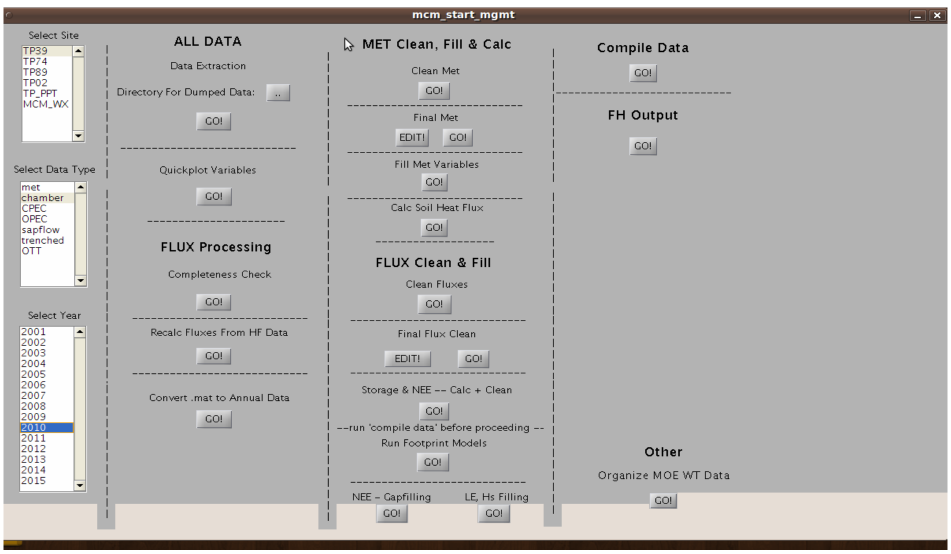


- connect by opening "Radmin Viewer" and typing in password 'goodluck'
- you can transfer data to the laptop by using the transfer button and selecting the folder which you would like to transfer the data to (to keep simple transfer data to 'field data' folder on desktop of laptop)
- you can also simply collect data by removing the purple 4GB USB key (backs up data daily) and replacing with an empty purple 4GB USB key

- put this data on the field laptop in the 'field data' folder and name with 'TP39_chamber_YYYYMMDD' and ensure it contains the following subfolders; MET-DATA, UBC_FLUX, and UBC_PC_SETUP
- this data will be moved to the data computer in the lab into the 'DUMP_data' folder within the TP39_chamber subfolder to be processed at a later time

2.2 Data Processing

- once data is in the DUMP_data folder under 'TP39_chamber' you can process the data(calculating fluxes)
- open Matlab and type in the command 'mcm_start' and press enter



- a screen will open (see image below). Select (1) site = TP39 (2) data type= chamber and (3) year
- under 'Directory for Dumped Data' press the corresponding button. Here you will need to select which group of data you would like to process. Now click GO!

- Matlab will ask if you want to add to the 'To Burn' folder, press enter, wait until Matlab is done!
- to calculate soil CO_2 efflux reselect the site, data type and year and press GO! under the 'Recalc Fluxes from HF Data' box. Matlab will prompt for a date , start date 'YYYY,MM,DD' press enter, end date 'YYYY,MM,DD' press enter.
- allow to calculate fluxes (this may take some time)
- now add new data to .mat files by selecting site, data type, and year once again and click the GO! button under 'Convert .mat to Annual Data'
- at the end Matlab will last to 'fill gaps with field data' select 'N' for now, the it will ask to 'plot all data' select 'Y' for yes
- it is important to view all your data to ensure all equipment if working

2.3 View Data for Analysis

- you will want to view the data on your own computer for further analysis and cleaning
- to find data go to 'My Computer' and select "fielddata on 'arainserv server (arainserv)'(Z:)"
- click on 'SiteData' folder, click on 'TP39_chamber', open 'MET-DATA'
- folders in 'MET-DATA' are; annual, data, hhour, hhour_field and log
- you will want data in the 'annual' folder, copy and paste data into a folder onto your own computer
- open Matlab
- open script 'clean_all_efflux_data_EN'
    - make sure the directory is correct for where your data is saved (in our case the C drive)
    - this script removes all data due to a daily system restart, spikes and occurrences when the chambers were broken
    - you will need to edit this script as you get new data from the field
    - cleaned data is saved into each year (see the last lines of the script)

