VARIABILITY IN SOIL CO_2 PRODUCTION AND SURFACE CO_2 EFFLUX ACROSS RIPARIAN-HILLSLOPE TRANSITIONS

by

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A thesis submitted in partial fulfillment
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in

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ABSTRACT

The spatial and temporal controls on soil CO_2 production and surface CO_2 efflux have been identified as an outstanding gap in our understanding of carbon cycling. I investigated both the spatial and temporal variability of soil CO_2 concentrations and surface CO_2 efflux across eight topographically distinct riparian-hillslope transitions in the ~300 ha subalpine upper-Stringer Creek Watershed in the Little Belt Mountains, Montana. Riparian-hillslope transitions provide ideal locations for investigating the spatial and temporal controls on soil CO_2 concentrations and surface CO_2 efflux due to strong gradients in respiration driving factors, including soil water content, soil temperature, and soil organic matter. I collected high frequency measurements of soil temperature, soil water content, soil air CO_2 concentrations (20 cm and 50 cm), surface CO_2 efflux, and soil C and N concentrations (once) at 32 locations along four transects. Soil CO_2 concentrations were more variable in riparian landscape positions, as compared to hillslope positions, as well as along transects with greater upslope accumulated area. This can be attributed to a greater range of soil water content and higher soil organic matter availability. Soil gas diffusion also differed between riparian and hillslope positions. Soil gas transport limited surface CO_2 efflux in riparian landscape positions due to high soil water content (despite strong concentration gradients), while efflux was gradient (production) limited in hillslope positions. This led to spring-fall reversal of maximum riparian and hillslope soil CO_2 concentrations, with highest hillslope concentrations near peak snowmelt and highest riparian concentrations during the late summer and early fall. Soil temperature was a dominant control on the overall temporal variability of soil CO_2. However, soil water content controlled differences in the timing of soil CO_2 concentration peaks within and between riparian and hillslope positions, as exemplified by those locations closest to Stringer Creek (wetter landscape positions) peaking up to three months later than those riparian locations near the riparian-hillslope transition. This work suggests that one control on the spatial and temporal variability of watershed soil CO_2 concentrations and surface CO_2 efflux is a soil water content mediated tradeoff between CO_2 production and transport.

CHAPTER 1

INTRODUCTION

Scientific Background

The scientific community is in general agreement that CO_2 is an important greenhouse gas (1995 IPCC Report; Hansen, 2001; Hansen et al., 2003). Soil respiration accounts for the largest terrestrial source of CO_2 to the atmosphere, emitting ~ 80 PgC/yr (Raich et al., 2002). However, the spatial and temporal variability of soil respiration is significant and only partially understood (Tang and Baldocchi, 2005). Further quantification of the spatial and temporal variability in soil CO_2 concentration and surface CO_2 efflux across different landscape elements (e.g. riparian and hillslope zones) is necessary to fully understand carbon (C) cycling at the ecosystem scale.

Traditionally, studies that addressed spatial and temporal variability of respiration (Fang et al., 1998; Miller et al., 1999) have been limited to small temporal or spatial scales or have ignored the influence of topography on the driving variables of soil CO_2 production and surface CO_2 efflux such as soil temperature, soil water content (SWC), and soil organic matter (SOM) quantity and quality. While many studies (Law et al., 1999; Elberling et al., 2003; Epron et al., 2004) have focused on the temporal patterns of soil respiration, Tang and Baldocchi (2005) note that relatively few have explored its spatial variability. Furthermore, while C dynamics have been investigated at many locations across North America, northern forested and subalpine ecosystems remain

greatly underrepresented in the literature. High elevation mountains play an important role in the C cycle as 70% of the Western U.S. C sink occurs at elevations greater than 750 m (Schimel et al., 2002). In mountainous terrain, topography exerts a strong control on soil temperature (Kang et al., 2000), SWC (Band et al., 1993, Kang et al., 2004), and SOM (Kang et al., 2003), which partially control soil respiration. This thesis seeks to address the spatial and temporal variability of soil CO_2 concentrations and surface CO_2 efflux in response to strong gradients in soil temperature, SWC, and SOM across riparian-hillslope transitions in a complex high elevation watershed in the northern Rocky Mountains. For the purpose of this thesis, a complex watershed is defined as having a range of slopes (e.g. 15 to 45%), aspects, landscape units (e.g. riparian and hillslope zones), and landcover (e.g. forests and meadows).

The spatial and temporal controls on soil CO_2 production and surface CO_2 efflux have been identified as an outstanding gap in our understanding of C cycling (Schimel, 2002). The National Science Foundation's Integrated Carbon Cycle Research Program (ICCR, 2003) notes that a key research area is the determination of the major processes and mechanisms controlling the distribution and redistribution of C in soils, and its exchange with the atmosphere. Furthermore, the AmeriFlux Network was established in 1996 to quantify variation in CO_2 and understand the underlying mechanisms responsible for observed fluxes and carbon pools (Hargrove et al., 2003). One of the main objectives of the AmeriFlux Network is to understand the spatial and temporal variability of the processes that control soil CO_2 production and surface CO_2 efflux heterogeneity. This objective is also shared by the ICCR.

Soil CO_2 Production and Gas Diffusion

CO_2 in soil air is the sum of heterotrophic (microbial) and autotrophic (root) respiration. As CO_2 accumulates in soil pores, a steep concentration gradient develops to the ground surface, which drives diffusion of CO_2 from the soil to the atmosphere. If soil diffusional properties are held constant, then soil surface CO_2 efflux will increase as the concentration gradient between the soil and the atmosphere steepens. Soil CO_2 diffusion is also controlled by soil properties such as soil texture, porosity, connectivity and tortuosity of pore spaces, and degree of saturation. Gasses can more easily diffuse through soil pores that have a higher degree of connectivity and less tortuosity (Hillel, 2004) as well as through drier versus wetter soil (Millington, 1959; Washington et al., 1994). Because the amount of CO_2 released to the atmosphere by soil respiration constitutes a C flux ten times greater than that from fossil fuel combustion (Andrews and Schlesinger, 2001), the release of CO_2 from soil has a major role in the C cycle.

Drivers of Respiration

The processes of microbial and root respiration are predominantly controlled by soil temperature and SWC, although SOM quantity and quality are also important. Soil temperature is usually considered to be the primary control and SWC the secondary control on soil CO_2 production (Raich and Schlesinger, 1992; Raich and Potter, 1995; Risk et al., 2002). However, SWC can become the limiting factor in soil respiration in saturated areas of the landscape (Happell and Chanton, 1993), or during warm summer months when soil temperatures are high and SWC is often low (Welsch and Hornberger, 2004). In general, respiration rates increase with increasing levels of both soil

temperature (Hamada and Tanaka, 2001; Raich et al., 2002; Pendall et al., 2004) and SWC (Holt et al., 1990; Rochette et al., 1991; Davidson et al., 2000; Liu et al., 2002). However, there is usually an optimal soil temperature for respiration, and temperatures above this value will depress soil metabolism. There is also an optimal SWC beyond which soil respiration rates greatly decline. Linn and Doran (1984) reported that soil biological activity was at or near its potential when soils were 50 to 80% saturated, and Melling et al. (2005) reported optimal respiration at SWC values of 45 to 57%. When soils become too wet, respiration rates sharply decline as oxygen is unable to diffuse into the soil profile, considerably slowing aerobic activity (Skopp et al., 1990). Gas diffusivity rates decrease as soil pores become water-filled (Davidson et al., 2000; Andrews and Schlesinger, 2001) as the diffusivity of gas through water is ~10,000 times lower than that for air (Fang and Moncrieff, 1999).

Soil respiration is dependent upon SOM quantity and quality. The main sources of SOM in terrestrial systems are litter from vegetation at the soil surface and root litter and exudates within the soil profile (Gleixner et al., 2005). SOM can be divided into labile and recalcitrant fractions. Carbohydrates, organic acids, and proteins are typically utilized first as they are easier to degrade than more recalcitrant SOM constituents such as lignin and lipids (Gleixner et al., 2001). Soil C:N ratios help to characterize the availability of SOM for microbial decomposition, with optimal ratios from 10:1 to 12:1 (Pierzynski et al., 2000). While C serves as the food source for microorganisms, nitrogen (N) must be present for the synthesis of amino acids, enzymes, and DNA (Brady and Weil, 2002). Litterfall or detritus with either a high C:N ratio (>25:1), such as straw or

sawdust, or a low C:N ratio (<6:1), such as municipal biosolids or poultry manure, will not be easily broken down by microorganisms (Pierzynski et al., 2000). In general, soil constituents with low C:N ratios (N-rich materials) will decompose more quickly than materials with high C:N ratios (Brady and Weil, 2002). Previous research has related soil C:N ratios to soil respiration. For example, Logomarsino et al. (2006) found a reduction in mineralizable C as soil C:N ratios increased and Eiland et al. (2001) found higher respiration rates in compost with lower C:N ratios.

Spatial Variability of Respiration Drivers

Topography exerts a major control on the drivers of respiration. For example, in a given climate, soil temperature is dependent upon landscape position, with southern aspects receiving more exposure to the sun than northern aspects (in the northern hemisphere). Hillslopes often exhibit greater soil temperature ranges than riparian zones due to differences in SWC. Topography exerts a strong control on SWC (Band et al., 1993, Kang et al., 2004). Convergent and concave landscape positions, especially those in riparian areas, will generally contain wetter soils (Freeze, 1972; Anderson and Burt, 1978; Bevin and Kirkby, 1979; Pennock et al., 1987; McGlynn et al., 2002; Seibert and McGlynn, 2007).

The accumulation of SOM is partially dependent upon topographic position, with wetter areas of the landscape often accumulating more SOM due to frequent saturation that retards microbial decomposition (Schlesinger, 1997; Oades, 1988). In a study on the spatial variation of soil organic C (SOC) pools, Yoo et al. (2005) attributed SOC variability across the landscape to topographically driven variations in plant inputs,

decomposition, soil texture, and soil C erosion and deposition. Soil respiration rates are generally greater in grasslands than in forests under similar growing conditions (Raich and Tufekcioglu, 2000), which the authors attributed to differences in the availability of labile C. Meadow soils usually have large labile C inputs from grass litterfall while forest soils are often characterized by more recalcitrant C detritus (Schlesinger, 1997; Hongve, 1999). Elberling (2003), in a study of soil CO_2 dynamics in Greenland, found that soil CO_2 efflux from areas with patchy vegetation was 30-40% less than areas with dense vegetation. Many researchers attribute the differences in soil CO_2 efflux between landscape elements to differences in the availability of labile soil C (Schimel and Clein, 1996; Brooks et al., 1996, 1997; Fahenstock et al., 1998). This variance in soil temperature, SWC, and SOM quantity and quality can greatly impact respiration rate heterogeneity across the landscape.

Temporal Variability of Respiration

Drivers

The drivers of respiration vary both on diurnal and seasonal timescales. Soil temperature is generally the dominant control on the temporal variability of soil respiration. Buchman (2000) found diurnal variation in soil respiration only when soil temperatures began to fluctuate. Riveros-Iregui et al. (in review) found a strong correlation between daily variations in soil CO_2 concentrations and soil temperature. Soil temperature also partially controls the seasonal variation of soil respiration (Davidson et al., 2000; Inubushi et al., 2003). While atmospheric CO_2 rates decline during the summer in the northern hemisphere due to net C uptake by vegetation, soil CO_2 emissions

generally peak in the summer when soil temperatures are the warmest (Raich and Potter, 1995). Kurganova et al. (2004) found distinct differences in seasonal CO_2 efflux from soils, with the largest values in the summer and fall. In general, peaks in soil CO_2 emission rates match periods of active plant growth, as those factors that favor soil microbial activity also favor plant growth (Raich and Potter, 1995). Seasonal variations in soil CO_2 concentrations and surface CO_2 efflux usually require distinct seasons with changing levels of soil temperature. In a tropical ecosystem, where soil temperatures remain relatively constant throughout the year, Melling et al. (2005) observed no distinct seasonal variation in soil surface CO_2 efflux, even though precipitation and water table depth fluctuated monthly. This confirmed that soil temperature was the dominant control of the seasonal variation in soil CO_2 concentrations and surface CO_2 efflux at their site. However, SWC can constrain the seasonal variation in soil respiration in either very dry (Conant et al., 1998) or humid (Buchman et al., 1997) environments.

Role of the Snowpack in Soil CO_2 Dynamics

The snowpack plays an important role in both the regulation of the seasonal variation in soil CO_2 concentrations and the release of CO_2 from the soil to the atmosphere (Jones et al., 1999; Hamada and Tanaka, 2001; Norton et al., 2001). The efflux of CO_2 through snow is important because significant snowcover is present during the winter in approximately 50% of terrestrial ecosystems (Sommerfeld et al., 1993). While winter has traditionally been viewed as a period of reduced activity, winter processes are recognized as important contributors to annual biogeochemical budgets (Campbell et al., 2005).

Recent research has shown significant soil heterotrophic activity in areas with consistent snowcover (Brooks et al., 2004). Although soil temperatures decline in the wintertime, the snow cover insulates the ground, which helps to stabilize soil temperatures and allow for the possibility of microbial activity (Schadt et al., 2003). The insulating effect of a deep snowpack can help the underlying soil maintain temperatures above -6.5ºC (Sommerfeld et al., 1996), which is thought to be the lowest temperature at which soil CO_2 production occurs (Coxson and Parkinson, 1987). This is supported by Dorland and Beauchamp (1991), who reported biological activity at soil temperatures of -2ºC. Furthermore, the snowpack and frost can trap gasses in the soil, which may promote CO_2 buildup (Hamada and Tanaka, 2001; Norton et al., 2001).

Minimum soil CO_2 concentrations are usually observed at the beginning of the snow season (Sommerfeld et al., 1996; Hubbard et al., 2004), corresponding to the coolest soil temperatures of the year. Maximum concentrations under snow usually occur just after the initiation of snowmelt as SWC begins to increase (Sommerfeld et al., 1996; Mast et al., 1998). Sommerfeld et al. (1996) found that soil CO_2 concentrations increased more than an order of magnitude from the start of the snow season to the time of maximum snow accumulation. Once snowmelt begins, soil CO_2 concentrations can decline as SWC levels become high and limit respiration. Surface CO_2 efflux often declines as snowmelt begins. Mast et al. (1998) found that soil CO_2 efflux decreased significantly at the onset of snowmelt, which they attributed to high SWC limiting diffusion of O_2 and CO_2 into and out of the soil. Elberling (2003) attributed the decline

of CO_2 efflux at the beginning of snowmelt to the formation of ice lenses within the snowpack, which greatly reduce the diffusion of CO_2 (Hardy et al., 1995).

Variations in the metamorphic conditions of the snowpack (depth, density, porosity, tortuosity, crystal shape, and ice lens structure) can affect the rate of gas diffusion through snow (Hardy et al., 1995). Furthermore, snowpack characteristics can vary spatially, with snow water equivalent and melt rates generally higher in meadows than adjacent forests (McCaughey and Farnes, 2001). Jones et al. (1999) found substantial differences in snow profiles in the Canadian Arctic, where snow crystals/grain type, density, and depth varied with changes in terrain. This would likely hold true at the Tenderfoot Creek Experimental Forest (research site for this thesis). Many studies (e.g. Sommerfeld et al., 1996; Swanson et al., 2005) note that understanding the spatial and temporal variability of soil CO_2 concentrations and surface CO_2 efflux under a significant snowpack is necessary to fully understand the C cycle.

Objectives of this Study

This research seeks to fill some of the gaps in our understanding of the C cycle by quantifying the spatial and temporal variability of soil CO_2 concentrations and surface CO_2 efflux across characteristic watershed riparian and hillslope zones in a complex subalpine watershed in the northern Rocky Mountains.

Study Area Background

This research was conducted in the Stringer Creek Watershed, which is a subwatershed of Tenderfoot Creek, located in the Tenderfoot Creek Experimental Forest

(TCEF). TCEF was established in 1961 and is located in the Little Belt Mountains of the Lewis and Clark National Forest in central Montana (Figure 1.1). The forest is characteristic of the many lodgepole pine forests found east of the continental divide; it is

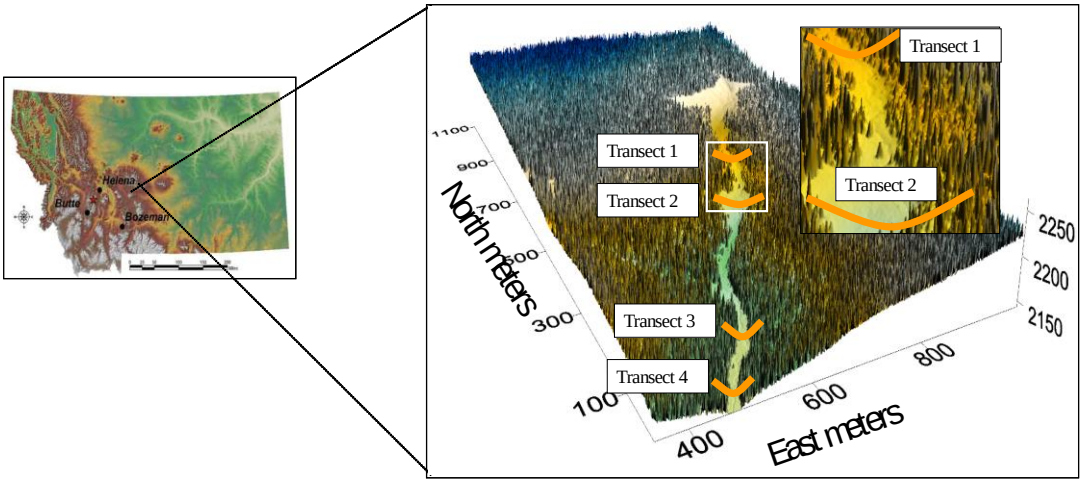


Figure 1.1: Location of the Stinger Creek Watershed, MT. LIDAR (ALSM) topographic data from upper Stringer Creek. Resolution is less than 1 m for bare earth and vegetation.

the only experimental forest formally dedicated to research on subalpine forests on the east slope of the northern Rocky Mountains. Tenderfoot Creek drains into the Smith River, which is a tributary of the Missouri River. TCEF elevation ranges from 1,840 to 2,421 m and encompasses 3,591 ha. The subcatchment of interest (Stringer Creek Watershed) is 555 ha and contains a second-order perennial stream (Stringer Creek) and a wide range of slope, aspect, and topographic convergence/divergence (Figure 1.2).

Farnes et al. (1995) characterized the climatic variables at the TCEF. Annual precipitation averages 880 mm and ranges between 594 to 1050 mm across the watershed, with the greatest amounts on the high ridges. Monthly precipitation generally peaks during December or January at 100 to 125 mm and declines to 50 to 60 mm from

July to October. Approximately 70% of the annual precipitation falls from November through May, usually in the form of snow. Runoff from the TCEF averages 250 mm per year with peak flow occurring in late May or early June. Freezing temperatures and snow can occur every month of the year. The growing season for the majority of the TCEF is 45 to 75 days, decreasing to 30 to 45 days on the ridges.

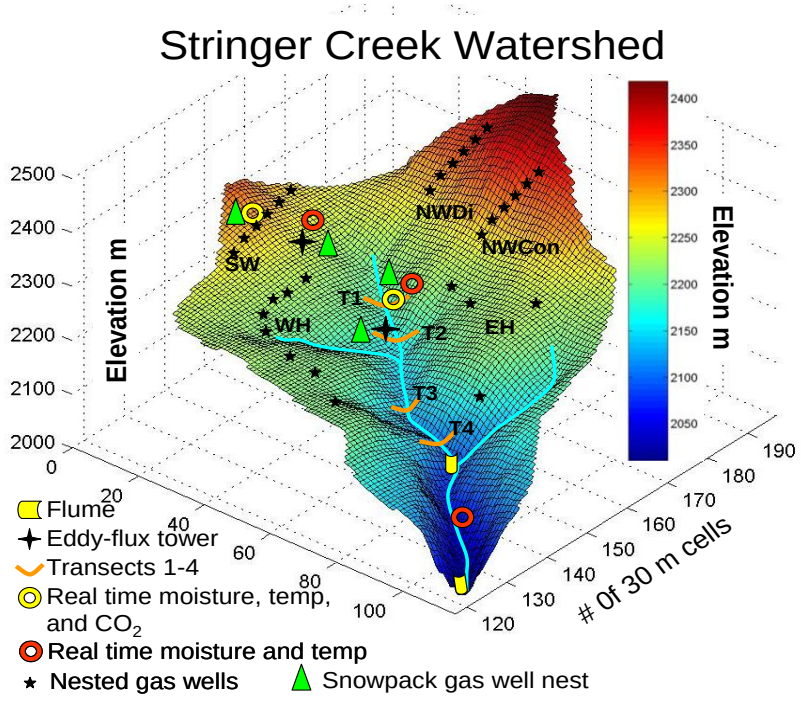


Figure 1.2: Stringer Creek Watershed, MT

Lodgepole pine (*Pinus contorta*) is the dominant tree species (Farnes et al., 1995); other species include subalpine fir (*Abies lasiocarpa*), Douglas fir (*Pseudotsuga menziesii*), Englemann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*). The riparian zones are predominantly composed of bluejoint reedgrass (*Calamagrostis canadensis*) while grouse whortleberry (*Vaccinium scoparium*) is the dominant understory species on the hillslopes (Mincemoyer and Birdsall, 2006). Tree height averages 15 m, and leaf area index (LAI) values range from 2.8 to 3.2 (Woods et al.,

2006). The most extensive soil types are the loamy skeletal, mixed Typic Cryochrepts, and clayey, mixed Aquic Cryoboralfs (Holdorf, 1981). The geology is characterized by granite gneiss, Wolsey shales, quartz porphyry, and Flathead quartzite (Farnes et al., 1995).

