Soil surface CO_2 efflux across the climatic gradient of the Oregon Transect for Terrestrial Ecological Research (OTTER)

by
Mark A. Martin

A THESIS

submitted to

Bioresource Research Program
Oregon State University

In partial fulfillment of
the requirements for the
Bachelors of Science degree in
Bioresource Research

Presented March 15,2002

Bachelor of Science in BioResource Research thesis of Mark A. Martin
Presented on March 15, 2002

Approved by:

Mentor: Dr. Barbara Bond — Date: 6/7/2002

Committee member: Nate McDowell — Date: 6/9/2002

BioResource Research Director: Dr. Anita Azarenko — Date: 12 June 02

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Mark A. Martin — Date: 6-5-02

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Informative Abstract

Soil CO_2 efflux is a major contributor of CO_2 to the atmosphere. The rate that CO_2 is respired out of the soil is called the soil flux (Fs). Many variables alter Fs. These variables differ drastically in the variety of ecosystems found on the earth. It is important to understand how Fs functions in each ecosystem so future concentrations of CO_2 in the atmosphere can be better understood. I studied Fs and its relationship to soil temperature, predawn soil water potential, and aboveground biomass in four ecosystems across the climatic gradient found in the Oregon transect for terrestrial ecological research (OTTER). I found strong relationships between Fs and temperature at the spruce and Douglas-fir sites, and no significant relationship between Fs and temperature at the pine and juniper sites in 2000. Initial water potential data show a relationship with Fs, but more work needs to be done to document it.

Descriptive Abstract

Due to soil respiration's (Fs) contribution of CO_2 to the atmosphere, it is important to understand all the variables that affect Fs in different environments. This study analyzes Fs in four ecosystems across a climatic transect from temperate rainforest to arid ecosystems. This report describes the role of climatic variables in the rate of Fs, and the importance of future studies in this field.

List of illustrations

I. Introduction

a. Frame of reference

Atmospheric carbon dioxide (CO_2) is of particular interest to scientists and the general public due to its potential for affecting the global climate. CO_2, a greenhouse gas, allows incident sunlight to strike the surface of the earth and warm it, yet when long-wave radiation tries to leave the earth, the CO_2 reflects it back to the surface, gradually increasing the earth's average temperature. As more CO_2 accumulates in the atmosphere, this "greenhouse effect" becomes stronger. Recent analysis of the global carbon cycle shows from the beginning of the industrial revolution to 1993, atmospheric concentrations of CO_2 have increased from approximately 280 ppm to 370 ppm (Fig. 1). Due to this well documented increase in CO_2 and its potential to lead to global warming, it is important to understand CO_2's origins and what controls its allocation to the atmosphere.

In the global carbon cycle there are many sources of CO_2 to the atmosphere. As seen in figure 2, the contributing sources of CO_2 are, respiration from oceans, soils, vegetation, as well as the net destruction of vegetation and burning of fossil fuels. In the biological sources, respiration is the efflux of CO_2 from the source to the atmosphere. The non-biological sources contribute CO_2 to the atmosphere through the by-products that come from burning fossil fuels and the net destruction of vegetation. Although the non-biological contributions are small, they cause concern among scientists because they are relatively new sources.

Of the terrestrial sources, soil respiration is one of the most important. There are two main contributors to Fs, root respiration and microbial respiration. There has been a lot of debate on how much each source contributes to the total Fs. Estimates of root respiration range from 30 – 90% (Raich *et.al.* 2000) leaving the rest to microbial respiration. The wide range of estimates comes from studies done in different forest types, therefore, the actual contributing amounts from root respiration and microbial respiration will differ from one forest to another.

Soil respiration is also the largest contributor among the terrestrial sources. This has been documented by many studies, which have been compiled and analyzed by Raich and Schlesinger (1992). They state that Fs is estimated to be 50-75 Pg C/yr. As one of the major fluxes in the global carbon cycle, this estimated rate places it second in effect only to gross primary productivity, and equal to or greater than net primary productivity. Raich and Potter (1995) re-examined the estimate of global Fs with their more recent study and found it to be 77 Pg C/yr. In 1999, Law estimated that soil in a ponderosa pine (*Pinus ponderosa*) forest in central Oregon is responsible for 76% of the total CO_2 respired from the forest (Law 1999: 4).

Because these studies show Fs to be a prominent source of CO_2 to the atmosphere, scientists are striving to gain a better understanding of it. Kirschbaum (2000) has acknowledged that due to the significant amount of carbon stores in the soil, if greenhouse gases affect climate change, there could be a significant acceleration of CO_2 added to the atmosphere by the soils. These concerns are founded in the understanding that soil respiration can be significantly altered by climatic change (Conant *et. al.* 2000: 383). Schlesinger and Andrews (2000) claim that soil respiration was in equilibrium with the global carbon cycle before human intervention, and that due in part to human intervention, soil respiration is changing. They stated "small changes in the magnitude of soil respiration could have a large effect on the concentration of CO_2 in the atmosphere."