- this script also plots your data for cleaning purposes

*NOTE: If Matlab cannot find files check to see what directory Matlab is looking in. Change if necessary

2.4 Checking data for goodness

- to ensure that you are getting good data you should do the following for data control
- open Matlab, open script 'check_CO2_data_EN'
    - this script has 2 commands (1) to check data for a group of days or (2) to check data for only 1 day
    - change the date within these lines to desired days, highlight and press F9
    - make sure you have copied 'data' files into a new folder on your computer under C:\DATA\data
    - a plot should open (see images below) with a title displaying chamber number, half hour and data file
    - x and y axis are time in seconds and CO2 concentration in ppm, respectively

- to read plot:
    - slope of line is written in black text and standard deviation (sd) is written in black text with brackets
    - delay time = blue dots with black circles
    - current chamber data= red dots with black circles
    - data used in calculation of slope= red dots with green circles
        - you can include more or less data by points by changing the 'slopeskipstart' in the 'ACS_init_all.txt' script (see UBC manual pg. 62 for example)

- check for good data:
  - when sd= 0.4 or less 'excellent data'
  - when sd= 0.5 to 0.6 'good data'
  - when sd= 0.6 or greater 'poor data'

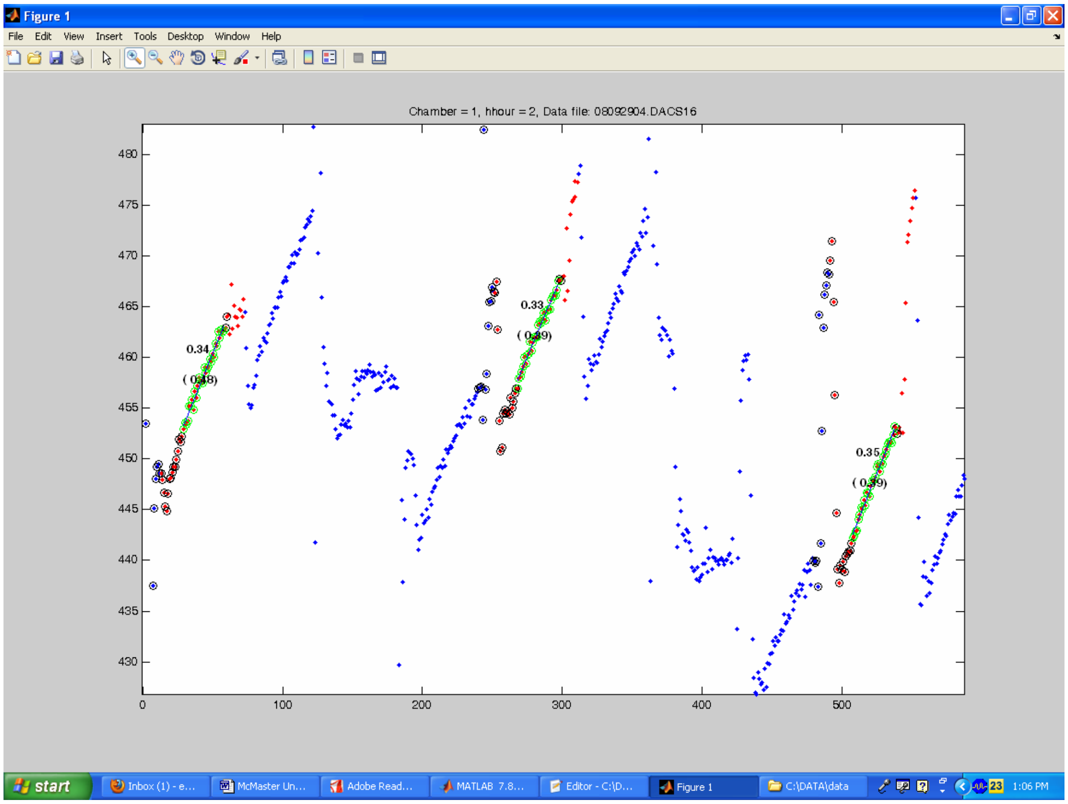
- example in picture 1:
  - Sample 1: slope= 0.34 sd= 0.48 'good'
  - Sample 2: slope= 0.33 sd= 0.39 'excellent'
  - Sample 3: slope= 0.35 sd= 0.39 'excellent'