Two full CO_2, H_2O, and energy budget flux towers are located in the Stringer Creek Watershed (though they are not the focus of this thesis). One tower is 3 m tall and is located in a riparian meadow adjacent to Transect 2 while the second tower is 33 m tall and is located in a lodgepole pine forest in an upland landscape position (Figure 1.2). Two snow survey telemetry (SNOTEL) stations located in TCEF (Onion Park – 2259 m, and Stringer Creek – 1996 m) provide real-time data on precipitation, radiation, wind speed, snow depth, and snow water equivalent.

Characterization of Transects

Four transects were installed within the Stringer Creek Watershed (Figure 1.2), each representing a different topographic setting (Figure 1.3). These transects differ in width and slope of riparian and hillslope zones, upslope accumulated area, aspect, soil properties, and vegetation cover. These differences in landscape characteristics provide variations in soil temperature, SWC, and soil C and N concentrations, which influence soil respiration rate heterogeneity across the landscape.

The transects originate at Stringer Creek, which flows north to south, and extend up the fall line on both sides of the creek through the riparian zones and the adjacent hillslopes (Figure 1.2). The transects are labeled 1 through 4, with T1 being the northern-most (upstream) transect and T4 being the southern-most (downstream) transect

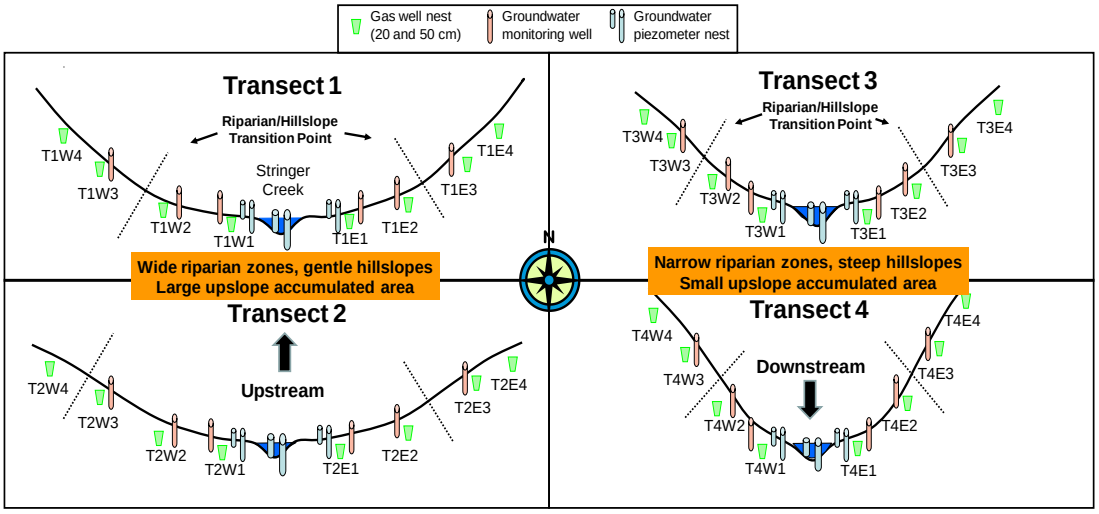


Figure 1.3: Cartoons of transect profiles.

(Figure 1.2). Each transect has 8 instrumentation nests, which contain gas wells and/or piezometers and/or groundwater wells. The nests along the east and west side of Stringer Creek are labeled "E" or "W", respectively, following the transect designation. Along both the east and west side of Stringer Creek, the following number designations identify the landscape position of the nest:

1. Beginning of the riparian zone, within 1 m of the bank of Stringer Creek.
2. Edge of the riparian zone, within 1 m of the riparian-hillslope transition.
3. Beginning of the hillslope zone, within 1 m of the riparian-hillslope transition.
4. Higher up in the hillslope zone, 20-30 m away from the bank of Stringer Creek.

For the purpose of this research, the riparian-hillslope transition was defined by a break in slope, change in vegetation, and soil properties. The letters and numbers following the transect and nest nomenclature identify which type of instrument is present. Groundwater wells (0.5 – 2 m completion depth) are identified with a "W", piezometers

with a “P”, stream piezometers with a “SP”, and gas wells with a “GW”. The shallow gas wells (0.2 m completion depth) and the shallow piezometers (0.5 - 1 m completion depth) are designated with a “1”, and the deep gas wells (0.5 m completion depth) and the deep piezometers (1 - 2 m completion depth) are designated with a “2”. Each transect contains two piezometers in the stream, and two piezometers at the first nest on the east and west side of Stringer Creek. Groundwater wells are located in the first through third nests on the east and west sides of Stringer Creek, and shallow and deep gas wells are located at each nest location.

The transects have the following characteristics and cover the range of riparian and hillslope settings in the Stringer Creek Watershed:

Transect 1: T1 has a large riparian zone (~10 and 12 m wide on the east and west side of Stringer Creek). Riparian vegetation is composed mainly of grasses (~80% ground cover) with few rocks or barren ground (~20% ground cover). The hillslope zones along T1 have relatively gentle slopes (~ 25 and 17% on the east and west slopes), and the riparian area has an open horizon that allows for large radiation inputs. T1 has an upslope accumulated area of ~13,800 m^2.

Transect 2: T2 has a very large riparian zone (~12 and 33 m wide on the east and west side of Stringer Creek). Riparian vegetation is composed mainly of dense grasses (~90% ground cover) with few rocks or barren ground (~10% ground cover). The hillslope zones along T2 have relatively gentle slopes (~ 25 and 15% on the east and west slopes). Of the four transects, T2 receives the greatest solar radiation, with the west riparian zone receiving more radiation than the east riparian zone. T2 has an upslope

accumulated area of ~42,600 m^2. Note that T2W3 is classified as a riparian zone nest due to its soil properties, vegetation cover, SWC, and water table dynamics.

Transect 3: T3 has a relatively small riparian zone (~8 and 11 m wide on the east and west side of Stringer Creek). The riparian zone has little grass vegetation (~20% ground cover), but large areas of rocks or barren ground (~80% ground cover). The hillslope zones along T3 are relatively steep (~ 28 and 32% on the east and west slopes). The relatively narrow riparian zone and steep hillslopes allow for little incoming solar radiation. T3 has an upslope accumulated area of ~7,500 m^2.

Transect 4: T4 has a very small riparian zone (~8 and 2 m wide on the east and west side of Stringer Creek). The riparian zone has sparse grass vegetation (~30% ground cover) with large areas of rocks or barren ground (~70% ground cover). The hillslope zones along T4 are very steep (~ 45 and 40% on the east and west slopes). T4 also receives little solar radiation and has an upslope accumulated area of ~6,200 m^2.

Purpose

The purpose of this study was to investigate both the spatial and temporal variability of soil CO_2 concentrations and surface CO_2 efflux across riparian-hillslope transitions in a complex mountainous subalpine watershed. This approach was chosen to quantify the role of different landscape elements in controlling the dynamics of soil CO_2 production and transport. I address three main research questions:

1) How do soil CO_2 dynamics and the drivers of soil respiration vary through *space* across riparian-hillslope transitions?

2) How do soil CO_2 dynamics and the drivers of soil respiration vary through *time* across riparian-hillslope transitions?
3) How does the relative importance of soil CO_2 diffusivity versus production differ between riparian and hillslope zones?

These questions were addressed by collecting measurements of soil CO_2 concentrations at two depths (20 cm and 50 cm), surface CO_2 efflux, soil temperature, SWC, and soil C and N concentrations (20 cm and 50 cm) across a range of spatial and temporal scales and identifying and determining the relationships between the primary drivers of soil CO_2 generation and surface CO_2 efflux. This approach allowed me to address the complex interaction of the biophysical controls on soil respiration and surface CO_2 efflux across environmental gradients within and between riparian and hillslope zones.

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CHAPTER 2

VARIABILITY IN SOIL CO_2 PRODUCTION AND SURFACE CO_2 EFFLUX ACROSS RIPARIAN-HILLSLOPE TRANSITIONS

Introduction

CO_2 is an important greenhouse gas (1995 IPCC Report; Hansen, 2001; Hansen et al., 2003), and soil respiration accounts for the largest terrestrial source of CO_2 to the atmosphere (Raich et al., 2002). Soil surface CO_2 efflux plays a significant role in the carbon (C) cycle, as the amount of CO_2 released to the atmosphere by soil respiration constitutes a C flux ten times greater than that from fossil fuel combustion (Andrews and Schlesinger, 2001). CO_2 in soil air is derived from heterotrophic (microbial) and autotrophic (root) respiration, with gas-filled soil pores typically containing 10 – 100 times the concentration of atmospheric CO_2 (Welles et al., 2001). As large amounts of CO_2 accumulate in soil air, a steep concentration gradient exists to the ground surface (e.g. ~40,000 ppm to ~380 ppm). This allows CO_2 to diffuse from the soil to the atmosphere (Hamada and Tanaka, 2001), on the order of 80 PgC/yr from the Earth's surface (Raich et al., 2002), accounting for 20-38% of the total annual biogenic CO_2 emissions to the atmosphere (Raich and Schlesinger, 1992; Raich and Potter, 1995).

This thesis addresses the variability of soil CO_2 concentrations, surface CO_2 efflux, and the drivers of soil respiration across a range of spatial and temporal scales as well as identifies differences in transport versus production limitations on soil gas

diffusion between riparian and hillslope zones. More specifically, this research investigates the spatial variability of soil CO_2 dynamics and the drivers of respiration within and between four topographically distinct riparian-hillslope transitions (yet characteristic of those throughout watershed) as well as both seasonal and diurnal CO_2 dynamics in a complex high elevation mountain watershed with strong seasonality and a 7-8 month snowpack. For the purpose of this thesis, a complex watershed is defined as having a range of slopes (e.g. 15 to 45%), aspects, landscape units (e.g. riparian and hillslope zones), and landcover (e.g. forests and meadows).

In the standing paradigm of soil water content (SWC)/temperature/CO_2 relationships, soil temperature is usually considered to be the primary control and SWC the secondary control on soil CO_2 production (Raich and Schlesinger, 1992; Raich and Potter, 1995; Risk et al., 2002a). In general, increases in soil temperatures promote higher rates of respiration (Hamada and Tanaka, 2001; Raich et al., 2002; Pendall et al., 2004). Soil respiration also generally increases as SWC increases (Davidson et al., 2000; Kelliher et al., 2004). However, when soils are too wet, respiration rates sharply decline as O_2 is unable to diffuse into the profile, and aerobic activity slows considerably (Skopp et al., 1990). Furthermore, as SWC increases, pores become water-filled; diffusivity decreases and diffusion of CO_2 out of and O_2 into the soil sharply decrease (Davidson et al., 2000; Andrews and Schlesinger, 2001). Fang and Moncrieff (1999) note that the diffusivity of gas through water is ~10,000 times lower than that for air. Davidson et al. (2000) note that the optimal SWC for respiration is usually at an intermediate level, often

near soil field capacity. Soil respiration also varies as a function of the quantity, age, and lability of soil organic matter (SOM) (Trumbore, 2000; Kelliher et al., 2004).

SWC can become the dominant control on soil CO_2 production during warm summer months when soil temperatures are high and SWC is low (Welsch and Hornberger, 2004), or in saturated areas of the landscape. For example, Happell and Chanton (1993) found that SWC was the dominant control on soil CO_2 efflux from flooded landscape positions while soil temperature was the dominant control in dry floodplain areas.

The drivers of soil respiration are spatially variable in response to topographic position. For example, soil temperature is dependent upon landscape position, with southern aspects receiving more exposure to the sun than northern aspects (in the northern hemisphere). Kang et al. (2006) found higher soil temperatures on south versus north facing slopes, with the greatest differences in early spring or late fall. Tang and Baldocchi (2005) found higher soil temperatures in open areas than under trees, which they attributed to shading by trees on sunny days. Hillslopes often have a higher degree of shading from trees than riparian areas, which can impact energy budgets and evapotranspiration. Local topography can generate considerable spatial variability in incoming solar radiation (Running et al., 1987; Kang et al., 2002), which can impact the drivers of respiration.

Topography can also control the spatial variability of SWC (Band et al., 1993; Kang et al., 2004; Wilson et al., 2005), with convergent landscape positions, especially those in riparian areas, often having higher SWC (Freeze, 1972; Anderson and Burt,

1978; Beven and Kirkby, 1979; Pennock et al., 1987; McGlynn et al., 2002; Seibert and McGlynn, 2007). Kang et al. (2003) found that both SWC and SOM were greater on north versus south facing slopes and concluded that SWC was the main factor controlling the spatial variability of soil respiration. Sjogersten et al. (2006) found that soil respiration was limited by substrate availability on dry ridges and anaerobic conditions in wet valley bottoms. In general, riparian areas have a greater accumulation of SOM than hillslopes because frequent saturation retards microbial decomposition (Schlesinger, 1997; Oades, 1988; Sjogersten et al., 2006).

Soil C:N ratios help to characterize the optimality of SOM for microbial decomposition. Soil constituents with low C:N ratios (N-rich materials) are generally more available for microbial decomposition (Brady and Weil, 2002). Recent studies have related soil C:N ratios to soil respiration. For example, Logomarsino et al. (2006) found a reduction in soil CO_2 concentrations as soil C:N ratios increased, and Eiland et al. (2001) found higher respiration rates in compost with lower C:N ratios. This variance in soil temperature, SWC, and SOM between landscape elements can greatly impact respiration rate heterogeneity.

While the spatial variability of soil respiration can be large across complex landscapes, the temporal variability can also be large, from diurnal to seasonal timescales. Soil temperature is generally the dominant control on the diurnal variability of soil respiration. For example, Buchman (2000) found that soil respiration rates remained constant when there were was no diurnal fluctuation of soil temperature, but measured higher respiration rates in the daytime as soon as soil temperatures began to

rise. Elberling (2003) found that more than 80% of the temporal variation in soil respiration could be explained by near-surface soil temperature alone, which was consistent with other field investigations (Brooks et al., 1997; Buchmann, 2000). Riveros-Iregui et al. (in review) found that while soil temperature controlled the diurnal variation in respiration in dry soils in the northern Rocky Mountains, high SWC also influenced daily fluctuations in respiration. Soil temperature is also a dominant control on the seasonal variation of soil respiration (Davidson et al., 2000; Inubushi et al., 2003), with soil CO_2 emission rates matching periods of active plant growth (Raich and Potter, 1995). However, low SWC can constrain the seasonal variation of soil respiration in seasonally dry landscapes (Conant et al., 1998, 2004; McLain and Martens, 2006), while high SWC may limit soil respiration in humid environments (Buchmann et al., 1997, 1998).

The snowpack plays a dominant role in the seasonal variation of soil respiration. Past studies have identified high levels of soil heterotrophic activity and litter decomposition under thick snow cover (Sommerfield et al., 1993; Hobbie and Chapin, 1996; Brooks et al., 1996, 1997, 1998), which suggests that winter respiration may be a significant component of total annual respiration. Although respiration rates greatly decline in the winter due to low soil temperatures, the snowpack acts as a thermal insulator for soil due to the large volume of air held between snow particles (Suzuki et al., 2006). This insulation can allow soil temperatures to remain high enough for microbial activity (Schadt et al., 2003). The snowpack can also reduce surface CO_2 efflux by increasing diffusive resistance to gas flow (Monson et al., 2006a). Monson et

al. (2006b) found that winters with thinner snowpacks exhibited decreased thermal insulation, lower soil temperatures, and lower ecosystem respiration rates.

Minimum soil CO_2 concentrations are usually observed at the beginning of the snow season (Sommerfeld et al., 1996; Hubbard et al., 2004) corresponding to the coldest soil temperatures of the year. As snow accumulates throughout the winter, the snowpack and soil frost trap CO_2 in the soil (Hamada and Tanaka, 2001; Norton et al., 2001). Furthermore, the formation of ice lenses within the snowpack can limit the diffusion of soil CO_2 to the atmosphere (Musselman et al., 2005), leading to a buildup of CO_2. Maximum concentrations under the snowpack usually occur just after the initiation of snowmelt (Sommerfeld et al., 1996; Mast et al., 1998), when soil temperatures are adequate for heterotrophic respiration, and SWC begins to increase. However, as snowmelt progresses, soil CO_2 concentrations can quickly decline as SWC increases to a level that inhibits respiration.

Wintertime efflux of CO_2 through snow is often significant, and may exceed 50% of total ecosystem respiration in areas where a snowpack is present the majority of the year (Law et al., 1999). Most studies of soil CO_2 efflux through snow have been conducted in alpine and tundra settings (Chapin et al., 1996; Oechel et al., 2000). Due to warmer soil temperatures, subalpine forested ecosystems are generally more productive (Sommerfeld et al., 1996; McDowell et al., 2000), but virtually no information exists on the spatial and temporal variability of soil CO_2 efflux through snow in subalpine environments (Hubbard et al., 2004).

The first order controls on soil respiration have been the focus of much research (Raich and Schlesinger, 1992; Raich and Potter, 1995; Risk et al., 2002a). However, little research has addressed the spatial (Longdoz et al., 2000; Kominami et al., 2003) or temporal (Longdoz et al., 2000) variability of soil CO_2 concentration and surface CO_2 efflux in complex terrain. Studies that have addressed this variability were limited to small temporal or spatial scales or have ignored the influence of topography on the driving factors of soil CO_2 dynamics. For example, Kang et al. (2003, 2006) investigated topographic effects on soil environments and respiration, but they only collected measurements once a month. Sjogersten et al. (2006) investigated how variations in SWC across the landscape controlled soil respiration, but collected measurements from only five locations on five days over two years. Both Musselman et al. (2005) and Baldocchi et al. (2006) investigated the spatial and temporal variability of soil CO_2 dynamics, but collected measurements at only two locations. Fang et al. (1998) examined the spatial and temporal variability of soil CO_2 concentrations and surface CO_2 efflux, but their study site was a 25 m^2 plot in a flat pine forest in Florida. A study conducted by Miller et al. (1999) investigated the fluxes of CH_4 and CO_2, but was conducted in a 20 m^2 forested wetland in central New York. Xu et al. (2004) note that the majority of ecosystem respiration studies do not capture a broad range of environmental or biological conditions. In mountainous terrain, topography exerts a strong control on both soil temperature (Kang, 2000), SWC (Band et al., 1993; Kang et al., 2004), and SOM (Kang et al., 2003), which partially control soil respiration. Therefore topographically controlled gradients in the drivers of respiration need to be

considered when evaluating the spatial and temporal variability of soil air CO_2 concentrations and surface CO_2 efflux across complex landscapes.

Soil CO_2 transport is a critical, yet often neglected, component of soil CO_2 dynamics (Risk et al., 2002b). While concentration gradients from the soil to the atmosphere are a main driver of soil surface CO_2 efflux, the transport of soil CO_2 to the atmosphere is also dependent upon soil gas diffusivity. Soil properties such as texture, porosity, and connectivity and tortuosity of pore spaces affect soil diffusivity (Hillel, 2004). SWC is also an important control on soil gas transport and storage (Millington, 1959; McCarthy and Johnson, 1995). The amount of water-filled pore space can greatly limit soil gas diffusivity (Millington, 1959; Washington et al., 1994; Davidson and Trumbore, 1995). Risk et al. (2002b) note that many studies assume that soil CO_2 production is the main driver of surface CO_2 efflux. However, surface CO_2 efflux and soil CO_2 production are separated by the mechanics of diffusive transport. Risk et al. (2002b) found that over an annual cycle, gas diffusivity rates changed by up to a factor of 10^4, while soil CO_2 concentrations varied by only a factor of 4. Thus, the efflux of CO_2 from the soil to the atmosphere is dependent upon both production and transport. However, our understanding of these processes and how they are affected by changes in climatic, soil, and topographic variables is poor (Jassal et al., 2005) and needs further quantification.

Objectives

The first-order controls on the spatial and temporal variability of soil CO_2 concentrations and surface CO_2 efflux, and the relative roles of soil gas production and

transport remain poorly understood. I collected measurements of soil CO_2 concentrations, surface CO_2 efflux, soil temperature, volumetric SWC, and soil C and N concentrations across eight riparian-hillslope transitions to address the following questions:

1) How do soil CO_2 dynamics and the drivers of soil respiration vary through *space* across riparian-hillslope transitions?
2) How do soil CO_2 dynamics and the drivers of soil respiration vary through *time* across riparian-hillslope transitions?
3) How does the relative importance of soil CO_2 diffusivity versus production differ between riparian and hillslope zones?

Changing landuse practices and a changing climate can greatly alter SWC, soil temperature, SOM and thus soil respiration rates and the efflux of soil CO_2 to the atmosphere (Raich and Schlesinger, 1992; Raich et al., 2002). Identification of the first order controls on the spatial and temporal variability of soil respiration and surface CO_2 efflux across complex landscapes is an outstanding gap in our knowledge of the C cycle and can play a pivotal role in informing land management.

Study Area Background

This study was conducted in the Stringer Creek Watershed, a subcatchment of Tenderfoot Creek, located in the United States Forest Service Tenderfoot Creek Experimental Forest (TCEF). The TCEF (lat. 46°55’ N., long. 110°52’ W.) is in the Little Belt Mountains on the Lewis and Clark National Forest of central Montana (Figure

2.1). TCEF elevation ranges from 1,840 to 2,421 m with a mean of 2205 m and encompasses 3,591 ha. The Stringer Creek Watershed is 555 ha and has a wide range of slope, aspect, and topographic convergence/divergence (Figure 2.2).