- We would keep all of this data because it is either excellent or good

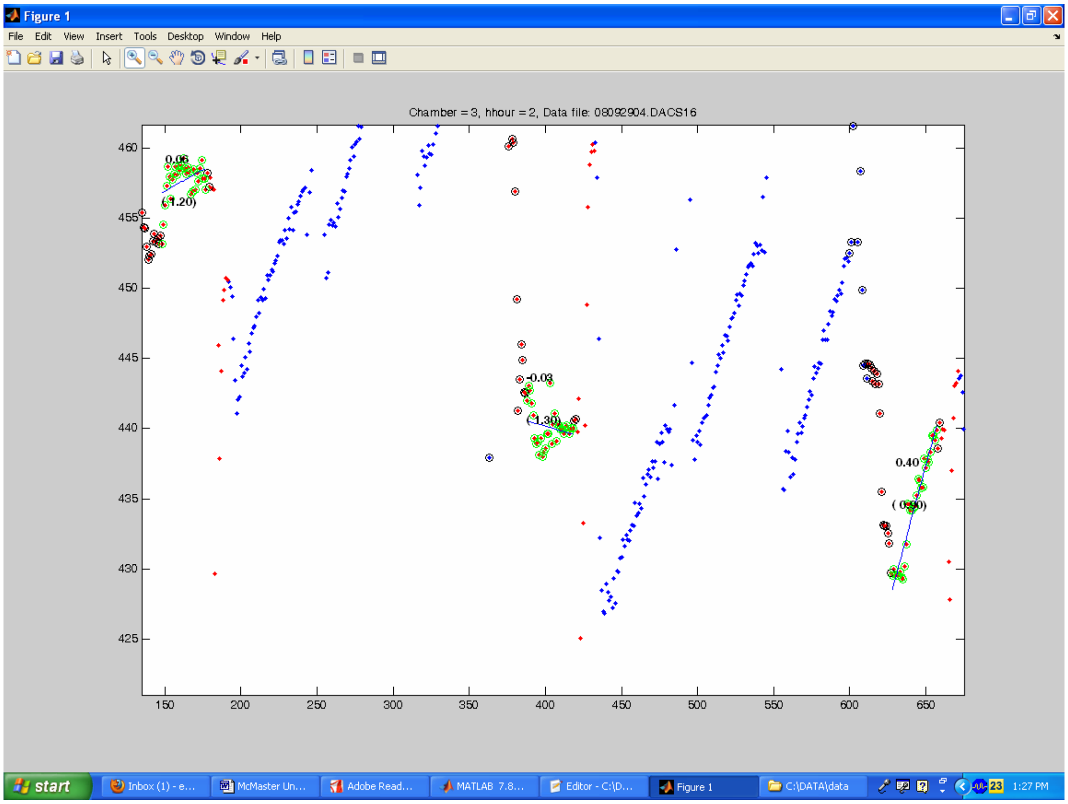
- example in picture 2:
  - Sample 1: slope= 0.06 sd= 1.2 'poor'
  - Sample 2: slope= -0.00 sd= 1.3 'poor'
  - Sample 3: slope= 0.40 sd= 0.9 'poor'

- We would not keep any of this data because it is all poor quality

- to view next chamber press enter and click on 'figure 1'
- to exit from viewing all data hold down together 'Ctrl + c'



Picture 1: Example of Good Quality Data



Picture 2: Example of Poor Quality Data

2.5 Cleaning winter data

- snowfall decreases the volume of the chamber, therefore when calculating the fluxes the volume needs to be modified
- once you have determined the new volumes of the chambers by snowfall depth you can fix your winter data
- to change the volume of the chamber open the text file 'ACS_intit_all.txt' and change the line 'chamvol' (should be at 0.69 m^3 currently)
    - see UBC chamber manual for an example of this file on page 62
- save text file with new volume and recalculate the fluxes for only specific days with a volume change

- make sure you change the volume back to the original volume after you are done

2.6 Scripts for chamber system

- See matalb scripts from the UBC chamber manual for software and calculation scripts
- Scripts used for post processing data are as follows:

(1) clean_all_efflux_EN.m

- used to plot raw efflux data, use this data to find spikes within data
- make data a NaN which with later be filled with modeled data in following scripts
- plot clean half hour data and check to see if bad data is removed
- this script also saves the clean data by each individual year

(2) interp_all_efflux_data_EN.m

- loads all clean data to fill gaps that are 3 or less half hours long by taking the average of the data points before and after the gap
- the interpolated data is saved and used for modeling the data

(3) Modeling Scripts

a) model_efflux_2008_EN.m (4 chambers as of June)
b) model_efflux_2009_EN.m (6 chambers as of May)
c) model_efflux_2010_EN.m (8 chambers as of May)

- these scripts use the interpolated data along with continuous soil moisture and soil temperature data to model gaps remaining in the efflux data
- the soil temperature and efflux is modeled using the Q10 relationship
- the residuals are taken from this relationship and plotted with rooting depth soil moisture using a logistic relationship
- the modeled data is then used to fill the efflux data where gaps are present
- in order to use this script you must choose the Ts and SM depths along with each soil pit
- I have used the rooting depth (0-15 cm) for SM and 5 cm depth for Ts
- Chamber 1,2,3,5,7 use the reference soil pit

- Chamber 4,6,8 use the drought soil pit
- 2008 soil pit data comes from the old pits (pit A)
- 2009 and 2010 soil pit data comes from the sapflow datalogger

(4) model_efflux_all_years_EN.m

- use this script to combine all years of data and plot continuous filled data
- it first loads all the filled data and then combines as one variable for each chamber

(5) check_CO2_data_EN.m

- use to check slopes of data
- see section 1.4 for more details

3.0 Common Questions and Troubleshooting

3.1 How do I get the computer to sample additional chambers?

a) You'll need to change one line in the acs_init_all.txt:
from:

```
c.chNbr = 6;            %Number of chambers connected to the system
```
to
```
c.chNbr = 8;            %Number of chambers connected to the system
```

b) And in the c:\ubc_flux\gii\ubc_GII-ACS-DC.ini (sometimes also called ubc_gii_LI840.ini) you edit:

```
numOfChambers = 8          ' Number of chambers connected to the system
```

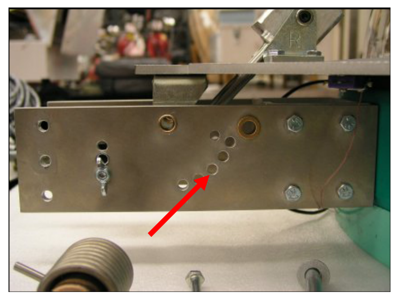
3.2 What do I do if the chambers are off (no lights are on)?

- Most likely the power bar tripped in the field due to inclement weather. All you do is simply unplug the battery from the main power bar and plug it back in. This will turn the entire system back on
- If the system does not turn back on, it is possible that there is not enough power due to the battery being off for a long period of time. Turn all switches to 'off' position and just turn the 'Li840' switch to 'on'. Let stand for some time and then turn all switches to how they originally were. Do not turn switches back on until you know that the Li-840 is on (green light is on)

3.3 What if the chambers are not opening, but the system is on?

- the chambers use compressed air to open, so if they will not open it is likely that the compressed air has run out
- it is also possible that the compressed air pressure is too low. As a rule it is good to keep it at 30 psi

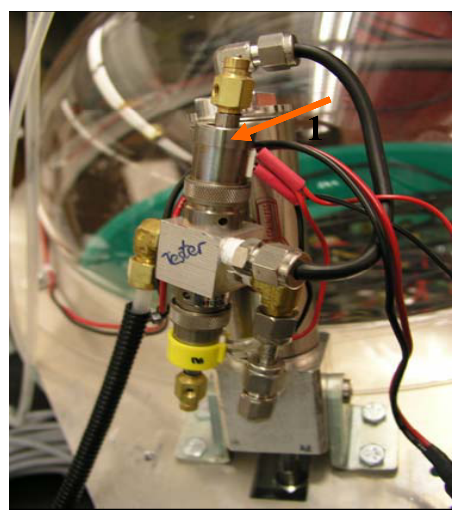
3.4 What if the chambers will not close, but the system is on?



- sometimes the spring can become disconnected so always check this first
- also, the spring may just be too loose. This is unlikely, but you can always adjust it to have more tension by moving the axle into higher notches (see image on left- more tension as you move up the notches)

3.5 What does it mean if the compressed air is being lost at a faster rate?

- Most likely there is a leak somewhere. Check all connections first will the 'Snoop'. Be sure to check at the chambers, at the main box and at the regulator



- If no leaks can be found then your pressure could be too high. Make sure that the pressure always remains between 30 to 35 psi
- It is also possible that compressed air is being leaked out of one of the pneumatic cylinder valves. If this is the case, they can be tightened with a wrench. An indication of this would be a hissing noise coming from the back of the chamber and you can feel a steady stream of compressed air coming out of the valve (see picture below—valves are labeled as 1 and 2)
- You will have to send it back if this is the case – e-mail Zoran to let him know.

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3.6 Why isn't all my data backing up on the USB key?

- this happens because the system always keeps all the half hour files. To get the system to back up newer data you must delete old data right off the computer system. Make sure whatever data you delete you have saved back in the lab on the data computer.

3.7 What do I do if the pressure of the Li-840 is low (below 75)?

- if all chambers are reading low numbers for the licor it is more than likely that the filter needs to be changed because it is dirty
- complete a calibration if you change the filter. Instructions for this are in section 3.2

3.8 What do I do if the pressure of the Li-840 is only low for one chamber?

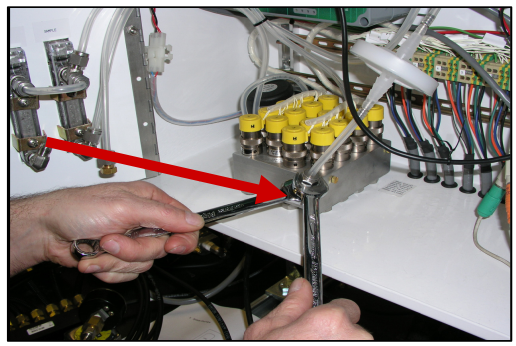
- If this is the case then something is obstructing the sample intake of this specific chamber. It may be due to snow, water or dirt being sucked up over time.
- First check the line and make sure nothing is stuck inside of it. If something is obstructing the tube then you will have to flush air through it.
- It is also possible that the intake port at the bottom of the box needs to be flushed to do an obstruction. The procedure is as follows:

1.

Ensure that the Main Power and the PC Relay switches are turned on. The power to the Licor and the computer can be on or off. Turn the pump and all the chamber switches to the off position. Disconnect the intake lines for the chamber(s) that will have their intake ports flushed.

2. Disconnect tubing from lower fitting on Bypass flow meter.

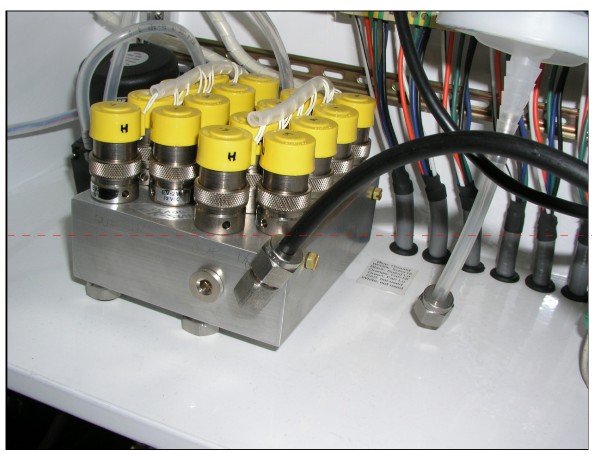
3. Plug the tubing with a Swagelok plug



4. Disconnect tubing from the manifold.

5. Connect pressure supply line from N2 tank and pressurize to **no more than** 20 psi.

6. Toggle the switch for the desired chamber from the off to the on position a few times. You should hear and feel air coming out of the corresponding intake port underneath the chamber control box.