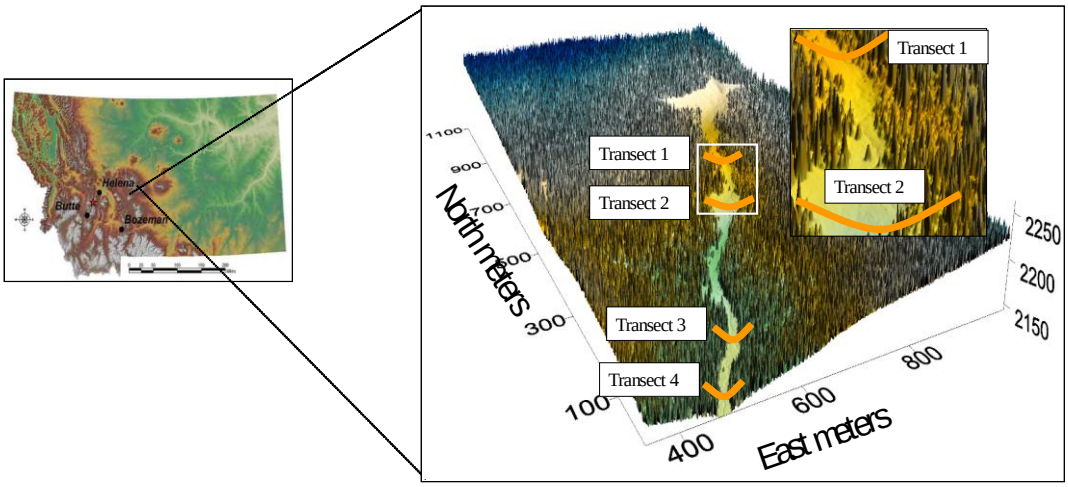


Figure 2.1: Location of the Stinger Creek Watershed, MT. LIDAR (ALSM) topographic image from upper Stringer Creek. Resolution is less than 1 m for bare earth and vegetation.

Farnes et al. (1995) characterized climatic variables at the TCEF. Annual precipitation averages 880 mm and ranges between 594 to 1050 mm across the watershed, with greater amounts on the high ridgetops. Monthly precipitation peaks in December or January at 100 to 125 mm and declines to 50 to 60 mm from July to October. Approximately 70 percent of the annual precipitation falls from November through May as snow, with typical winter snow depths of 1-2 m with snow water equivalents of ~ 600 mm. Runoff from the TCEF averages 250 mm per year with peak flow occurring in late May or early June. The TCEF has a mean annual temperature of 0°C, with mean daily temperatures ranging from -8.4°C in December to 12.8°C in July. The growing season for the majority of the TCEF is 45 to 75 days, decreasing to 30 to 45

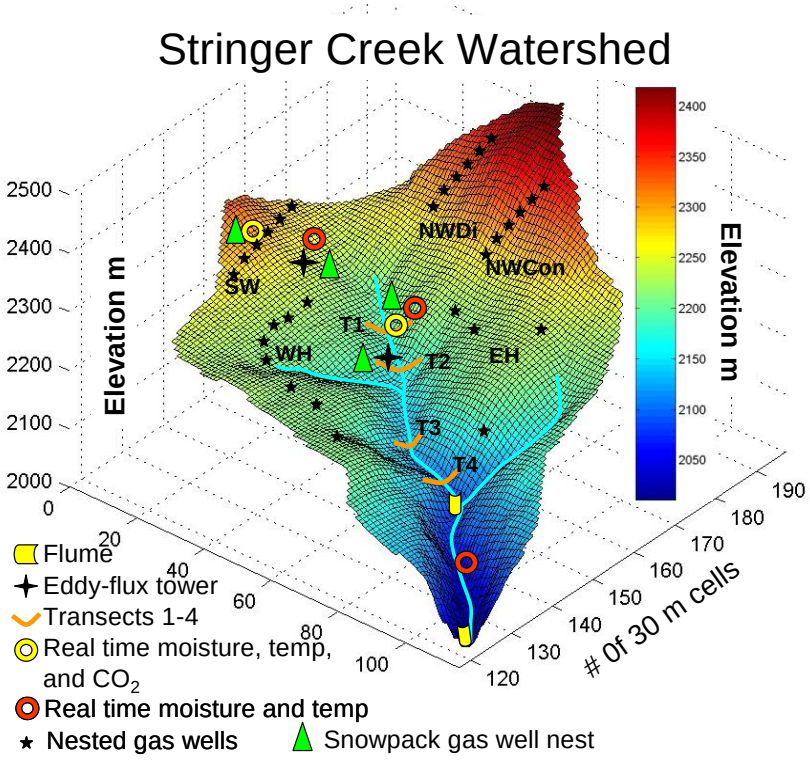


Figure 2.2: Stringer Creek Watershed, MT

days on the ridges. Lodgepole pine (*Pinus contorta*) is the dominant tree species (Farnes et al., 1995); other species include subalpine fir (*Abies lasiocarpa*), Douglas fir (*Pseudotsuga menziesii*), Englemann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*). The riparian zones are predominantly composed of bluejoint reedgrass (*Calamagrostis canadensis*), while grouse whortleberry (*Vaccinium scoparium*) is the dominant understory species on the hillslopes (Mincemoyer and Birdsall, 2006). Tree height averages 15 m, and leaf area index (LAI) values range from 2.8 to 3.2 (Woods et al., 2006). The most extensive soil types are the loamy skeletal, mixed Typic Cryochrepts, and clayey, mixed Aquic Cryoboralfs (Holdorf, 1981). The geology is

characterized by granite gneiss, Wolsey shales, quartz porphyry, and Flathead quartzite (Farnes et al., 1995).

Landscape Characterization

Four transects were installed within the Stringer Creek Watershed (Figure 2.2), each representing a different topographic setting (Figure 2.3). These transects originate at Stringer Creek, which flows north to south, and extend up the fall line on both sides of the creek approximately 30 m through the riparian zones and the adjacent hillslopes. Eight instrumentation nests were installed along each transect, two in the riparian and two in the hillslope zones on the east and west side of Stringer Creek. The riparian-hillslope

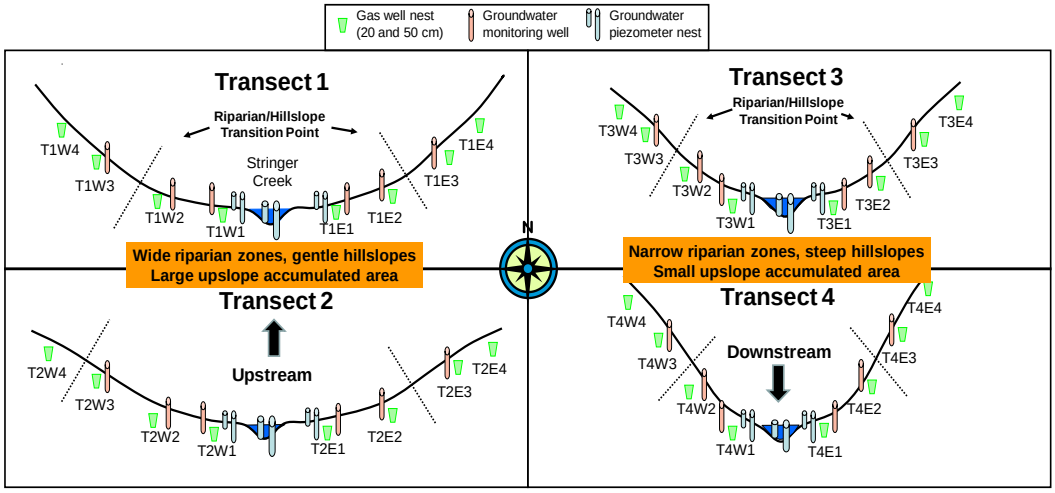


Figure 2.3: Cartoons of transect profiles.

transition was defined by a break in slope as well as change in vegetation and soil properties. The transects were labeled 1 through 4, with T1 being the northern-most (upstream) transect and T4 being the southern-most (downstream) transect (Figure 2.2). The nests were designated as either east (E) or west (W) (of Stringer Creek), and labeled 1-4, corresponding to their proximity to Stringer Creek, with 1 being closest to the creek

on both the east and west side (Figure 2.3). Gas wells were labeled "GW1" or "GW2", corresponding to the 20 or 50 cm completion depth.

The transects differ in length and slope of riparian and hillslope zones, aspect, vegetation cover, and upslope accumulated area. The hillslopes along each transect are characterized by similar vegetation, mainly lodgepole pine (*Pinus contorta*) and grouse whortleberry (*Vaccinium scoparium*). Riparian vegetation along each transect is composed mainly of bluejoint reedgrass (*Calamagrostis canadensis*).

T1 has a relatively large riparian zone (~10 and 12 m wide on the east and west side of Stringer Creek), gentle hillslopes (~ 25 and 17% on the east and west side), dense grass vegetation in the riparian zones (~80% ground cover), and an upslope accumulated of area of ~13,800 m^2. T2 has a very large riparian zone (~12 and 33 m wide on the east and west side of Stringer Creek), gentle hillslopes (~ 25 and 15% on the east and west side), very dense grass vegetation in the riparian zones (~90% ground cover), and an upslope accumulated of area of ~ 42,800 m^2. Note that T2W3 is classified as a riparian zone nest due to its soil properties, vegetation cover, SWC, and water table dynamics. T3 has a relatively narrow riparian zone (~8 and 11 m wide on the east and west side of Stringer Creek), steep hillslopes (~ 28 and 32% on the east and west side), sparse grass vegetation in the riparian zones (~20% ground cover), and an upslope accumulated of area of ~ 7,500 m^2. T4 has a very narrow riparian zone (~8 and 2 m wide on the east and west side of Stringer Creek), very steep hillslopes (~ 43 and 40% on the east and west side), sparse grass vegetation in the riparian zones (~10% ground cover), and an upslope accumulated of area of ~ 6,200 m^2. These differences in landscape characteristics

provide variations in soil temperature, SWC, and soil C and N concentrations, which influence soil respiration rate heterogeneity across the landscape.

Methods

Environmental Measurements

Daily environmental measurements were collected from all nest locations along each transect during the summer field season, weekly during the fall and spring, and monthly during the winter. Soil temperature at 12 cm was measured manually once at each nest location with a soil thermometer (12 cm soil thermometer, measurement range of -20ºC to 120ºC, Reotemp Instrument Corporation, San Diego, California, USA). Volumetric SWC (cm^3 H_2O/cm^3 soil) was measured manually three times at each nest location with a portable water content meter that integrated over the top 20 cm of soil (Hydrosense, Campbell Scientific Inc., Utah, USA). The Hydrosense used a standard calibration for a silt-loam soil and represents a relative measure of SWC. Two real-time data stations were installed along Transect 1, one each in the riparian and hillslope zones along the east side of Stringer Creek (Figure 2). Both soil temperature (L type T thermocouple wire – copper constantan, Campbell Scientific Inc., Utah, USA) and volumetric SWC (CS-616, Campbell Scientific Inc., Utah, USA) at 20 and 50 cm depths were recorded every 20-30 min with dataloggers (CR-10x, Campbell Scientific Inc., Utah, USA) to coincide with real-time soil CO_2 concentration measurements.

Two full CO_2, H_2O, and energy budget flux towers are located in the Stringer Creek Watershed (though not the focus of this thesis). One tower is 3 m tall and is located in a riparian meadow along Transect 2, while the second tower is 33 m tall and is

located in a lodgepole pine (*Pinus contorta*) forest in an upland landscape position (Figure 2.2). Two snow survey telemetry (SNOTEL) stations located in the TCEF (Onion Park – 2259 m, and Stringer Creek – 1996 m) provide real-time data on snow depth and snow water equivalent, as well as an abundance of information on climatic variables such as precipitation, radiation, and wind speed.

Soil CO_2 Concentration and Surface CO_2 Efflux Measurements

Soil CO_2 Concentration Measurements. Soil air CO_2 concentrations were measured using portable infrared gas analyzers (IRGA) (model EGM-3, accurate to within 1% of calibrated range (0 to 50,000 ppm); PP Systems, Massachusetts, USA;) or (model GM70 with M170 pump and GMP 221 CO_2 probe, accurate to within 1.5% of calibrated range (0 to 50,000 ppm) plus 2% of reading; Vaisala, Finland). With the exception of monthly diurnal sampling during the summer, all measurements were collected between 0900 and 1700 h to limit complications of temporal variability. Measurements also began at a different transect each day to limit a systematic sampling bias (i.e. sampling the same transect at the hottest time of the day).

At all nest locations along each transect, gas wells that equilibrate with the soil atmosphere were installed at 20 and 50 cm depths following the methods described by Andrews and Schlesinger (2001) and Welsch and Hornberger (2004). The gas wells consisted of a 15-cm section of 5.25 cm (inside diameter) PVC inserted into a hole augered to the depth of interest. The top of the PVC was capped with a rubber stopper (size 11) through which passed two pieces of PVC tubing (4.8 mm inside diameter

Nalgene 180 clear PVC, Nalge Nunc International, Rochester, N.Y., USA) that extended above the ground surface. The tubing was joined above the ground surface with plastic connectors (6-8 mm HDPE FisherBrand tubing connectors, Fisher Scientific, USA) to ensure that no gas escaped while measurements were not being collected.

To measure soil air CO_2 concentration, the two sections of tubing from the gas well were attached to the IRGA, which circulates the air from the gas well through the IRGA and back into the gas well. This created a closed loop and minimized pressure changes during sampling. The gas wells were installed during the summer of 2004 to allow the soil to equilibrate before the initiation of data collection in October, 2004. To measure soil CO_2 concentrations from the gas wells while snow was present, 1 m tubing extenders were attached to a 2 m post at each nest location prior to snowfall. Soil air CO_2 concentrations were also measured (GMT221 CO_2 probe with transmitter, accurate to within 1.5% of calibrated range (0 to 50,000 ppm) plus 2% of reading; Vaisala, Finland) every 20-30 minutes at the 20 cm depth at the real-time data station located in the riparian zone on the east side of T1.

Surface CO_2 Efflux Measurements. A surface CO_2 efflux plot was located at each nest location. These plots consisted of a 0.5 m^2 area that was roped off to minimize soil trampling, which could impact soil diffusional properties. Three surface CO_2 efflux measurements were collected from each plot on all sampling days using a soil respiration chamber in conjunction with an IRGA (SRC-1 chamber, accurate to within 1% of calibrated range (0 to 9.99 g CO_2 m^{-2} hr^{-1}) and EGM-4 IRGA, accurate to within 1% of calibrated range (0 to 2,000 ppm); PP Systems, Massachusetts, USA). The air within the

chamber is gently mixed with an internal fan to ensure representative sampling and is vented to minimize pressure differences between the chamber and the ambient atmosphere. The efflux chamber was 15 cm high and 10 cm in diameter with a measurement surface area of 314.2 cm^2 and chamber volume of 1178 cm^3.

Prior to placing the chamber on the soil, all vegetation within the efflux plot was clipped and removed to minimize the effect of photosynthesis on CO_2 concentrations inside the chamber. It is likely that plants adjacent to the efflux plot had roots that extended into the plot, so the chamber measurement was still a measure of autotrophic and heterotrophic respiration. Care was taken to place the chamber on flat ground, as sloped surfaces can introduce error in chamber measurements of soil surface CO_2 efflux (Hanson et al., 1993). Prior to each measurement, the chamber was flushed with ambient air for 15 seconds. The chamber was inserted 3 cm into the soil to ensure a good seal between the chamber and the ground surface. The CO_2 concentration was measured every 8 seconds, and the sampling period lasted for 120 s, or until the CO_2 concentration inside the chamber increased by 60 ppm. The rate of CO_2 increase inside the chamber should be linear over time, although exchange with the outside air will cause it to decrease. The measurement was automatically stopped if the relationship became excessively nonlinear. To determine the CO_2 efflux during the measurement, a quadratic equation was fitted to the relationship between the increasing CO_2 concentration and elapsed time.

To collect efflux measurements from the snowpack, a "snowshoe" was constructed of fine metal screen attached to a 0.5 m^2 PVC frame (2.5 cm inside diameter).

A hole was cut into the screen to allow the base of the chamber to be inserted into the snowpack. The chamber was modified to extend its length by attaching a 5 cm wide metal ring to its base to ensure a good seal with the snowpack. In a study of snow CO_2 efflux in Idaho, McDowell et al. (2000) found that the "snowshoe" method was most appropriate as it caused minimal disturbance to the snowpack.

Soil Carbon and Nitrogen Concentrations

Soil samples (20 and 50 cm) were collected with an auger (3 inch diameter) from July 26-30, 2005 from all nest locations along each transect. In the laboratory, samples were sieved (60-mesh screen) and ground into a fine powder using a mortar and pestle. Each sample was then weighed and analyzed for total C and N concentrations using a C and N determinator (LECO TruSpec CN, Leco Corporation, St. Joseph, Michigan, USA). The LECO uses a total combustion method with the furnace set to 950ºC. All C and N in a soil sample was converted to CO_2 and N_2 for measurement by an infra-red detector for CO_2 gas and a thermal conductivity cell for N_2 gas.

Hydrologic Measurements

Nested piezometers open only at completion depths (shallow: 0.5-1 m; deep: 1-2 m) were installed in Stringer Creek as well as within 2 m of Stringer Creek in both the east and west riparian zones along each transect. Groundwater wells screened from the completion depth (0.5-2 m) to within 0.2 m of the ground surface were installed at all east and west riparian zone nests as well as on all hillslopes just upslope of the riparian-hillslope transition (Figure 2.3). Two flumes are located in Stringer Creek, one at the basin outlet (1.22 m H-flume), the other just downstream of T4 (1.07 m H-flume) (Figure

2.3). Groundwater levels in all wells and piezometers as well as stream stage in stilling wells were recorded every 30 min or less using capacitance rods (+/- 1 mm resolution, Trutrack, New Zealand).

Statistical Analyses

Statistical analyses were performed using SPSS (version 14, SPSS Inc., Chicago, USA) with $\alpha = 0.10$. Analysis of variance (ANOVA) was applied to soil C and N concentrations and C:N ratios. Repeated measures ANOVA was applied to soil CO_2 concentrations, surface CO_2 efflux, soil temperature, and SWC data, as these parameters were collected multiple times. The repeated measures ANOVA was applied to data from June through October, 2005 because data was collected from all 4 transects during only this time period. The data was also analyzed to include more months but fewer transects, but similar results were obtained, so only the 4-transect analysis is reported. All data was averaged by month. For statistical comparisons between riparian and hillslope zones, riparian and hillslope nests were averaged across all four transects; to make statistical comparisons between transects, all nest locations were averaged within each transect. Inclusion of wet areas along relatively dry transects or areas of dense vegetation along transects with a high degree of barren ground must be considered when interpreting statistical results.

Results

Soil CO_2 Concentrations

Spatial Variability. There were significant differences in soil CO_2 concentrations between riparian and hillslope landscape positions as well as by transect (Table 1). At the 20 cm depth, there were significant differences in soil air CO_2 concentrations between riparian and hillslope landscape positions, (averaging 9450 ppm and 3643 ppm across all four transects from June through October, 2005; $p = 0.081$), but not by transect. At the 50 cm depth, there were significant differences in soil air CO_2 concentrations by transect (p-value of 0.074), but not by riparian versus hillslope position (averaging 2757 ppm and 3652 ppm across all four transects during the same period).

Figures 2.4 and 2.5 show bivariate plots of soil temperature and soil CO_2 concentrations at 20 and 50 cm at all riparian and hillslope nests along each transect collected from October, 2004 to November, 2005. The majority of hillslope gas wells (20 and 50 cm) remained below 5000 ppm over the period of measurement (although up to 12,275 ppm at T1W4-50). Many riparian locations exceeded concentrations of 20,000 ppm, with those in wetter landscape positions along T1 and T2 exceeding concentrations of 30,000 ppm (and as high as 54,209 ppm at T1W2-20). Higher riparian zone soil CO_2 concentrations are evident in Figures 2.6F and 2.7F, which show data collected from October 15, 2004 to November 15, 2005 along T1. Figures 2.8 and 2.9 expand the x-axis from Figures 2.6 and 2.7 to include just June 12, 2005 to October 5, 2005. Note the differences in scale on the y-axis (CO_2 concentration) between these figures. Figure 2.10 shows cross-sections of soil CO_2 concentrations and surface efflux at nest locations along

Table 1. Repeated Measures Analysis of Variance Statistics for Soil CO_2 Concentrations (20 and 50 cm), Surface CO_2 Efflux, Soil Temperature, and Soil Water Content. Position refers to riparian vs. hillslope position.

	df	mean-sq	F	p-value
CO_2 - 20 cm				
Transect	3	67467984.200	0.454	0.729
Error	4	148553434.350		
Position	1	337328640.000	4.407	0.081
Error	6	76548175.000		
CO_2 - 50 cm				
Transect	3	5984902.825	5.113	0.074
Error	4	1170502.575		
Position	1	806276.025	0.222	0.654
Error	6	3638407.125		
Efflux				
Transect	3	0.015	0.624	0.636
Error	4	0.024		
Position	1	0.033	1.853	0.222
Error	6	0.018		
Soil Temperature				
Transect	3	0.313	0.269	0.846
Error	4	1.165		
Position	1	0.462	0.540	0.490
Error	6	0.856		
Soil H_2O Content				
Transect	3	833.562	15.196	0.864
Error	4	3468.107		
Position	1	13619.790	29.680	0.002
Error	6	458.887		

T1 at eight "snapshots-in-time". These profiles show differences between riparian and hillslope zone soil CO_2 concentrations (denoted by white (20 cm) and black (50 cm) circles). The largest concentrations were in the riparian zones on nearly all dates shown. Figures 2.11A and 2.11B show boxplots of soil CO_2 concentrations, with both higher and wider ranges of CO_2 concentrations in the riparian zones.

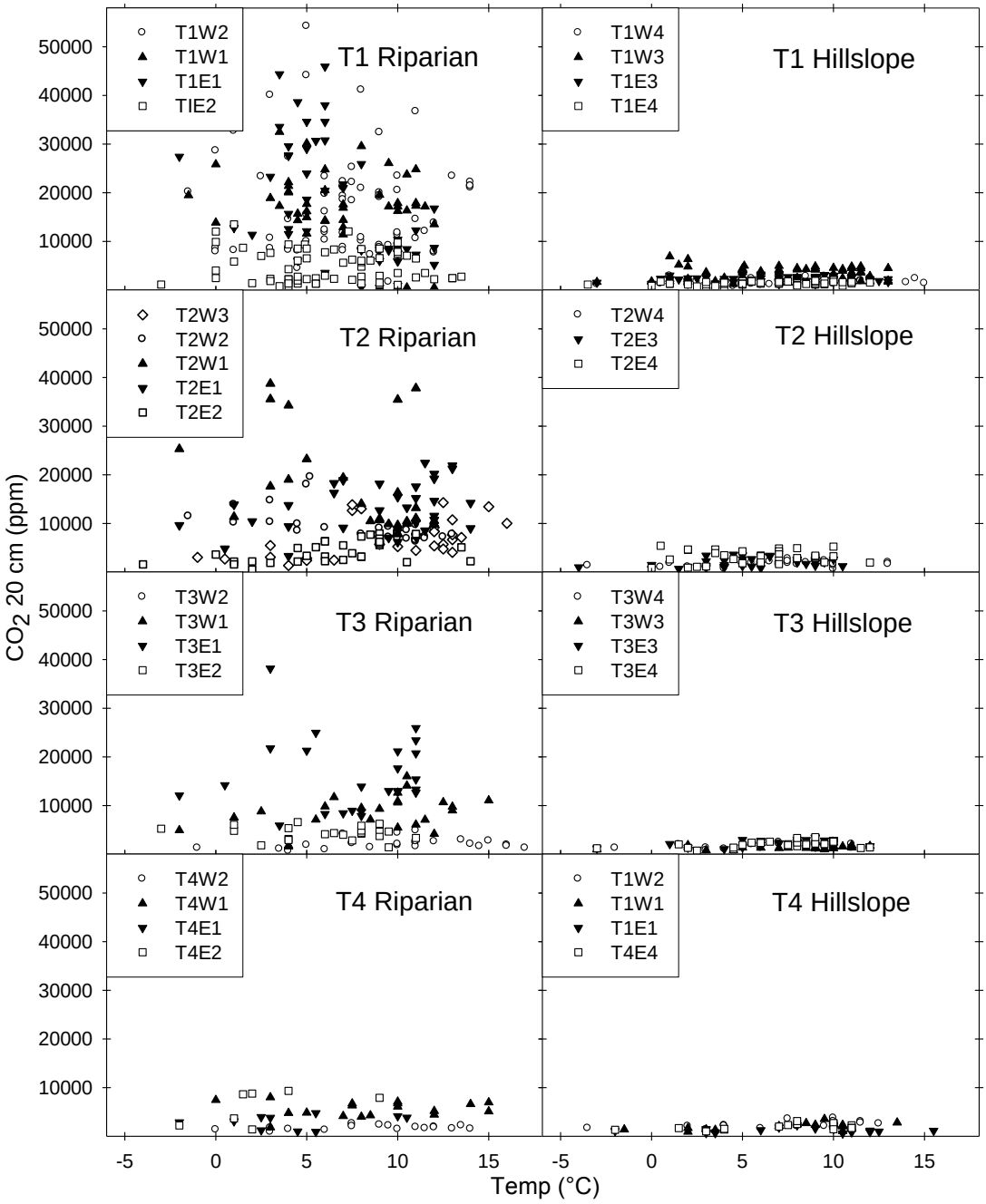


Figure 2.4: Bivariate plots of soil temperature and soil CO_2 concentration at 20 cm at riparian and hillslope zones along each transect, collected from October, 2004 to November, 2005. Filled symbols denote landscape positions closer to Stringer Creek for both riparian and hillslope zones.

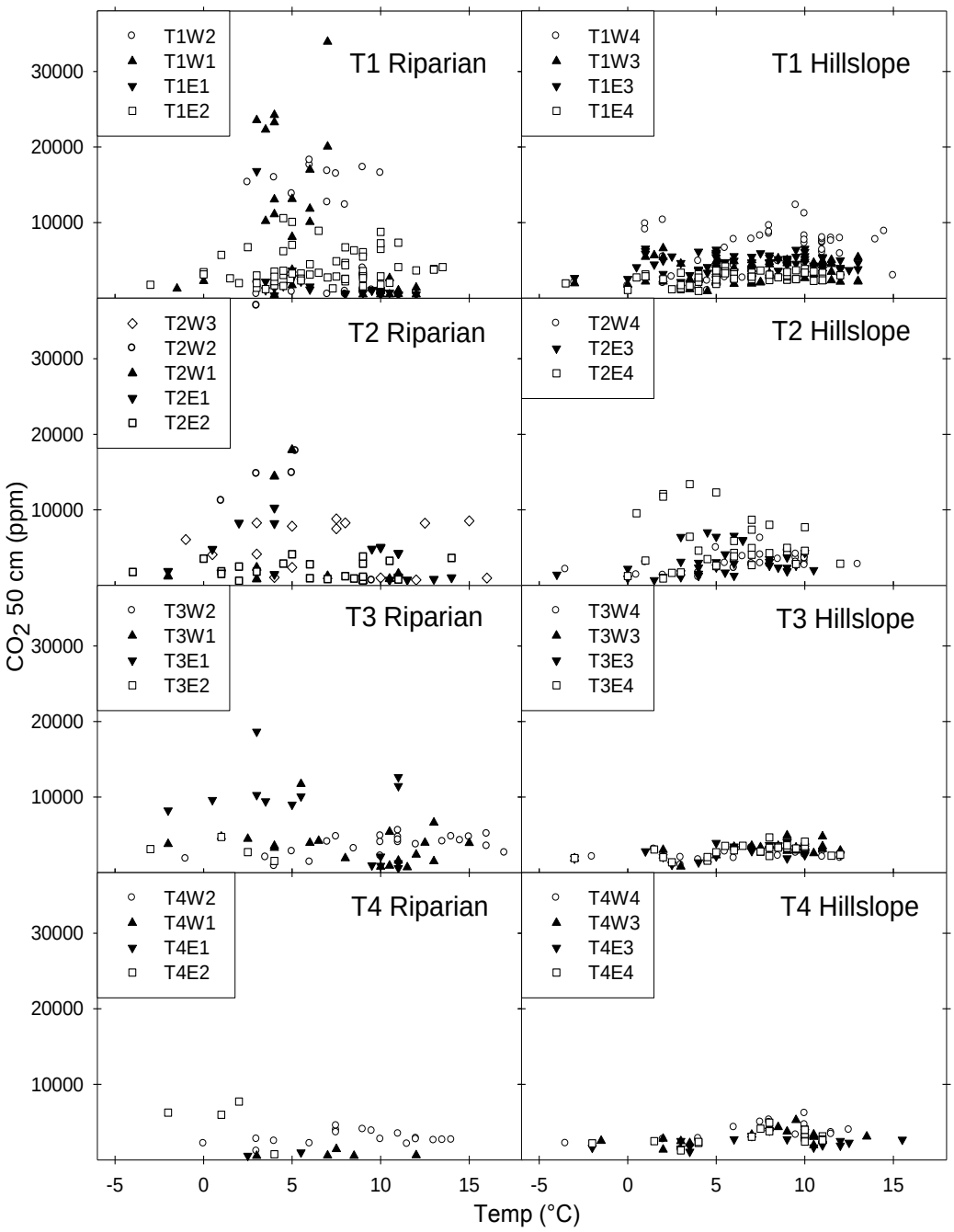


Figure 2.5: Bivariate plots of soil temperature and soil CO_2 concentration at 50 cm at riparian and hillslope zones along each transect, collected from October, 2004 to November, 2005. Filled symbols denote landscape positions closer to Stringer Creek for both riparian and hillslope zones.

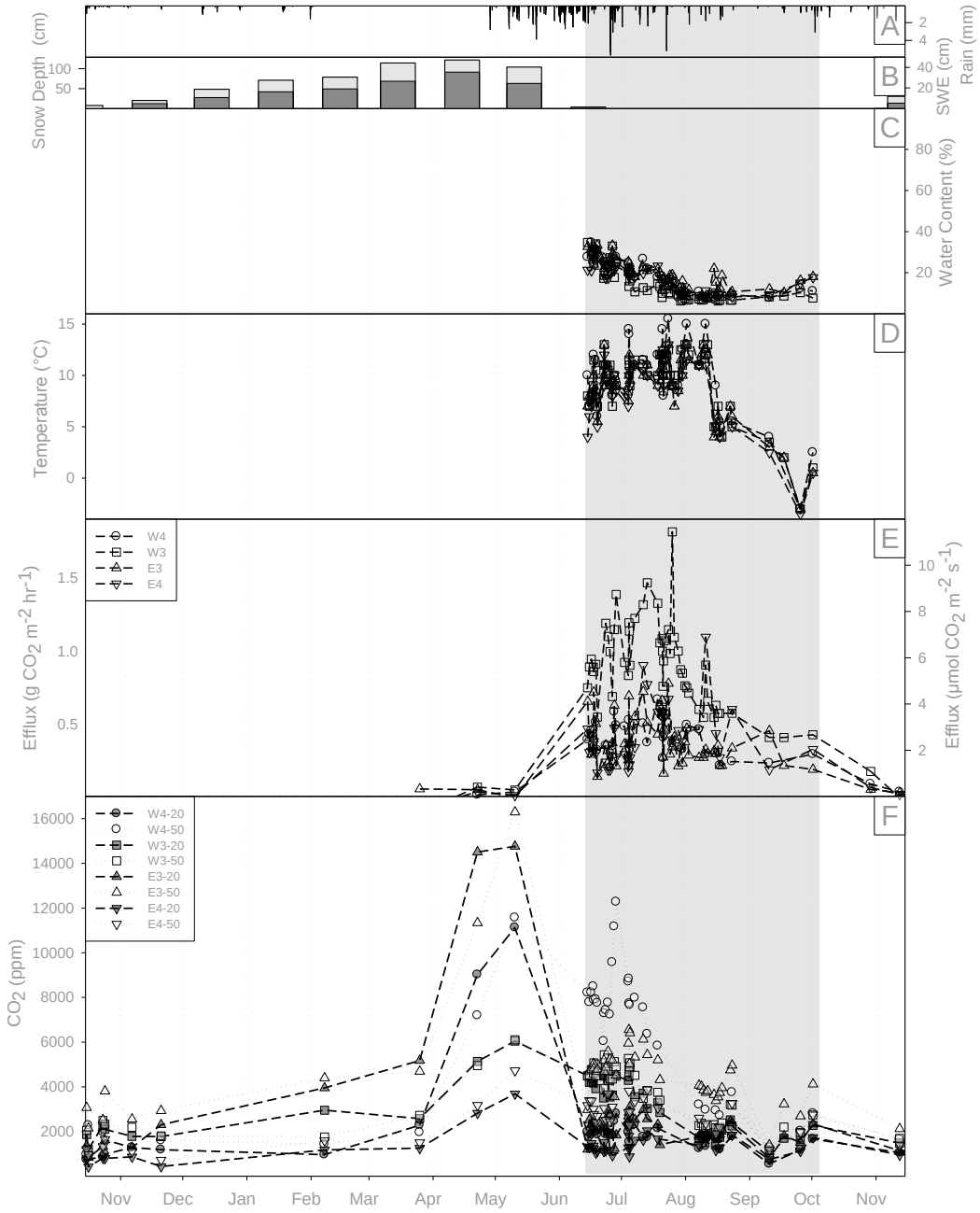


Figure 2.6: Riparian measurements along Transect 1 from October 15, 2004 to November 15, 2005 of (A) rain; (B) snow depth (grey) and snow water equivalent (SWE – black); (C) volumetric SWC; (D) soil temperature; (E) soil surface CO_2 efflux; and (F) soil CO_2 concentrations (20 cm = black symbols, 50 cm = white symbols). Soil temperature and SWC were not measured during the winter, and efflux measurements did not begin until the end of April. Shaded area is expanded upon in Figure 2.8.

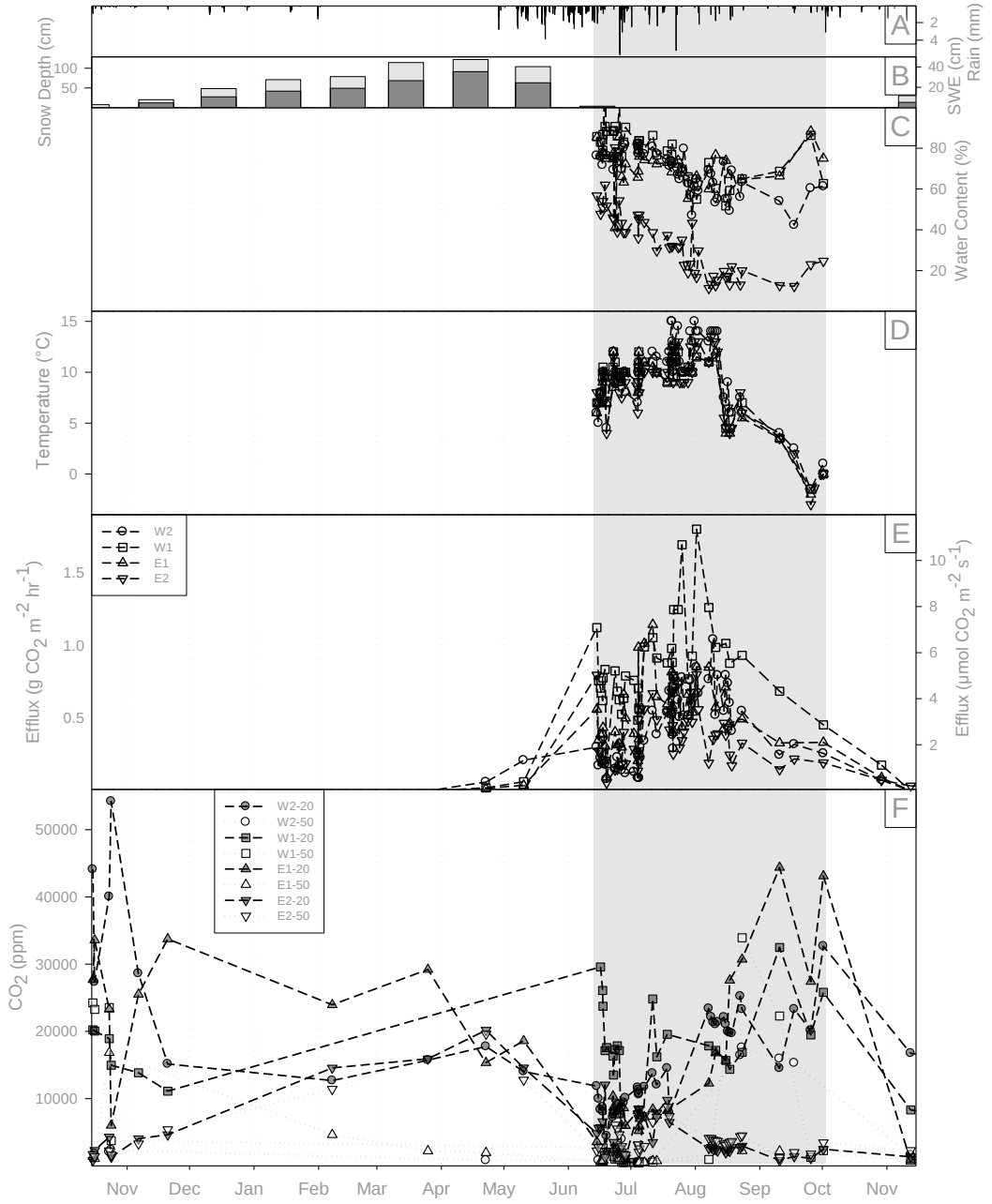


Figure 2.7: Hillslope measurements along Transect 1 from October 15, 2004 to November 15, 2005 of (A) rain; (B) snow depth (grey) and snow water equivalent (SWE – black); (C) volumetric SWC; (D) soil temperature; (E) soil surface CO_2 efflux; and (F) soil CO_2 concentrations (20 cm = black symbols, 50 cm = white symbols). Soil temperature and SWC were not measured during the winter, and efflux measurements did not begin until the end of April. Shaded area is expanded upon in Figure 2.9.

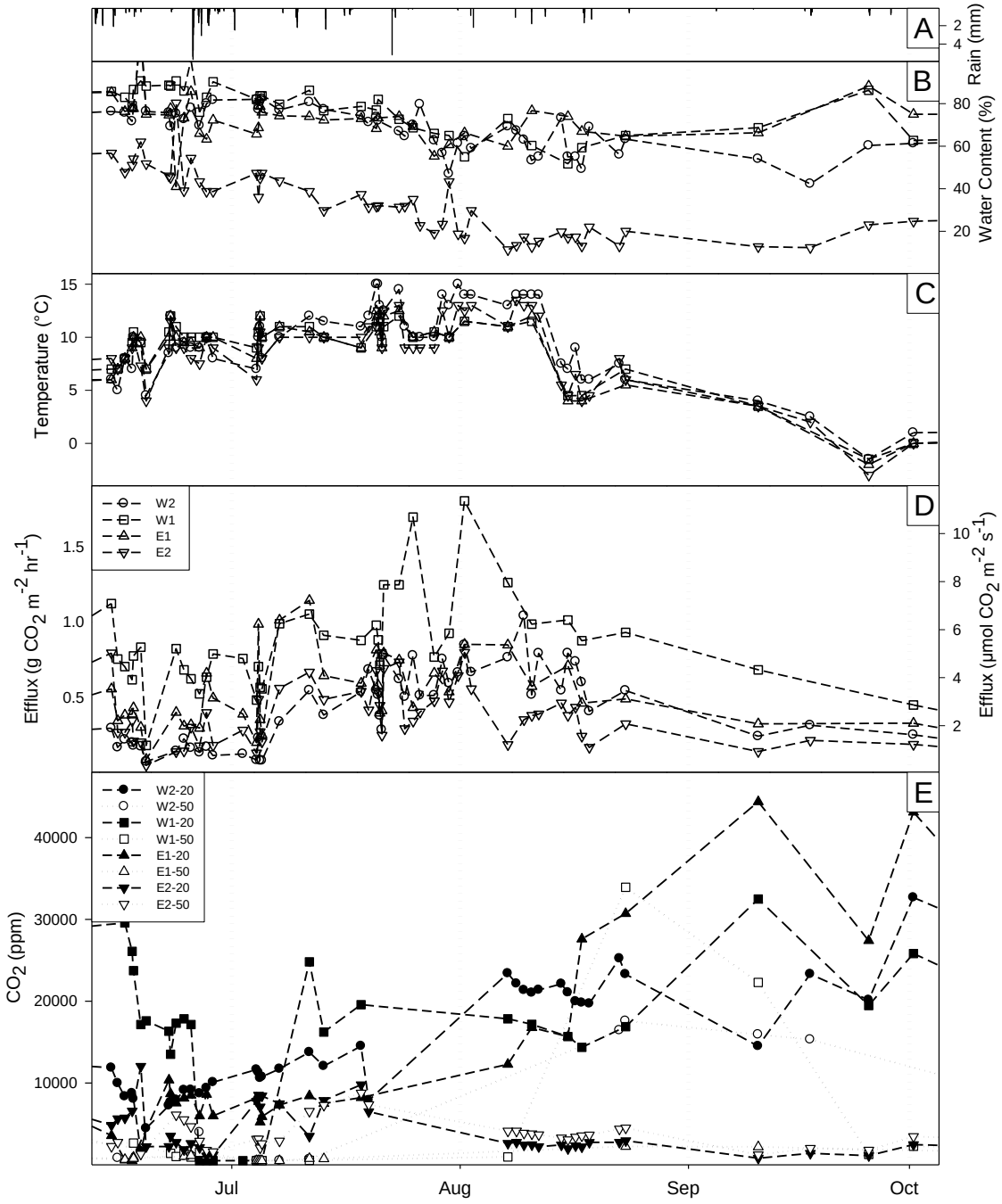


Figure 2.8: Riparian measurements along Transect 1 from June 6, 2005 to October 5, 2005 of (A) rain; (B) volumetric SWC; (C) soil temperature; (D) soil surface CO_2 efflux; and (E) soil CO_2 concentrations (20 cm = black symbols, 50 cm = white symbols).