7. After this is completed, put system back as it was, and check if the flow/ pressure problems have improved.

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4.0 Installation and Maintenance

4.1 Installing the Chamber

- After a location was selected the base of the chamber was dug into the ground about 4 cm to ensure that it doesn't move when the chamber is in operation. Once this piece is in the soil you can place the chamber metal flange and dome to the base.
- Hook up all tubing and ensure that it is tight so there are no leaks. To check for leaks use SNOOP from the trailer.
- Plug in the main plug and then go to the main unit and turn the switch to the 'on' position. If the chamber closes and sampling the turn it to the 'auto' position.
- Now you will have to change the program using the instructions for section 2.1.
- The chamber settings should be as follows for normal use:

M/C Manual 'Auto'	N/A 'Auto'
PC Relays 'ON'	Pump 'ON'
LI840 'ON'	Chambers 'Auto'
Computer 'ON'	Main Switch 'ON'

4.2 Maintenance of the Li-840

- For specific details on the Li-840 please see the attached manual
- The Li-840 should be calibrated once a year at the beginning of the growing season
- The filter also needs to be changed before you calibrate.
- To calibrate the Li-840 you must

- Turn off entire chamber system and set all switches to off, then turn main switch off
- Remove the filter and replace with a new one
- Take out green connector which is plugged inside the Li-840 (remember red=1, black=2)
- Unscrew the 'in' and 'out' tubes and the computer plug
- Unscrew the Li-840 from the metal bracket and completely remove from the box and bring to trailer to do actual calibration
- Replace the green connector with one of the gashound green connectors, i.e. Li-820. Make sure the wires are in the same place, red=1, black=2.
- Hook up to laptop using the 'LICOR' grey serial cable and the back 'LYNX' box with USB adaptor.
- Open Li-840 program and connect through port 2
- Connect the ground CO2-Li820 tube to where the CPEC was connected
- Run N2- and zero CO2 after turning N2 cal tank on and turning black dial to left
- After completed turn N2 black dial off
- Turn on CO2 cal, type in CO2 concentration of tank, span CO2 and turn off tank and dial when done
- Turn the N2 dial back on and check to see that all numbers read zero.
- Turn off all gases and put things back to how they were before.

4.3 Maintenance of the Chambers

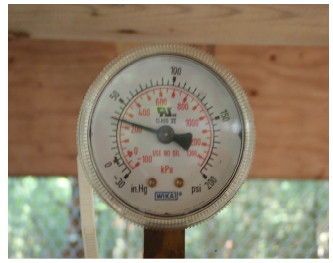
4.3.1 Yearly Maintenance

- Every year in the spring all the fans should be changed in each chamber regardless of the condition they are in. This will prevent you from having to possibly change them during the winter
- The fans are ordered online from Newark (Multicomp Axial Fan: Part # 70K8506)
- Website for the fans is http://canada.newark.com/
- As stated above, do the Li-840 calibration and change the filter

4.3.2 Bi-yearly Maintenance

- You should also clean the domes and under the flange with a cloth/paper towel and water to remove dirt and dead bugs. This can be done approximately 2-3 times a year during the growing season.
- Also, every month all the connections should be checked with 'SNOOP' to ensure that there are no leaks. While you are doing this you can also make sure no animals have been chewing any of the tubes.

4.3.3 Monthly or Every Field Visit



- Every time you do a field visit check to see if all the chambers are closing and opening properly. The chambers should form a tight seal when they are closed and when opening the dome should move in a smooth motion
- Each visit, check the compressed air tanks to ensure they still have air left. Also check the pressure at which the tanks are at, it should be 30 psi (see image to right)
- When changing a compressed air cylinder you must close both cylinders before you detach them from the dual regulator. Turn the 'Service' dial to have the arrow pointing at the cylinder that that is not empty. Remove the empty cylinder and put on a full one. Turn both compressed air cylinders back on and check for leaks. Also, ensure that the pressure is still at 30 psi.
- During the winter snow will accumulate on the collar edges so it is necessary to brush this snow off to keep a complete seal when the chamber is taking measurements. Also, in the winter the chambers may freeze shut. If you are able to lift them up do so, if not leave them until the ice melt and they open themselves.
- Most of the data loss occurs during the winter months due to the snow accumulation inside the chamber, however this data can be modeled at a later time.

  If the chamber is completely buried with snow and closed, brush all the snow off so that the chamber can function properly.