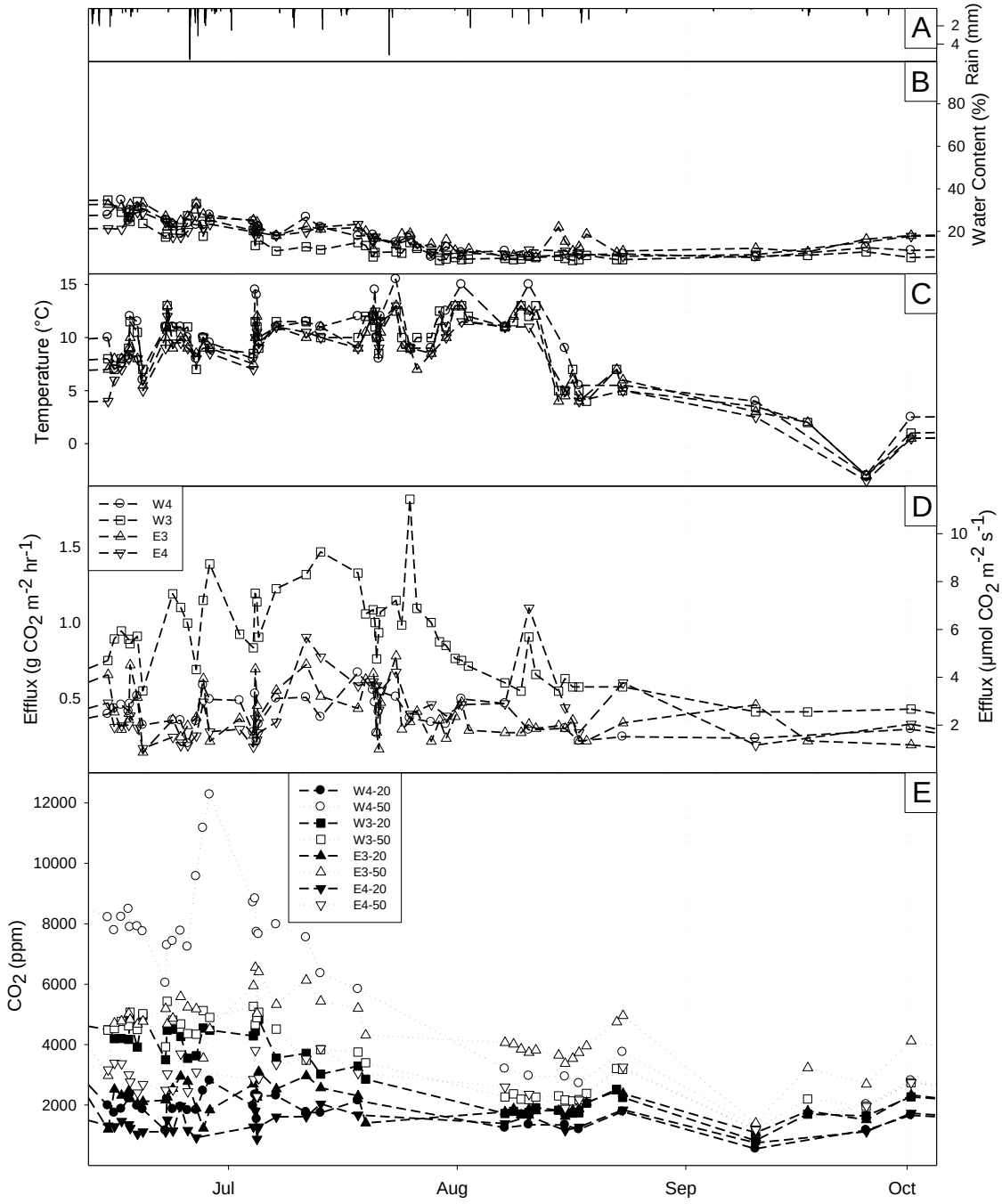


Figure 2.9: Hillslope measurements along Transect 1 from June 12, 2005 to October 5, 2005 of (A) rain; (B) volumetric SWC; (C) soil temperature; (D) soil surface CO_2 efflux; and (E) soil CO_2 concentrations (20 cm = black symbols, 50 cm = white symbols).

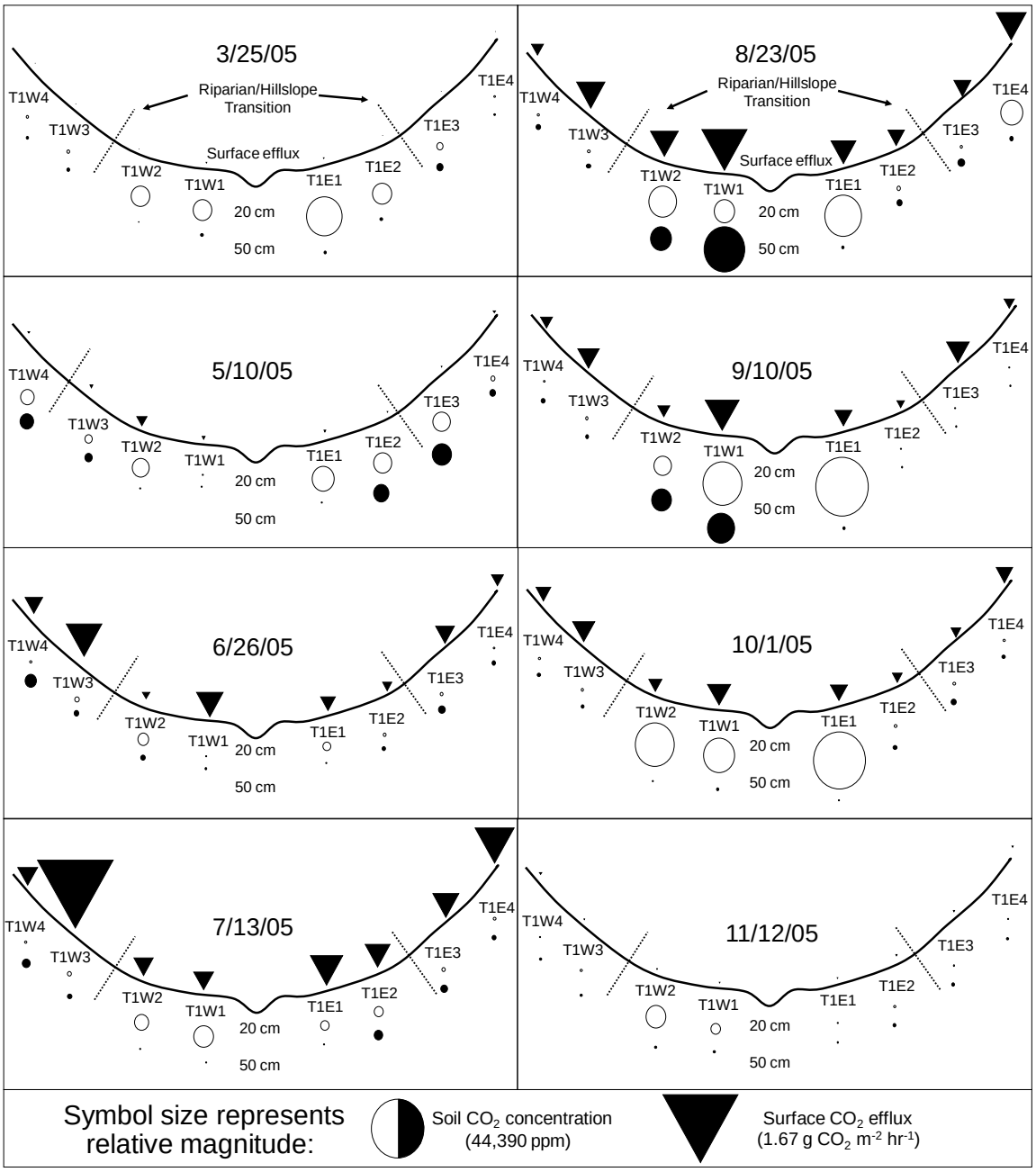


Figure 2.10: Cross-section diagrams of soil CO_2 concentrations at 20 cm (white circles) and 50 cm (black circles), and surface CO_2 efflux (triangles) at all nest locations along Transect 1 at eight points in time. Note that symbol size represents relative magnitude. A circle half the size of the largest circle in the diagram represents a soil CO_2 concentration of ~22,000 ppm; a triangle half the size of the largest triangle represents a surface CO_2 efflux value of ~ 0.85 g CO_2 m^{-2} hr^{-1}.

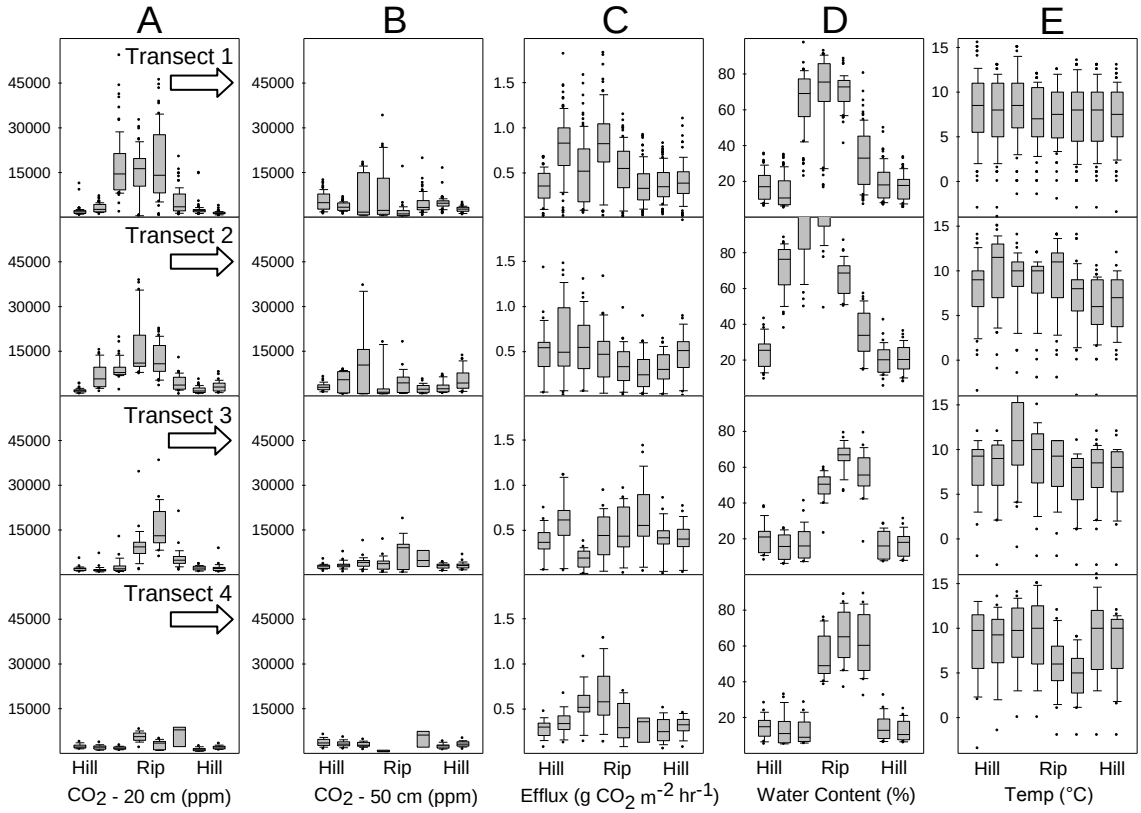


Figure 2.11: Box-plots of (A) soil CO_2 concentration – 20 cm; (B) soil CO_2 concentration – 50 cm; (C) surface CO_2 efflux; (D) soil water content; and (E) soil temperature across all four transects from October, 2004 to November, 2005.

Soil CO_2 concentrations decreased both in magnitude and variability at 20 and 50 cm (Figures 2.4 and 2.5) from T1 (upstream) to T4 (downstream). These decreases occurred in both riparian and hillslope nest locations. The downstream decrease of both soil CO_2 concentration magnitude and variability was much more pronounced in the riparian zones, especially at the 20 cm depth. Note that these are peak values and may not reflect the characteristic range of soil CO_2 concentrations shown in Figures 2.4 and 2.5. The downstream decrease of soil CO_2 concentrations is also shown in Figures 2.11A and 2.11B.

In general, there were also differences in soil CO_2 concentrations between the 20 and 50 cm depths within the riparian zones along each transect (Figure 2.6). Higher concentrations were measured at 20 versus 50 cm (averaging 9451 ppm and 3368 ppm from June through October, 2005 across all transects). Conversely, hillslope locations did not show significant differences by depth (Figure 2.7), with 20 and 50 cm concentrations averaging 3643 ppm and 3651 ppm during the same period across all transects. The differences between soil CO_2 concentrations with depth in the riparian zones, but not the hillslope zones, is evident when comparing Figures 2.4 and 2.5 (note the difference in scale), as well as Figures 2.6 and 2.7 (note the difference in scale).

Seasonal Variability. There was a high degree of seasonal variability in soil CO_2 concentrations in both riparian and hillslope landscape positions (Figures 2.6F and 2.7F), with peaks occurring during both winter and summer. There were differences between riparian and hillslope zones in both the timing and magnitude of maximum soil CO_2 concentrations. Hillslope nests showed similarity in both the timing and magnitude of peak soil CO_2 concentrations (Figure 2.7F). Hillslope soil CO_2 concentrations were low during the fall of 2004 (generally between 600 and 2,200 ppm) and gradually increased over the winter. Large peaks occurred near the middle of May, 2005 (approximate time of peak snowmelt), which were the largest values measured at the hillslope nests over the period of measurement (up to 16,295 ppm at TIE3-50 on May 10, 2005).

The majority of riparian zone nests had relatively low soil CO_2 concentrations during the fall of 2004, with the exception being nests in the wettest landscape positions. At these nests, concentrations remained high throughout the fall (up to 54,209 ppm at

T1W2-20 on October 24, 2004), with most decreasing by the beginning of November, 2004. Soil CO_2 concentrations gradually increased over the winter at most riparian nests (Figure 2.7F), with the majority having a winter peak just below 20,000 ppm at the end of April, nearly a month earlier than the adjacent hillslopes. The exception to this was T1E1-20, which peaked at 29,210 ppm on March 25, 2005.

There were also temporal differences in summer/fall peaks in soil CO_2 concentrations between the riparian and hillslope nests along T1 (Figures 2.8E and 2.9E). The hillslope nests all peaked near the end of June or beginning of July, 2005 at both the 20 and 50 cm gas wells, with peaks ranging from 2000-5000 ppm. The exceptions to this were T1W4-50, which peaked at 12,275 ppm on June 28, 2005, and T1E3-50, which peaked at 6653 ppm on July 4, 2005. On the other hand, riparian nests along T1 exhibited staggered peaks in soil CO_2 concentrations (up to 44,390 ppm at T1E1-20 on September 10, 2005) between the end of July and the beginning of October, with those nests closest to Stringer Creek or in wetter landscape positions peaking up to three months later than those riparian nests near the riparian-hillslope transition.

Diurnal Variability. Soil CO_2 concentrations showed a high degree of diurnal variability at 20 and 50 cm in both riparian and hillslope zones along T1 on July 4, 2005 (Figures 2.12D and 2.13D, respectively). Note that in Figure 2.12D, data is not shown from four gas wells (T1W2-50, T1W1-20, T1W2-20, and T1E1-50) as they were located beneath the water table and could not be measured. Soil CO_2 concentrations at 20 and 50 cm at both riparian and hillslope positions were relatively high at 0700 h, changed minimally (slight increase or decrease) by 1500 h, then decreased by 2100 h. By 0300 h,

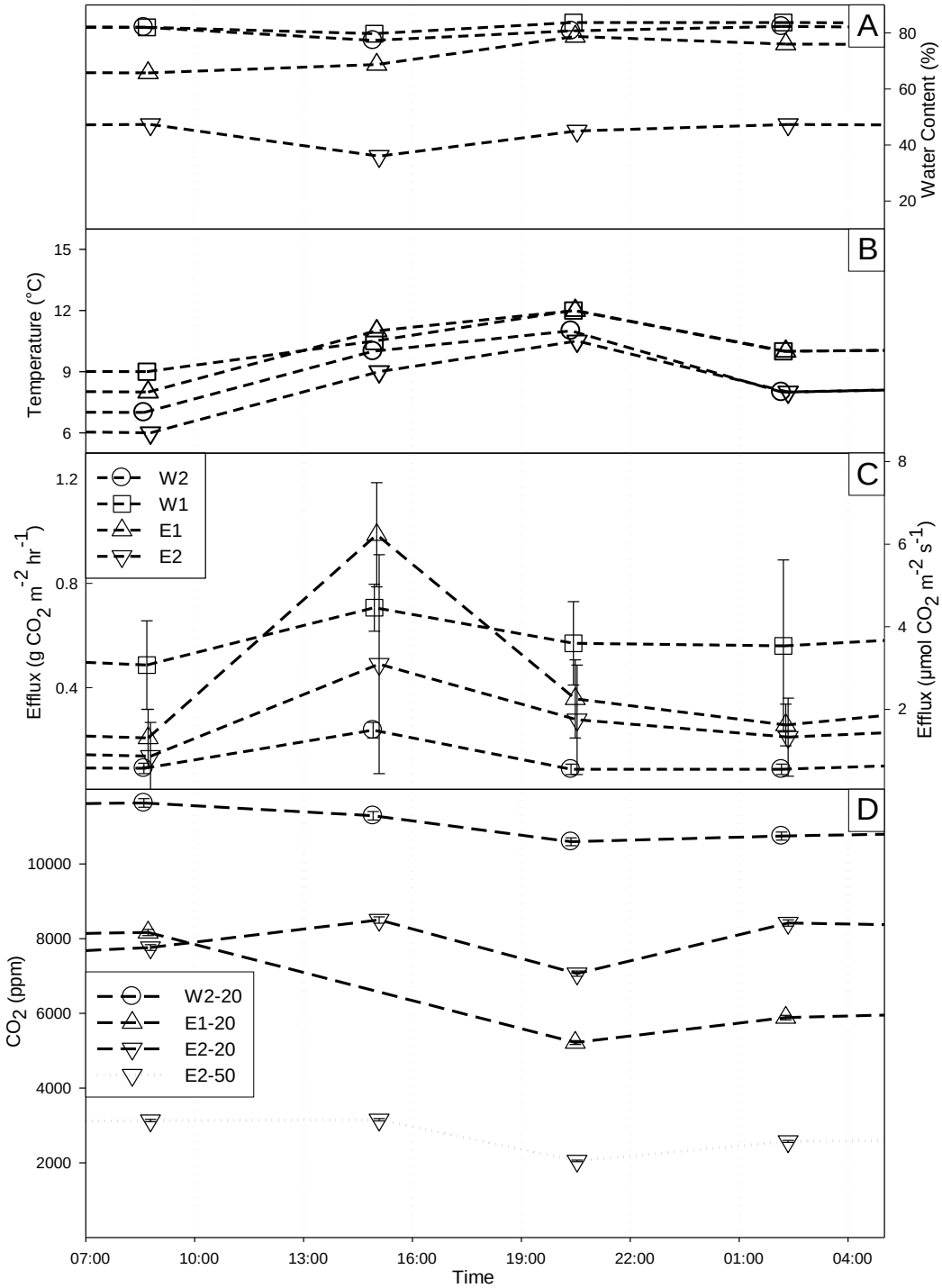


Figure 2.12: 24 hour data from riparian nest locations along Transect 1, beginning at 0900 on July 4, 2005, with measurements collected every 6 hours (0900, 1500, 2100, 0300). Graphs show (A) volumetric SWC; (B) soil temperature; (C) surface CO_2 efflux with error bars representing standard deviation from 3 flux measurements; and (D) soil CO_2 concentrations at 20 cm (dashed line) and 50 cm (dotted line) with error bars representing 1% measurement error.

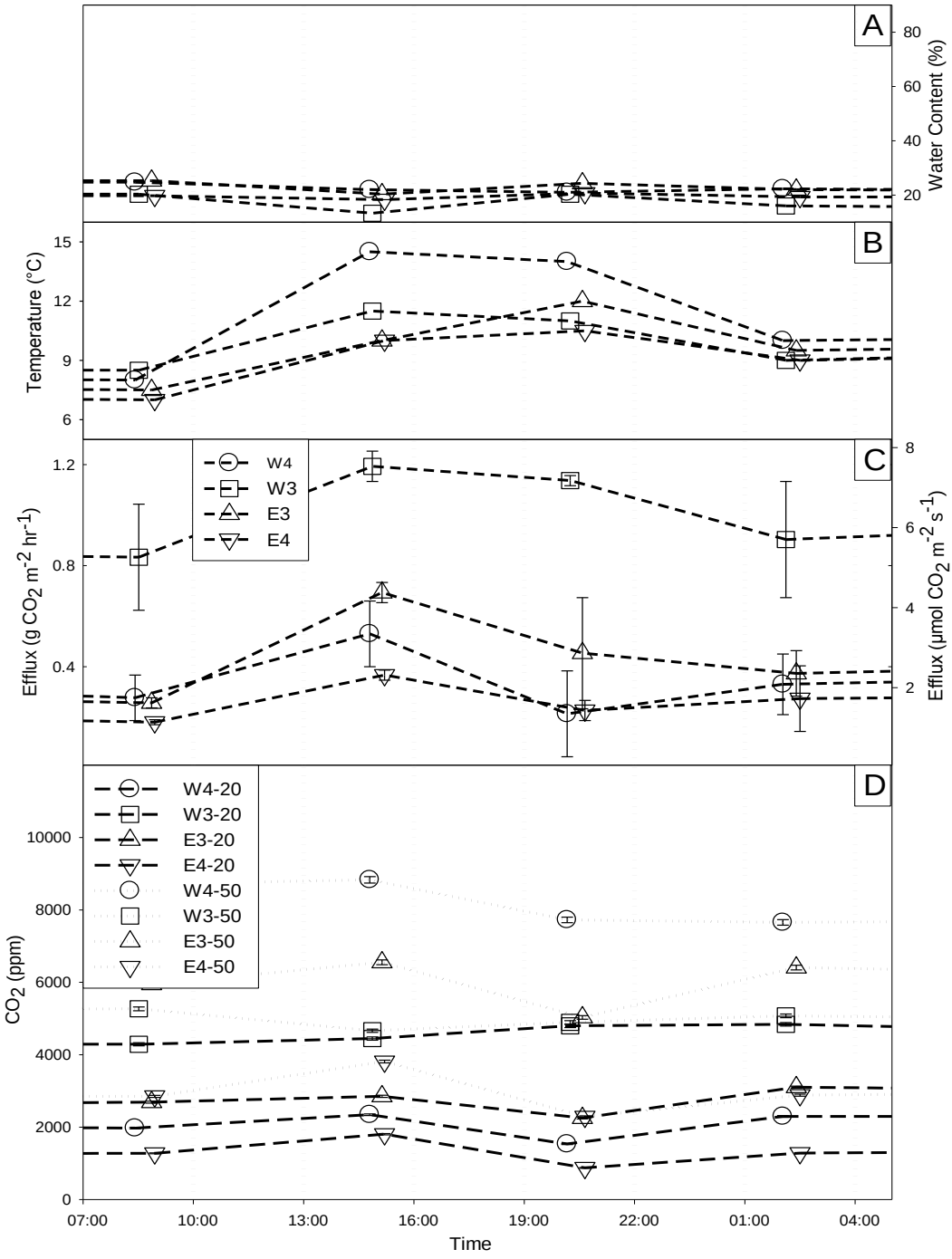


Figure 2.13: 24 hour data from hillslope nest locations along Transect 1, beginning at 0900 on July 4, 2005, with measurements collected every 6 hours (0900, 1500, 2100, 0300). Graphs show (A) volumetric SWC; (B) soil temperature; (C) surface CO_2 efflux with error bars representing standard deviation from 3 flux measurements; and (D) soil CO_2 concentrations at 20 cm (black symbols) and 50 cm (white symbols) with error bars representing 1% measurement error.

concentrations rose in most gas wells to a level near that measured at 1500 h. The average diurnal variation of soil CO_2 concentrations across T1 was 1322 ppm (27.5%) at 20 cm and 1154 ppm (28.5%) at 50 cm. A second diurnal data collection run began on July 20, 2005, which showed similar results to those shown in Figures 2.12D and 2.13D.

Surface CO_2 Efflux

Spatial Variability. Soil surface CO_2 efflux was not significantly different by transect or riparian versus hillslope landscape position (Table 1). Figure 2.14 shows bivariate plots of surface CO_2 efflux and SWC in both riparian and hillslope nests along each transect collected from October, 2004 to November, 2005. Soil surface CO_2 efflux was slightly greater and more variable in the riparian zones than the hillslope zones, but in general showed greater similarity than riparian and hillslope zone soil CO_2 concentrations. This is also apparent when comparing Figures 2.6E and 2.7E. Figure 2.10 shows similar surface CO_2 efflux across riparian and hillslope landscape positions. Notice the comparable symbol sizes of riparian and hillslope surface CO_2 efflux (triangles) on the same date, relative to riparian and hillslope soil CO_2 concentrations (circles) at both 20 and 50 cm. Figure 2.11C shows similar surface CO_2 efflux across riparian and hillslope zones as well as transects.

While surface CO_2 efflux was similar between riparian and hillslope zones within each transect (relative to soil CO_2 concentrations, Figures 2.4 and 2.5), Figure 2.14 suggests small differences between transects. Upstream transects generally had higher soil surface CO_2 efflux than downstream transects, with average values from June

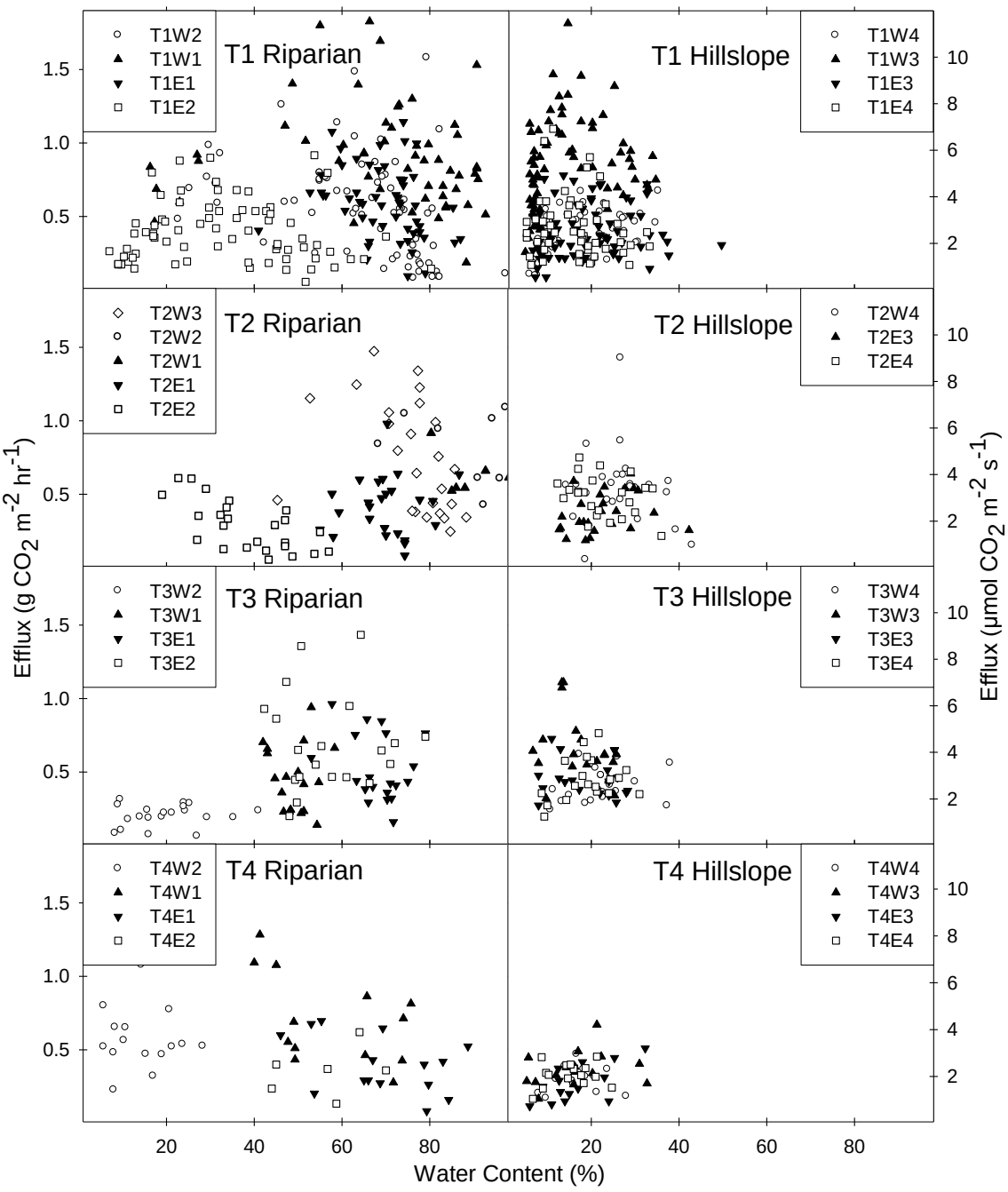


Figure 2.14: Bivariate plots of volumetric SWC and surface CO_2 efflux in riparian and hillslope zones along each transect, collected from October, 2004 to November, 2005. Filled symbols denote landscape positions closer to Stringer Creek for both riparian and hillslope zones.

through October, 2005 of 0.50 g CO_2 m^{-2} hr^{-1} across T1 and T2, and 0.35 g CO_2 m^{-2} hr^{-1} across T3 and T4.

Seasonal Variability. Soil surface CO_2 efflux showed a high degree of seasonal variability in both riparian and hillslope zones along T1 (Figures 2.6E and 2.7E). Note that surface CO_2 efflux data collection did not begin until the end of April, 2005 due to equipment malfunction. During late spring, there was snow accumulation of up to 120 cm (Figures 2.6B and 2.7B), and surface CO_2 efflux was relatively low, << 0.1 g CO_2 m^{-2} hr^{-1} at nearly all nest locations. By the middle of June, the majority of the ground surface was snow-free, and surface CO_2 efflux rose nearly an order of magnitude from spring (with an average of ~ 0.5 g CO_2 m^{-2} hr^{-1} across T1) in both riparian and hillslope landscape positions (Figures 2.6E, 2.7E, 2.8D, and 2.9D). Values remained high until the middle of August, then gradually began to decrease. During September and October, surface CO_2 efflux continued to decrease (with an average of ~ 0.25 g CO_2 m^{-2} hr^{-1} across T1), but remained higher than those values observed during the spring when there was a deep snowpack. By the middle of November, 2005, surface CO_2 efflux decreased to similar values observed during the previous spring.

Diurnal Variability. Soil surface CO_2 efflux also showed a high degree of diurnal variability in both riparian and hillslope zones (Figures 2.12C and 2.13C). Surface CO_2 efflux was relatively low at 0700 h, peaked at 1500 h, decreased by 2100 h, and remained low at 0300 h. The average diurnal variation of soil surface CO_2 efflux across T1 was 0.35 g CO_2 m^{-2} hr^{-1} (50.5%). A separate diurnal data collection run began on July 20, 2005, which showed similar results as those displayed in Figures 2.12C and 2.13C.

Soil Temperature

Spatial Variability. Soil temperature (12 cm) was not significantly different by transect or riparian versus hillslope landscape position (Table 1, Figures 2.6D and 2.7D, 2.4 and 2.5, and 2.11E), and ranged from -0.4°C to 16 °C. Note that soil temperature measurements did not begin until the middle of June, 2005 due to deep snow accumulation. Average soil temperatures at riparian and hillslope nests along all four transects from June through October, 2005 were 5.9°C and 5.7°C, respectively.

Seasonal Variability. Soil temperature (12 cm) showed considerable seasonal variability in both riparian and hillslope zones along Transect 1 (Figures 2.6D and 2.7D). Near the middle of June, when soil temperature measurements began, soil temperatures were 4 to 10°C along T1, with the lowest soil temperatures under or near patches of snow in the hillslopes. Soil temperatures increased over the summer by ~10°C by the beginning of August at most nest locations. A sharp decrease (~8°C) occurred near the middle of August. Soil temperatures at all nest locations along T1 decreased from ~12°C to ~4°C, which coincided with cool weather and periodic snow. Soil temperatures then rose slightly (~2°C) at the end of August, but decreased to below freezing by the end of September (averaging -3°C). Soil temperatures then increased in October to just above freezing, coinciding with the beginning of snow accumulation.

Diurnal Variability. Soil temperature (12 cm) showed a high degree of diurnal variability in both riparian and hillslope zones (Figures 2.12B and 2.13B). Soil temperatures were lowest at 0700 h, and rose significantly by 1500 h. Soil temperatures

continued to rise by 2100 h, and by 0300 h, soil temperatures decreased below those temperatures observed at 1500 h, but above those observed at 0700 h the previous morning. The average diurnal variation of soil temperature across T1 was 4.25°C (35%). A separate diurnal data collection run began on July 20, 2005, which produced similar results as those displayed in Figures 2.12B and 2.13B.

Soil Water Content

Spatial Variability. Differences in SWC (integrated over top 20 cm) were significant by riparian versus hillslope landscape position ($p = 0.002$), but not by transect (Table 1). Figures 2.6C, 2.7C, 2.8C, 2.9C, 2.11D, and 2.14 show higher SWC in the riparian versus hillslope zones, averaging 54.8% and 17.8% across all four transects from June through October, 2005. SWC was not measured until the middle of June, 2005 due to significant snow accumulation. Figures 2.11D and 2.14 show a downstream decrease in both the magnitude and variability of SWC, with an average SWC of 43.1% along T1 and T2 from June through October, 2005, as compared to 29.5% along T3 and T4 during the same period. The downstream decrease in SWC occurred at both riparian and hillslope nests, but was more pronounced in the riparian zones along each transect (Figure 2.11D). An exception to this was the east riparian zone of T4, in which T4E1 and T4E2 were located near a groundwater seep area. These nests had much higher SWC than other riparian nests along T4 and many nests in upstream transects.

Seasonal Variability. SWC varied considerably from June through November, 2005 along T1 (Figures 2.6C and 2.7C). In the middle of June, 2005, SWC was the

highest measured over the year, reaching saturation at many riparian nest locations, but never going above 40% in the hillslopes. High SWC in June corresponded to the recent peak in snowmelt (middle of May). SWC then decreased over the summer, with the lowest values (5-10%) in August and September at many hillslope nests or drier riparian nests.

Diurnal Variability. SWC showed little diurnal variability in either riparian or hillslope zones (Figures 2.12A and 2.13A). This was corroborated with real-time SWC (20 cm) at T1E2 (unpublished data). A separate diurnal data collection run began on July 20, 2005, which showed similar results as those displayed in Figures 2.12A and 2.13A.

Soil Carbon Concentrations.

Spatial Variability. Differences in soil C concentrations were significant by depth (20 versus 50 cm) and transect ($p = 0.001$ and 0.063), but not by riparian versus hillslope landscape position (Table 2). C concentrations were higher at 20 versus 50 cm, averaging 3.48 and 2.23% across all four transects. This is shown in Figure 2.15, in which the white and black circles represent the relative magnitude of the C concentration at 20 and 50 cm at each nest location, with the largest circle representing a C concentration of 4.78%. Note that the C concentration at four sampling locations were outliers and not included in the relative magnitude calculation as they caused the data to depart significantly from normality. Outliers were present at T2W1-20 (31.57%), T2W1-50 (24.06%), T4W3-20 (7.57%), and T4W4-20 (5.85%).

Table 2. Analysis of Variance Statistics for Soil C and N Concentrations and C:N Ratios. Position refers to riparian vs. hillslope position.

	df	mean-sq	F	p-value
C Concentrations				
Transect	3	2.449	2.599	0.063
Position	1	0.722	0.766	0.386
Depth	1	12.323	13.075	0.001
Tran x Position	3	2.14	2.271	0.092
Tran x Depth	3	2.064	2.19	0.101
Position x Depth	1	0.309	0.328	0.57
Error	48	0.942		
N Concentrations				
Transect	3	0.006	2.358	0.084
Position	1	0.023	8.837	0.005
Depth	1	0.017	6.721	0.013
Tran x Position	3	0.005	1.802	0.16
Tran x Depth	3	0.007	2.822	0.049
Position x Depth	1	0.001	0.499	0.483
Error	47	0.003		
C:N Ratios				
Transect	3	0.054	2.087	0.114
Position	1	0.896	34.473	< 0.001
Depth	1	0.003	0.097	0.757
Tran x Position	3	0.029	1.102	0.357
Tran x Depth	3	0.007	0.283	0.838
Position x Depth	1	0.012	0.452	0.504
Error	49	0.026		

Soil Nitrogen Concentrations.

Spatial Variability. Differences in soil N concentrations were statistically significant by depth (20 vs. 50 cm) and riparian versus hillslope landscape position ($p = 0.013$ and 0.005), but not by transect (Table 2). N concentrations were higher at 20 versus 50 cm, averaging 0.20 and 0.13% as well as at riparian versus hillslope positions,

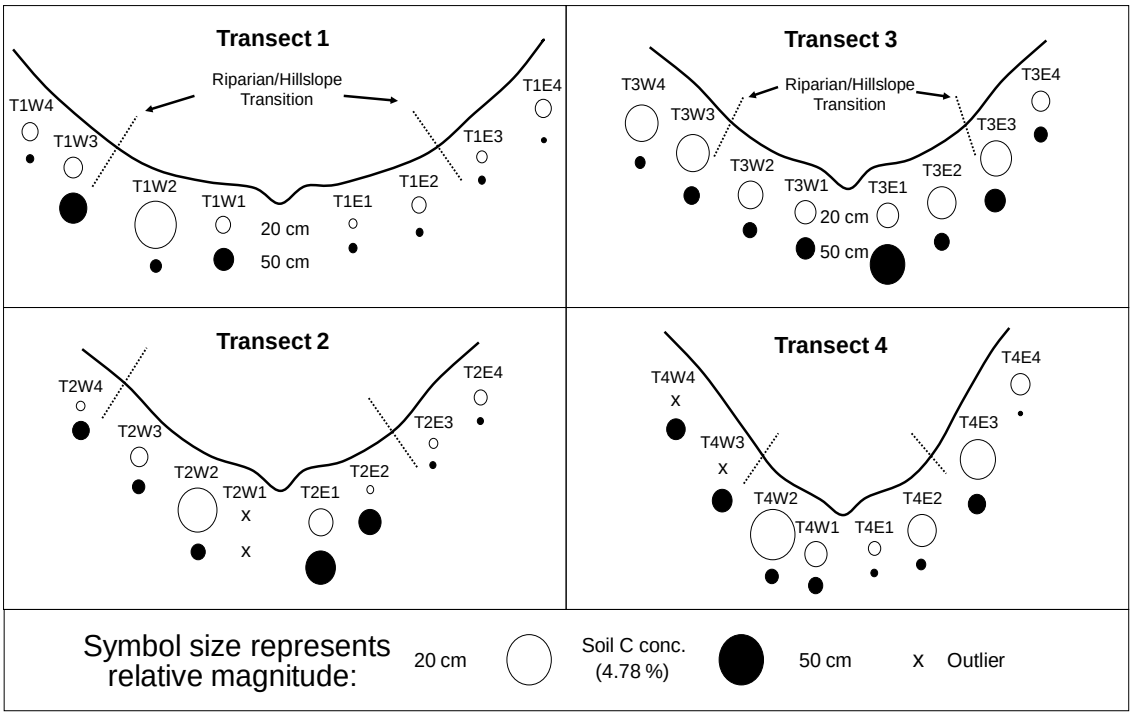


Figure 2.15: Cross-section diagrams of soil C concentrations at 20 (white) and 50 cm (black) at all nest locations along each transect. Note that symbol size represents relative magnitude. A circle half the size of the largest in the diagram represents a concentration of ~ 2.4%.

averaging 0.25 and 0.08% across all four transects. This is shown in Figure 2.16, in which the white and black circles represent the relative magnitude of the N concentration at 20 and 50 cm at each nest location, with the largest circle representing a N concentration of 0.23%. Note that the N concentration at four sampling locations were outliers and not included in the relative magnitude calculation as they caused the data to depart significantly from normality. Outliers were present at T1W2-20 (0.31%), T2W1-20 (2.22%), T2W1-50 (1.54%), and T2W2-20 (0.38%).

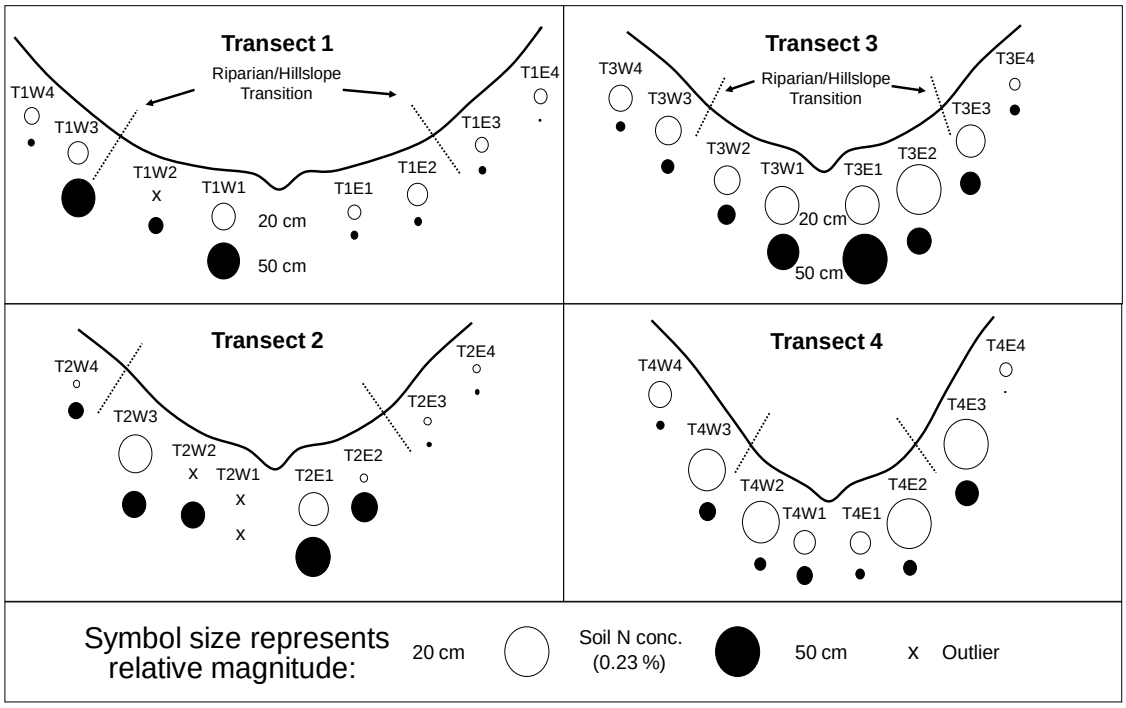


Figure 2.16: Cross-section diagrams of soil N concentrations at 20 (white) and 50 cm (black) at all nest locations along each transect. Note that symbol size represents relative magnitude. A circle half the size of the largest in the diagram represents a concentration of ~ 0.12%.

Soil C:N Ratios.

Spatial Variability. There were statistically significant differences in C:N ratios between riparian and hillslope landscape positions along each transect ($p<0.001$), but not by soil depth (Table 2). The riparian zones along each transect had more narrow C:N ratio ranges than the adjacent hillslopes, averaging 16.02 and 29.33, respectively, across all four transects. This is shown in Figure 2.17, in which the white and black circles represent the relative magnitude of the C:N ratio at 20 and 50 cm at each nest location, with the largest circle representing a C:N ratio of 52.7:1. Figure 2.17 suggests that C:N ratios were different by transect. Soil C:N ratios increased from T1 (upstream) to T4

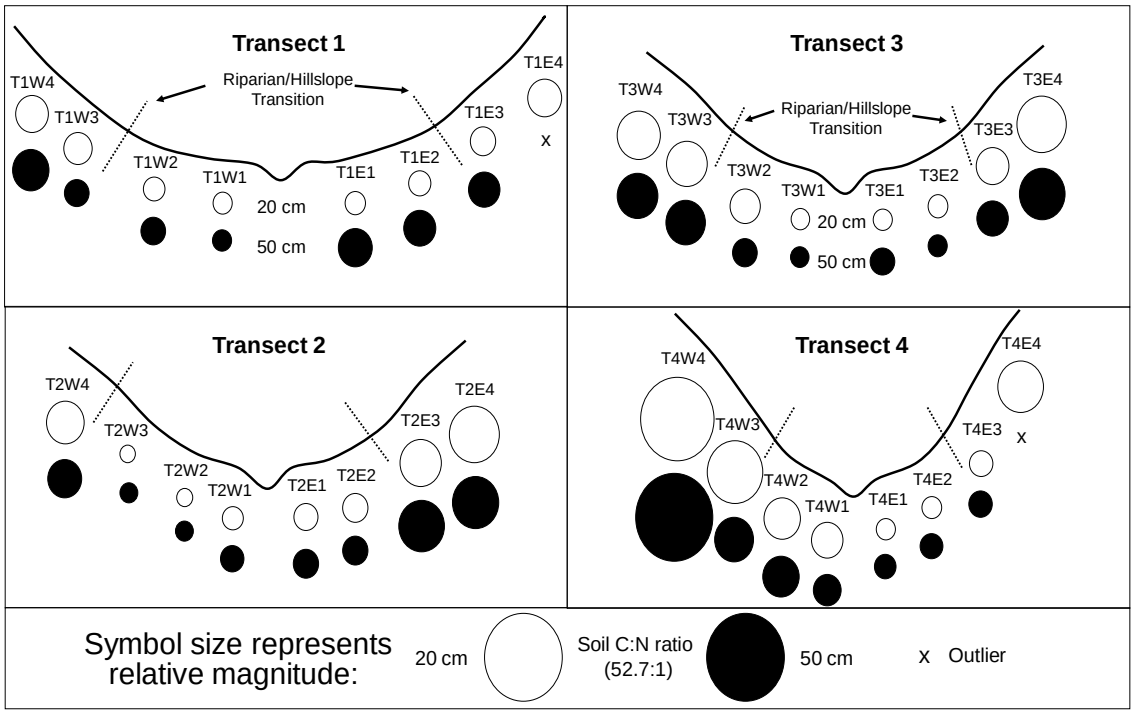


Figure 2.17: Cross-section diagrams of soil C:N ratios at 20 (white) and 50 cm (black) at all nest locations along each transect. Note that symbol size represents relative magnitude. A circle half the size of the largest in the diagram represents a C:N ratio of ~ 26:1.

(downstream), averaging 20.8 and 29.3, respectively. Note that the C:N ratio at two nests were outliers and not included in the relative magnitude calculations as they caused the data to depart significantly from normality. Outliers were present at T1E4-50 (60.7:1) and T4E4-50 (96.6:1).

Discussion

The objective of this investigation was to measure and quantify the range of soil CO_2 dynamics across riparian-hillslope transitions over a topographically complex watershed. Soil respiration driving variables were measured, capturing a range of soil temperature, SWC, and SOM availability across a mountain landscape. However, it was

necessary to group sites for statistical analyses. This variation must be considered when interpreting processes across environmental gradients, as the general trends may be more informative than the statistical differences.

Soil CO_2 Dynamics through *Space*

Soil CO_2 Concentrations: Riparian versus Hillslope Position

Soil CO_2 concentrations were higher in riparian zones along each transect. Note that only the 20 cm depth was significantly greater in the riparian versus hillslope zones along each transect (Table 1), although at 50 cm, the highest soil CO_2 concentrations were in riparian soils (Figure 2.5).

Higher riparian zone soil CO_2 concentrations were likely the result of significantly higher riparian zone SWC (Table 1). Conversely, low concentrations were found at hillslope landscape positions with relatively low SWC. Increasing SWC generally promotes higher soil CO_2 concentrations (Davidson et al., 2000), likely in response to increased production and decreased transport. However, respiration was likely inhibited at many riparian locations with high SWC. This is consistent with other investigations (Clark and Gilmour, 1983; Davidson et al., 2000; Sjogersten et al., 2006), which concluded that optimal soil respiration occurred at intermediate values of SWC. Riparian zones generally had higher soil CO_2 concentrations than the adjacent hillslopes, except at or near times of riparian zone saturation. When the riparian zones were saturated, higher soil CO_2 concentrations were measured at many hillslope nests, although unsaturated riparian nests usually had higher concentrations than the adjacent hillslopes.

Soil temperature did not vary significantly between either riparian and hillslope landscape position or by transect (Table 1, Figures 2.4 – 2.7, 2.11E). This suggested that soil temperature had little effect on the spatial variability of soil CO_2 concentrations in the Stringer Creek Watershed. This finding is supported by Scott-Denton et al. (2003), who suggested that variations in SOM rather than soil temperature across the landscape controlled the spatial variability of soil respiration. This premise likely holds true at the TCEF.

Soil C:N ratios, which help to characterize the availability of SOM for microbial decomposition, were significantly lower in the riparian versus hillslope zones along each transect (Figure 2.17; averaging 16.02 and 29.33). Soils with low C:N ratios (nitrogen-rich soils) are generally more available for microbial decomposition (Brady and Weil, 2002), with optimal ratios ranging from 10:1 to 12:1 (Pierzynski et al., 2000). Such ratios were found primarily in the riparian zones within the Stringer Creek Watershed (Figure 2.17), where soil CO_2 concentrations were higher than the adjacent hillslopes at both 20 and 50 cm (Figures 2.4 and 2.5). This indicated that as soil C:N ratios decreased (although only to a certain point, as very small C:N ratios can limit heterotrophic respiration), soil respiration was likely to increase. These results are supported by Eiland et al. (2001) and Logomarsino et al. (2006), both of which found higher respiration rates in material with lower C:N ratios.

Soil CO_2 Concentrations: Transect versus Transect. Soil CO_2 concentrations varied considerably by transect, with higher values at both 20 and 50 cm (although only significant at 50 cm) in upstream transects (Figures 2.4, 2.5, 2.11A, and 2.12B). The

decrease in soil CO_2 concentrations from upstream to downstream was likely in response to the downstream decrease in upslope accumulated area and riparian zone width as well as the increase in slope (Figure 2.2). Landscape positions with larger upslope accumulated areas and lower slope angles generally have greater SWC (Freeze, 1972; Beven and Kirkby, 1979; Anderson and Burt, 1978; Pennock et al., 1987; McGlynn et al., 2002; Seibert and McGlynn, 2007).

While SWC did not vary significantly by transect, Figures 2.11D and 2.14 suggest a downstream decrease in SWC, as supported by unpublished data. It is important to note that both T4E1 and T4E2 were located near groundwater seep areas. These nests remained saturated until the end of July, 2005, after which SWC slowly declined. Without the two nests located in this seep area, T4 would have a much lower overall SWC.

Another explanation for the downstream decrease in soil CO_2 concentrations may be differences in SOM availability. Frequent saturation retards microbial decomposition (Schlesinger, 1997; Oades, 1988; Sjogersten et al., 2006), suggesting that landscape positions with greater upslope accumulated area (e.g. T1 and T2 versus T3 and T4 in the Stringer Creek Watershed) are likely to have higher SOM. Kang et al. (2003, 2006) suggest that higher respiration rates on north versus south-facing slopes were due to both higher SWC and SOM. While the amount of SOM along each transect was not measured, SOM was generally more available for microbial decomposition along upstream transects, as suggested by increasing C:N ratios moving downstream (Figure 2.17, averages of 20.8 and 29.3 on Transects 1 and 4).

Soil CO_2 Concentrations: 20 versus 50 cm. Significant spatial variability in soil CO_2 concentrations was found by depth, with the largest differences between 20 and 50 cm concentrations in the riparian zones. At most riparian nests, soil CO_2 concentrations were much higher at 20 cm (Figure 2.8E). Some riparian zone soil CO_2 concentrations were up to nearly two orders of magnitude higher at 20 cm than 50 cm (e.g. T1E1 near the end of August and beginning of September, Figure 2.8E). After snowmelt many riparian locations at both 20 and 50 cm were saturated, which likely inhibited soil respiration. However, as the summer progressed and the water table declined, only the 50 cm locations remained saturated in the riparian zone. While SWC dropped below saturation at 20 cm, it remained relatively high. This, in conjunction with relatively high SOM availability for microbial decomposition (low C:N ratios), likely led to large differences in soil CO_2 concentrations between the 20 and 50 cm depths at riparian landscape positions, with much higher concentrations at 20 cm.

In the hillslopes, soil CO_2 concentrations were relatively similar between the 20 and 50 cm depth, with slightly higher concentrations at 50 cm (Figure 2.9E). This was likely the result of increased diffusivity in response to relatively low SWC, which allowed for rapid diffusion of CO_2 out of the soil profile. Furthermore, water tables in the hillslope rarely rose to within 50 cm of the ground surface (unpublished data). This suggested that water table fluctuations and saturated conditions had little effect on the small differences in soil CO_2 concentrations by depth in the hillslopes. Overall, vertical hillslope CO_2 concentrations were more similar than those found in riparian zones.

Surface CO_2 Efflux. While soil CO_2 concentrations at 20 cm were significantly greater in riparian zones, differences in riparian and hillslope surface CO_2 efflux were not significant. Concentration gradients from the soil to the atmosphere exert a large control on soil surface CO_2 efflux. Greater efflux was expected in the riparian zones, which had significantly greater soil CO_2 concentrations and a steeper gradient from the soil to the atmosphere. However, SWC was also significantly greater in the riparian zones, which likely limited the diffusion of CO_2 from the soil to the atmosphere. Furthermore, high riparian zone SWC likely constrained soil CO_2 production by limiting the diffusion of O_2 into the profile. I suggest that soil gas transport limited surface CO_2 efflux in riparian zones due to high SWC (despite strong concentration gradients), while surface CO_2 efflux was gradient (production) limited in the hillslopes. See page 81 for additional discussion of drivers of soil gas diffusion.

While surface CO_2 efflux was not significantly different by transect, Figures 2.11 and 2.14 suggest a general downstream decrease in surface CO_2 efflux. This is supported by comparing average efflux (between October, 2004 and November, 2005) between T1 and T2, and T3 and T4 (0.50 versus 0.35 g CO_2 m^{-2} hr^{-1}). Lower downstream surface CO_2 efflux was likely the result of the downstream decrease in soil CO_2 concentrations in response to lower SWC and SOM availability (higher C:N ratios).

Soil CO_2 Dynamics through *Time*

Both soil CO_2 concentrations and surface CO_2 efflux varied through time across riparian-hillslope transitions on diurnal through seasonal timescales within the Stringer Creek Watershed. Note that data analysis on the temporal variability of soil CO_2

dynamics and the drivers of soil respiration is shown only for T1, which had the highest sampling frequency. Figure 2.10 shows profiles of both soil CO_2 concentrations (20 and 50 cm) and surface CO_2 efflux at eight dates throughout the year along T1, where symbol size represents relative magnitude, provides a good characterization of the temporal variability of soil CO_2 dynamics. Note that soil temperature and SWC measurements were not collected while snow was on the ground (to minimize snowpack disturbance and associated soil CO_2 dynamics), and surface CO_2 efflux measurements did not begin until the middle of April, 2005 due to equipment malfunction.

Winter Soil CO_2 Concentration Dynamics. Minimum soil CO_2 concentrations were measured in both riparian and hillslope zones along T1 during October and November, 2004 (Figures 2.6F and 2.7F). This was likely in response to low soil temperatures. Soil CO_2 concentrations at both the 20 and 50 cm depth increased as the snow began to accumulate (Figures 2.6B and 2.7B). Snowpacks can act as a poorly permeable resistive barrier to gas diffusion (Musselman et al., 2005; Monson et al., 2006a) while at the same time insulating the soil below (Suzuki et al., 2006). At our site, this likely led to peaks in soil CO_2 concentrations at the end of April through the beginning of May, which corresponded to the deepest snowpack and greatest snow water equivalent of the year (120 cm and 46 cm, Figures 2.6B and 2.7B) and the beginning of snowmelt. Musselman et al. (2005) observed a similar late winter increase in soil CO_2 concentrations and suggested that snowpack ripening leads to increased snowpack density, which in turn increases the diffusive resistance of the snow.

Winter soil CO_2 concentrations peaked at 16,295 ppm in the hillslopes, and 29,210 ppm in the riparian zones (Figures 2.6F and 2.7F), which is substantially higher than those measured at other subalpine locations. Musselman et al. (2005) reported a range of 1000-5000 ppm at an elevation of 3100 m in Wyoming; Monson et al. (2006a) observed a range from ~500-2700 ppm at an elevation of 3030 m at Niwot Ridge in Colorado; and Sommerfeld et al. (1996) measured a winter peak of 10,464 ppm at a subalpine meadow at 3180 m in Wyoming. One possible explanation for higher winter soil CO_2 concentrations at TCEF is that it is located at a lower elevation (2200 m) than those cited above. At this elevation in the northern Rocky Mountains, a deep snowpack is often present for over 6 months of the year (generally from mid-October to mid-May). However, the lower elevation of TCEF relative to the cited studies increases the likelihood of above-freezing air temperatures to occur intermittently over the winter (which was observed at TCEF). This likely increased the frequency of melt/refreeze events, which impact snowpack structure and metamorphism. Melt/refreeze events can lead to the formation of ice lenses within the snowpack, which can reduce gas diffusion and allow for increased soil CO_2 concentrations. Mast et al. (1998) reported the formation of a 2 to 5 cm ice layer due to warm weather in early spring and measured CO_2 concentrations below the ice layer over three times greater than those measured above the ice layer.

Temporal differences in wintertime peaks of soil CO_2 concentrations were observed between the riparian and hillslope zones along T1. Most riparian nests peaked during the middle of April, while hillslope nests peaked nearly a month later, at the

middle of May, 2005 (Figures 2.6F and 2.7F). This is also apparent when comparing 3/25/05 and 5/10/05 in Figure 2.10. Musselman et al. (2005) observed a similar trend between different landscape positions, with soil CO_2 concentrations under a deep snowpack increasing sooner in a meadow than in a forest in a subalpine site in the Snowy Range in Wyoming. The riparian zones in the Stringer Creek Watershed have little to no tree cover, while the hillslope zones are forested and more shaded. The snow in the riparian zones likely became isothermal and ripe sooner than in the hillslope zones due to differences in the energy balance at these locations. A ripe snowpack would likely promote earlier melt infiltration in riparian zones, therefore stimulating respiration and/or increasing the diffusive resistance of the snow, thus leading to an earlier riparian zone maximum in wintertime soil CO_2 concentrations. Riparian zones melting first and hillslopes last were observed at TCEF.

Winter Surface CO_2 Efflux Dynamics. Winter measurements of surface CO_2 efflux began near the end of April at TCEF. Surface CO_2 efflux was much lower when snow was present (Figures 2.6E and 2.7E), ranging from less than 0.01 to 0.20 g CO_2 m^{-2} hr^{-1}. Efflux was slightly higher in riparian versus hillslope landscape positions, with winter measurements averaging 0.056 and 0.033 g CO_2 m^{-2} hr^{-1}. Our results agree with those of Musselman et al. (2005), who reported higher CO_2 snow efflux in subalpine meadows than forests, ranging from 0.088 to 0.199 g CO_2 m^{-2} hr^{-1} in the meadows and 0.059 to 0.127 g CO_2 m^{-2} hr^{-1} in the forests. Both Sommerfeld et al. (1996) and Hubbard et al. (2005) reported similar, though higher, ranges of winter CO_2 efflux through snow at subalpine sites, ranging from 0.049 to 0.256 g CO_2 m^{-2} hr^{-1} and

0.058 to 0.203 g CO_2 m^{-2} hr^{-1}, respectively. While winter CO_2 efflux is generally much lower than growing season CO_2 efflux, it is often a significant component of the annual efflux (Monson et al., 2006a). This was true at TCEF, where winter riparian and hillslope surface CO_2 efflux comprised ~15 and 9% of the total annual efflux. This is consistent with research at other subalpine locations. Mast et al. (1998) found that winter efflux rates comprised 8-23% of the total annual efflux across a range of SWC at a subalpine site in Colorado, and McDowell et al. (2000) estimated 16% at a subalpine location in Wyoming.

CO_2 Dynamics during Snowmelt. My data suggests that snowmelt, which occurred between May and June, 2005 (Figures 2.6B and 2.7B), exerted a large control on soil CO_2 dynamics. There was a large decrease in soil CO_2 concentrations between the middle of May and the middle of June (Figures 2.6F and 2.7F) (note that measurements were not collected from mid-May to mid-June due to inaccessibility of the field site). This was likely a period of high surface CO_2 efflux (Monson et al., 2006a). The sharp decrease in soil CO_2 concentrations were likely exacerbated by the rapid increase of SWC from snowmelt, which can inhibit soil respiration. Decreased soil CO_2 concentrations could also result from the decrease in soil temperature without snowpack insulation. While soil CO_2 concentrations decreased following peak snowmelt, soil surface CO_2 efflux increased (Figures 2.6E and 2.7E). This is also evident when comparing 6/26/05 to the previous winter months in Figure 2.10. It is likely that as the snowpack melted and the ground surface became exposed, the CO_2 that accumulated in the soil over the winter was able to diffuse to the atmosphere.

Summer CO_2 Dynamics. Soil CO_2 concentrations began to increase at the beginning of the summer in response to changes in SWC and soil temperature. As the summer progressed, SWC dropped below the level at which respiration was inhibited, though remained relatively high compared to the end of the summer (Figures 2.8B and 2.9B – note that the x-axis is expanded from Figures 2.6 and 2.7). Soil temperatures also increased throughout the summer (Figures 2.8C and 2.9C).

The timing of soil CO_2 peak concentrations depended upon landscape position. The hillslope nests along T1 all peaked near the beginning of July at both the 20 and 50 cm depths (Figure 2.9E). Conversely, riparian nests along T1 exhibited staggered soil CO_2 concentration peaks between the end of July and the middle of October, with locations closest to Stringer Creek or in wetter landscape positions peaking latest (Figure 2.8E). This difference between the timing of riparian and hillslope zone summer peaks in soil CO_2 concentration is also shown in Figure 2.10 and is likely the result of water table fluctuations and respiration-inhibiting SWC. On 7/13/05, most riparian zone nests had relatively high soil CO_2 concentrations at 20 cm, while many 50 cm locations likely had no CO_2 production as the soil was at or near saturation. However, by 8/23/05, the water table dropped (unpublished data) and SWC decreased, leading to rapid increases in soil CO_2 concentrations at many 50 cm locations in the riparian zone. The exception was T1E1, which, due to its low elevation and proximity to Stringer Creek, remained close to saturation throughout the year.

Fall CO_2 Dynamics. Beginning in mid-August, soil temperatures quickly began to decrease, which led to a decrease in soil CO_2 concentrations at many nest locations,

especially those in the hillslopes. The exception to this was wet locations in the riparian zone (e.g. T1W1 and T1E1), where soil CO_2 concentrations continued to rise until the end of October as SWC continued to decrease. However, at the end of September, soil temperatures quickly rose, leading to a sharp rise in soil CO_2 concentrations, but not surface CO_2 efflux (Figures 2.6 and 2.7). The rise in soil temperature was due to a short period of warm weather. During the last week of September, maximum air temperatures were just above 0°C, then rose to near 15°C for a four day period (unpublished meteorological data). This likely stimulated soil respiration and caused soil CO_2 concentrations to rise (Figures 2.6F and 2.7F). A small rain event also occurred (Figures 2.6C and 2.7C) just after soil temperatures began to rise, which likely stimulated soil respiration. However, the increase in SWC could have also limited soil gas diffusion, possibly explaining why soil surface CO_2 efflux showed little to no increase in response to increasing soil CO_2 concentrations. Throughout the rest of the fall, soil CO_2 concentrations and surface CO_2 efflux decreased to levels near those measured during November, 2004, corresponding to the beginning of significant snow accumulation.

Timing of Largest Soil CO_2 Concentration Peaks. The timing of peaks in soil CO_2 concentrations varied across riparian-hillslope landscape positions. The largest peaks at most hillslope nests occurred during the end of April or beginning of May (though generally lower than the adjacent riparian nests; Figures 2.6F and 2.7.F), when snow depth and snow water equivalent were at or near their maximum (120 cm and 46 cm, Figures 2.6B and 2.7B). Conversely, the largest peaks in riparian zone soil CO_2 concentrations did not occur until the summer or fall. The latest peaks occurred at

locations closest to Stringer Creek or at wetter landscape positions, when SWC was relatively high, yet likely below the point at which respiration becomes inhibited.

Hillslope zones had low SWC, relative to the adjacent riparian zones (Figure 2.6C versus 2.7C), and summer peaks in soil CO_2 concentrations were much lower than those observed the previous winter (Figure 2.7F). Thus, in the Stringer Creek Watershed, the relative magnitude of riparian and hillslope zone soil CO_2 concentrations reversed from spring to fall, with greater hillslope values in the spring and larger riparian values during the summer and fall. While soil temperature was a dominant control on the seasonal variability of soil CO_2 dynamics, it is likely that SWC was a major control on the differences in the timing of the largest peaks in soil CO_2 concentrations between riparian and hillslope landscape positions.

Timing of Largest Peaks in Surface CO_2 Efflux. There were also differences in the timing of maximum surface CO_2 efflux between riparian and hillslope zones (Figure 2.10), however maximum efflux was more coincident than maximum soil CO_2 concentration (Figure 2.6E versus 2.7E). Maximum riparian and hillslope zone surface CO_2 efflux generally occurred within a month of one another during July and August, with many hillslope locations peaking first. This was different than the timing of maximum soil CO_2 concentrations between riparian and hillslope zones, highlighting that differences in gas diffusion drivers (concentration gradients and diffusivity) likely existed between riparian and hillslope zones. See page 81 for additional discussion of soil gas diffusion drivers.

Diurnal Soil CO_2 Dynamics. Soil CO_2 dynamics varied on a diurnal timescale, though to a lesser degree than the seasonal variation. Soil surface CO_2 efflux showed the highest degree of variation, changing by an average of 0.35 g CO_2 m^{-2} hr^{-1} (50.5%) along T1 over the 24 hour period beginning at 0900 on July 4, 2005 (Figures 21.2C and 2.13C). Soil CO_2 concentrations also varied considerably, with average variations of 1322 ppm (27.5%) and 1154 ppm (28.5%) at 20 and 50 cm. SWC showed minimal diurnal variation, indicating it exerted little control on the diurnal variability of soil CO_2 dynamics. This is corroborated by Tang et al. (2005), who found that daily variations in SWC are negligible and have little influence on the diurnal variability of soil respiration. Conversely, soil temperature varied considerably over the 24 hour period, with slightly smaller fluctuations in the riparian versus hillslope landscape positions, 3.9°C (34%) and 4.6°C (36%) (Figures 2.12B and 2.13B). This may be due to higher riparian versus hillslope zone SWC along T1, which averaged 68.6% and 20.5% (Figures 2.12A and 2.13A), as the high specific heat capacity of water can dampen soil temperature fluctuations (Hillel, 2004).

Soil surface CO_2 efflux peaked in the early afternoon (1500 h) before peak soil temperature (2100 h). This is consistent with other field investigations (Xu and Qi, 2001; Subke et al., 2003; Riveros-Iregui et al., in review). Soil CO_2 concentrations increased from 0900 h to 1500 h, in phase with an increase in soil temperature, suggesting that soil temperature was the dominant control on the diurnal variability of soil CO_2 concentrations. However, after soil CO_2 concentrations decreased from 1500 h to 2100 h, they increased from 2100 h to 0300 h the following morning, while soil temperatures

decreased during the same period (corroborated by real-time data); this suggests that another control on the diurnal variability of soil CO_2 concentrations was present.

Time Lag between Respiration and Photosynthesis. One possible control on the diurnal variation of soil respiration is that photosynthesis was strongly correlated with respiration, leading to a time delay between peaks in photosynthesis and heterotrophic respiration (and subsequent rise in soil CO_2 concentrations). Tang et al. (2005) suggest that the delay may represent the time needed for the translocation of carbohydrates from leaves to roots to soil (root exudates), which mcan stimulate microbial respiration. Time delays in soil respiration following peaks in photosynthesis have been described in recent research. Tang et al. (2005) found a time delay of 7-12 h, and Baldocchi et al. (2006) reported a time lag of 5 h. However, to determine the specific duration of the time lag, one needs high frequency temporal sampling, which can be accomplished with real-time soil CO_2 concentration and temperature measurements. While such instrumentation is installed at TCEF, it was not operational during the summer of 2005.

Previous research has shown the decoupling of photosynthesis from respiration to be more pronounced under certain vegetation covers. Tang and Baldocchi (2005) found the decoupling of photosynthesis and respiration to be more pronounced under trees than in open areas. However, they collected diurnal measurements during a hot and dry summer when grasses in the open areas were not active. Thus, heterotrophic respiration was the only source of soil respiration. I did not observe differences in the degree of decoupling between riparian and hillslope zones at TCEF (Figures 2.12 and 2.13), as the annual grasses were still active when measurements were collected. Active plant activity

likely allowed for both autotrophic and heterotrophic soil respiration and thus similar coupling of respiration and photosynthesis between riparian and hillslope landscape positions.

Soil CO_2 Diffusivity versus Production

The efflux of gas from the soil to the atmosphere is dependent upon both production and diffusivity. The efflux (F) can be determined from Fick's Law:

$$F = -D\left(\frac{\partial C}{\partial z}\right) \quad (1)$$

where D is the diffusivity (m^2s^{-1}), C is the CO_2 concentration (ppm), and z is the depth (m).

Soil gas diffusion is dependent upon both the concentration gradient from the soil to the atmosphere as well as soil gas diffusivity. Soil gas diffusivity is controlled by soil properties such as soil texture, porosity, connectivity and tortuosity of pore spaces, and degree of saturation. The concentration gradient is controlled by both production and transport. Soil CO_2 production is controlled by SWC, soil temperature, and SOM quantity and quality. Transport can partially control the concentration gradient because limited transport can increase soil gas concentration. A high concentration gradient can result from either high soil gas production or limited soil gas transport, or an intermediate combination of both variables. From Equation 1, similar efflux can result from different combinations of the variables. As both soil gas production and transport can vary greatly across the landscape, further quantification of the controls on soil gas diffusion at various landscape positions is necessary.

Large differences in the controls on soil gas diffusion were found between riparian and hillslope landscape positions within the Stringer Creek Watershed. Soil CO_2 concentrations were significantly higher in riparian landscape positions, yet surface CO_2 efflux showed little variability between riparian and hillslope zones (Figure 2.11A-C). As concentration gradients are one driver of soil gas diffusion, higher surface CO_2 efflux was expected in riparian zones, where relatively large gradients in CO_2 concentrations were present between the soil and the atmosphere (e.g. ~40,000 ppm at 20 cm to ~380 ppm in the atmosphere). However, SWC was also significantly greater in riparian versus hillslope landscape positions (Figure 2.11D), which can limit soil gas diffusion. This suggests that while large gradients in riparian zone soil CO_2 concentrations existed from the soil to the atmosphere (likely a result of high soil CO_2 production due to relatively high SWC and SOM), surface CO_2 efflux was limited by high SWC.

Conversely, hillslopes had relatively low CO_2 concentration gradients (e.g. ~5,000 ppm at 20 cm to ~380 ppm in the atmosphere). This was likely due to low soil CO_2 production in response to low SWC and SOM, as well as high gas diffusivity. Low soil CO_2 concentration gradients in the hillslopes suggested that surface CO_2 efflux would be low, relative to the riparian zones, yet they were comparable. This was likely in response to low SWC in the hillslopes, which allowed for greater diffusivity than in the riparian zones (even though concentration gradients were low). This premise is supported by Risk et al. (2002b), who reported low soil gas diffusivity when SWC was high, and high values when SWC was low. Risk et al. (2002b) suggested that surface CO_2 efflux and soil CO_2 production were not directly related, but separated by the

mechanics of diffusive gas transport. It is likely that high soil CO_2 concentrations at wet landscape positions (or at dry landscape positions following a rain event) were the result of both high production and low gas diffusivity. Jassal et al. (2005) suggested that large increases in soil CO_2 concentrations following rain events were likely attributed to both a decrease in soil gas diffusivity as well as a rapid increase in heterotrophic respiration.

I suggest that surface CO_2 efflux in the Stringer Creek Watershed was controlled by a shift between production and transport-limiting SWC (see conceptual model, Figure 2.18). In the Stringer Creek Watershed, soil CO_2 concentrations often increased with

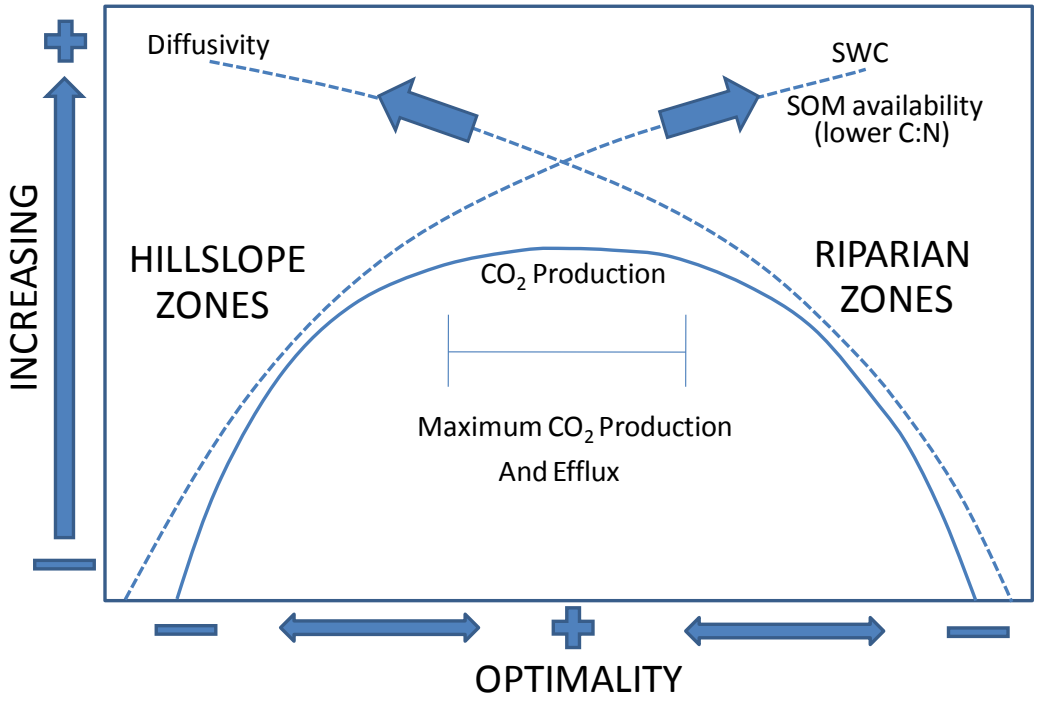


Figure 2.18: Conceptual model of soil CO_2 dynamics and select drivers of respiration.

increasing SWC, with the highest concentrations generally occurring at intermediate SWC (which past research (Clark and Gilmour, 1983; Davidson et al., 2000; Sjogersten et al., 2006) suggests is the optimal level for soil CO_2 production as production can sharply decrease at very high and low SWC). In the Stringer Creek Watershed, surface

CO_2 efflux was similar between riparian and hillslope zones (Figure 2.11C), potentially due to a SWC-mediated tradeoff between production and transport. Soil gas diffusivity increases as SWC decreases, with optimal diffusivity at low SWC (Figure 2.18). Riparian zones likely had lower diffusivity in response to high SWC, but relatively high soil CO_2 production due to high SWC and SOM availability. This suggests that high soil CO_2 concentrations in the riparian zones resulted from a combination of high production and low diffusivity, which led to a large gradient in CO_2 concentrations from the soil to the atmosphere. In contrast, CO_2 production was likely low in the hillslopes in response to low SWC and SOM availability, yet diffusivity was high due to low SWC. This suggests that similar surface CO_2 efflux across both riparian and hillslope zones were the result of a tradeoff between CO_2 production and transport (Figure 2.18). From early spring to fall, hillslope and riparian zones shift from the right to the left in the conceptual model diagram. I suggest hillslopes occupy the "more optimal" conceptual model space in late spring/early summer while riparian zones move toward "more optimal" conceptual model space in mid to late summer (Figure 2.18), partially explaining the timing and magnitude of soil CO_2 concentrations and surface efflux.

Conclusions

Measurements of soil CO_2 concentrations (20 and 50 cm), surface CO_2 efflux, soil temperature, SWC, and SOM across a range of spatial and temporal scales focused on riparian-hillslope transitions within the Stringer Creek Watershed suggested that:

1) Soil surface CO_2 efflux was relatively homogenous across the landscape as compared to riparian zone soil CO_2 concentrations that were greater and more variable than the adjacent hillslope zones along each transect. There was also a downstream decrease in soil CO_2 concentrations. This likely resulted from the downstream decrease in SWC and SOM in response to the downstream decrease in upslope accumulated area and riparian zone width as well as the increase in slope.
2) SWC and SOM availability likely controlled the spatial variability of soil CO_2 dynamics (within and between transects), while soil temperature was the dominant control on the seasonal variability. It is likely that a time lag between photosynthesis and soil respiration controlled the diurnal variability of soil CO_2 dynamics.
3) Hillslope zone soil CO_2 concentrations peaked at similar points in time, with the largest peaks during the late spring when snow depth and snow water equivalent were greatest. Conversely, riparian zones exhibited staggered peaks, the largest of which occurred during the late summer or early fall, with those locations closest to Stringer Creek or in wetter landscape positions peaking up to three months later than drier riparian landscape positions.
4) One primary control of the spatial and temporal variability of watershed soil CO_2 concentrations and surface CO_2 efflux was a SWC mediated tradeoff between soil CO_2 production and transport. Soil gas transport likely limited surface CO_2 efflux

in riparian zones due to high SWC (despite strong concentration gradients), while surface CO_2 efflux was gradient (production) limited in hillslope zones.

The first-order controls on soil respiration have been the focus of much research (Raich and Schlesinger, 1992; Raich and Potter, 1995; Risk et al., 2002a). However, the spatial (Longdoz et al., 2000; Kominami et al., 2003) and temporal (Longdoz et al., 2000) variability of soil CO_2 dynamics are poorly understood, especially across complex landscapes. Studies that have addressed this variability have been limited to small temporal or spatial scales or have ignored the influence of landscape position on the driving factors of soil CO_2 dynamics such as soil temperature, SWC, and SOM. Furthermore, no studies to my knowledge have investigated the variability of soil CO_2 dynamics between riparian and hillslope landscape positions.

The results of this research highlight the importance of landscape position in controlling the spatial and temporal variability of soil CO_2 dynamics and the drivers of respiration within and between riparian-hillslope transitions in a complex mountain watershed. Changes in SWC and SOM in response to differences in upslope accumulated area, riparian zone width, and steepness of hillslopes led to great spatial variability in both soil CO_2 concentrations and surface CO_2 efflux within and between riparian and hillslope zones. In the Stringer Creek Watershed, significantly higher soil CO_2 concentrations were found in the riparian zones and along transects with greater upslope accumulated area, wider riparian zones, and gentle slopes. SWC was a major control on the differences in summer peaks in soil CO_2 concentrations, with wetter riparian

landscape positions peaking up to three months later than drier positions. Surface CO_2 efflux was less variable across the landscape than soil CO_2 concentrations, indicating that the drivers of gas diffusion differed between riparian and hillslope zones in response to a SWC-mediated tradeoff between soil CO_2 production and transport.

There were also differences in the temporal variability of soil CO_2 dynamics between riparian and hillslope zones. Peaks in winter soil CO_2 concentrations occurred nearly a month earlier in the riparian zones than the adjacent hillslopes, which, to my knowledge, has not ever been described by past research. This was likely in response to the snowpack becoming isothermal sooner in the riparian zones, which could have promoted melt infiltration and reduced diffusivity that led to an earlier winter peak in riparian soil CO_2 concentrations. Furthermore, hillslope landscape positions showed similar temporal peaks in soil CO_2 concentrations throughout the year while riparian zones exhibited staggered peaks during both the growing and non-growing season due to spatial and temporal dynamics of SWC. Finally, the hillslopes exhibited their largest peaks in soil CO_2 concentrations during the winter, while the riparian zones peaked during the late summer or early fall. These results suggest that significant differences in soil CO_2 dynamics may exist within and between riparian and hillslope landscape positions and must be considered when investigating drivers of ecosystem C exchange and attempting to scale observations to whole watersheds and landscapes.

This research provides insight into how and when various landscape positions behave differently with respect to soil CO_2 dynamics, as well as how SWC, soil temperature, SOM availability, and the snowpack control the variability of soil CO_2

dynamics through both space and time. To continue to improve our understanding of the spatial and temporal variability of soil CO_2 dynamics across different landscape elements, it is imperative that further studies across a range of spatial and temporal scales be undertaken, especially in areas of complex topography.

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CHAPTER 3

SUMMARY

Soil CO_2 dynamics across topographically complex watersheds remain poorly understood. A better understanding of landscape controls on soil CO_2 dynamics is important to ecologists, hydrologists, biologists, and landuse managers. This research provides insight into the variability of soil water content (SWC), soil temperature, and soil organic matter (SOM) across riparian and hillslope zones in a complex mountain watershed, which in turn control the variability of soil CO_2 concentrations and surface CO_2 efflux through both space and time.

In this study I collected measurements of soil CO_2 concentrations (20 and 50 cm), surface CO_2 efflux, soil temperature, SWC, and SOM across a range of spatial and temporal scales in order to investigate the following questions:

1) How do soil CO_2 dynamics and the drivers of soil respiration vary through *space* across riparian-hillslope transitions?
2) How do soil CO_2 dynamics and the drivers of soil respiration vary through *time* across riparian-hillslope transitions?
3) How does the relative importance of soil CO_2 diffusivity versus production differ between riparian and hillslope zones?

This combination of measurements at multiple spatial and temporal scales suggested that:

1) Soil surface CO_2 efflux was relatively homogenous across the landscape as compared to riparian zone soil CO_2 concentrations that were greater and more

variable than the adjacent hillslope zones along each transect. There was also a downstream decrease in soil CO_2 concentrations. This likely resulted from the downstream decrease in SWC and SOM in response to the downstream decrease in upslope accumulated area and riparian zone width as well as the increase in slope.

2) SWC and SOM availability likely controlled the spatial variability of soil CO_2 dynamics (within and between transects), while soil temperature was the dominant control on the seasonal variability. It is likely that a time lag between photosynthesis and soil respiration controlled the diurnal variability of soil CO_2 dynamics.
3) Hillslope zone soil CO_2 concentrations peaked at similar points in time, with the largest peaks during the late spring when snow depth and snow water equivalent were greatest. Conversely, riparian zones exhibited staggered peaks, the largest of which occurred during the late summer or early fall with those locations closest to Stringer Creek or in wetter landscape positions peaking up to three months later than drier riparian landscape positions.
4) One primary control of the spatial and temporal variability of watershed soil CO_2 concentrations and surface CO_2 efflux was a SWC mediated tradeoff between soil CO_2 production and transport. Soil gas transport likely limited surface CO_2 efflux in riparian zones due to high SWC (despite strong concentration gradients), while surface CO_2 efflux was gradient (production) limited in hillslope zones.

The spatial and temporal variability of soil respiration is significant to ecosystem carbon (C) exchange, yet only partially understood (Tang and Baldocchi, 2005). Further quantification of the spatial and temporal variability in soil CO_2 concentration and surface CO_2 efflux across different landscape positions (e.g. riparian and hillslope zones) is necessary to fully understand C cycling at the ecosystem scale. Traditionally, studies that addressed this variability (Fang et al., 1998; Miller et al., 1999) have been limited to small temporal or spatial scales or have ignored the influence of topography on the driving variables of soil CO_2 production and surface CO_2 efflux such as soil temperature, SWC, and SOM. The results from this research highlight that the variability of the drivers of respiration and both soil CO_2 concentrations and surface CO_2 efflux can vary significantly through both space and time across riparian-hillslope transitions in a topographically complex mountain watershed.

Soil CO_2 concentrations showed considerable spatial variability between both topographically distinct riparian and hillslope landscape positions and transects. Riparian zone soil CO_2 concentrations were higher and more variable than the adjacent hillslope zones. This was attributed to higher SWC and greater SOM availability in the riparian zones. There was also a downstream decrease in soil CO_2 concentrations, which was likely due to the downstream decrease in upslope accumulated area and thus SWC and SOM.

While soil CO_2 concentrations varied significantly through space, surface CO_2 efflux was relatively homogenous across riparian-hillslope transitions. This highlights

that the drivers of soil gas diffusion (production and transport) may differ across riparian and hillslope landscape positions. I suggest that while concentration gradients were large in the riparian zones, high SWC limited soil gas transport to the atmosphere. Conversely, low concentration gradients, likely due to limited production, limited surface CO_2 efflux in the hillslope zones.

Soil CO_2 dynamics also varied across the landscape on both seasonal and diurnal timescales. Soil temperature was generally the dominant control on the temporal variability, although my results suggest that a time lag between photosynthesis and soil respiration likely controlled the diurnal variation. In general, peaks in winter hillslope zone soil CO_2 concentrations were greater than those observed during the growing season, with nearly all hillslope locations peaking at similar points in time throughout the year. Conversely, riparian zones had higher soil CO_2 concentrations during the growing season, with water table fluctuations likely controlling the timing of riparian zone peaks (with wetter landscape positions peaking last). Furthermore, winter respiration was a significant component of total annual respiration, constituting 15 and 9% at the riparian and hillslope zones, respectively.

Identification of the variability of soil CO_2 dynamics across landscape elements can play a pivotal role in informing land management. Changing landuse practices can greatly alter SWC and soil temperature and thus soil respiration rates and the efflux of soil CO_2 to the atmosphere (Raich and Schlesinger, 1992; Raich et al., 2002). This should be considered by landuse managers in municipal, agricultural, and forest

ecosystems as soil respiration is the largest terrestrial source of CO_2 to the atmosphere (Raich et al., 2002).

This research provides insight into how various landscape elements behave with respect to soil CO_2 dynamics, as well as how SWC, soil temperature, and SOM availability control the variability of soil CO_2 dynamics through both space and time. Furthermore, this research highlights the differences in the dependence of production versus transport on soil gas diffusion across riparian and hillslope zones. To continue to improve our understanding of the spatial and temporal variability of soil CO_2 dynamics across different landscape elements it is imperative that further studies of soil CO_2 dynamics and the drivers of soil respiration across a range of spatial and temporal scales be undertaken, especially in areas of complex topography.

Future research directions should include investigating CO_2 dynamics across larger and smaller spatial and temporal scales, applying a model of catchment respiration, and quantifying C export at the watershed scale. The relative proportions and the controlling variables of microbial and root respiration, and how they change through space and time, needs further investigation. Comparison of CO_2 dynamics throughout a wet and dry year would allow for further quantification of the relative roles of soil respiration driving variables. To fully understand winter soil CO_2 dynamics, it is necessary to characterize the variability of CO_2 concentrations within the snowpack as well as further investigate the role of snowmelt in controlling the spatial and temporal variability of soil CO_2 production and surface efflux. Quantification of source areas and export patterns of both dissolved organic and inorganic C, as well as C cycling and fate

during stream transport at the stream network scale is necessary to fully understand C export at the watershed scale. Finally, applying a model of catchment respiration would allow for improved understanding of the first order controls on soil respiration, and their variability through space and time.

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