It is essential to gain a better understanding of Fs in all ecosystems so that better models can be created to predict future levels of CO_2 in the atmosphere. I studied Fs across four different climatic ecosystems in an effort to understand future Fs rates in a variety of ecosystems.

b. **Problem base**

My study was based on the lack of understanding of soil respiration across different ecosystems. In the last 10 to 15 years many studies have been completed on Fs and its contributing factors. Among these studies are: the Bowden *et al.* (1993) study completed in an 80-year-old mixed hard wood forest in central Massachusetts; the Conant *et al.* (2000) study completed in semiarid ecosystems; the Law B.E. (1999) study completed in a Ponderosa pine forest in central Oregon; and finally, the Thierron *et* al. (1996) study completed in an oak forest in France. As is illustrated by these studies, past research on Fs has predominantly included single site (forest type) studies. Little work has been completed to compare Fs rates across climatic and vegetative gradients. In addition, previous research has left some ecosystems barely studied. For example, arid and semiarid lands have received considerably less attention than other ecosystems (Conant 2000: 383). This limits our understanding of soil respiration and its controlling factors. As we move across climatic gradients, significant differences in the soil microclimate, carbon storage, temperature extremes, precipitation amounts, and decomposition rates are found. Each of these variables could have an important role in the rate of CO_2 efflux from the soil surface. Without knowing how the different variables affect each system's contribution of CO_2, we cannot accurately estimate the amount of CO_2 present in the atmosphere.

c. **Scope of research**

The scope of my research was to answer the question, "how do ecosystem variables affect Fs in different climates?" We studied soil respiration in four different ecosystems ranging from the Oregon coast to the central Oregon desert. My objective was to find correlations between Fs and soil temperature, soil water content, predawn water potential, and aboveground biomass.

c. **Overview of means and methods**

We measured Fs five times in the year 2000 and once in the spring of 2001 to capture a time span of 12 months. Fs measurements were performed using a dynamic closed-chamber infrared gas analyzer (IRGA) (LI-6200 Li-Cor, Inc., Lincoln, NE). Ancillary measurements of soil temperature, soil water content, and predawn water potential were measured each time Fs were measured. The aboveground biomass was calculated at each site at the beginning of the study.

Work continued on this study throughout 2001 (of which I was not a part) following a similar design and those results are included here for the sake of discussion.

II. Materials and Methods

a. Site description

The study was conducted at four sites along a east-west transect in Oregon. The most western site, a spruce (*Picea sitchensis*) forest on the coast, has an average annual temperature of 10.6 °C, an average annual precipitation of about 187.6 cm, and is located at an elevation of approximately 335 m. The soil at the spruce site is Neskowin-Salander silt loam 5 to 35% slopes. The second site, a Douglas-fir (*Pseudotsuga meniesii*) forest, is in the Oregon Coast Range with an average temperature of 11.1 °C, an average annual precipitation of 174.9 cm, and an elevation of 300m. The soil at the Douglas-fir sit is Apt silty clay loam, 5 to 25% slopes. The third site is in the Cascade mountain range at an elevation of approximately 1143 m, in a ponderosa pine (*Pinus ponderosa*) forest. The average annual temperature is 6.8 °C and the average annual precipitation is 35.6 cm. The soil at the pine site is a Smiling-Windego complex 15 –30% slopes. The fourth site is a western juniper (*Juniperus occidentalis*) forest in central Oregon near the town of Sisters. The juniper site is located at an elevation of approximately 969 m; it receives an average of 27.9 cm of precipitation a year, and has an average annual temperature of 7.7 °C. The soil at the juniper site is Holmzie-Searles complex, 0 to 15% slopes. For the study I delineated three permanent 400m^2 plots at each site where all of the measurements were taken.

b. **Measurement of soil CO_2 efflux**

Fs measurements were performed with a Li-COR 6200 infrared gas analyzer (IRGA). The IRGA was attached to collars made of PVC piping, inserted 3 cm into the mineral soil for a minimum of 12 hours prior to the sampling time. The 12-hr period allowed for equilibration of the rhizosphere to ensure *in situ* flux rates. Eighteen measurements were taken at each site per visit. The measurements were taken at random locations within the fixed 400-m^2 plots. Fs was always measured in the morning hours at each site, which could give low estimates of the actual Fs rates. Due to the possibility of flux variation throughout the day, we conducted one set of diurnal measurements (approximately every 4 hrs from 6:00 am to 6:00 pm) at each site in the summer of 2000; these data ensure that we were not misrepresenting the average flux rate for the day.

c. **Ancillary measurements:**

Many ancillary measurements were made to determine their relationship with Fs. Hobos (small electronic thermometers contained within a plastic casing the size of a tic-tack box) were used to measure soil temperature at 10cm of depth in the mineral soil. One Hobo at each site was placed above ground to measure air temperature. The measurement periods for both soil and air temperature were recorded from the start of the study to its completion, every half hour in the soil, and every hour in the air.

Soil moisture was measured gravimetrically using soil cores, and soil water potential was measured using predawn measurements of seedling water potential. Water potential measurements were performed with a Scholander-type pressure chamber.

Above ground biomass was calculated at each site by measuring the diameter at breast height (DBH) of all the major vegetation. These measurements were they put into equations established by Gholz *et.al.* to give above ground biomass.

III. Results

Soil CO_2 flux was measured six times at the spruce and Douglas-fir sites, and five times at the pine and juniper sites in 2000. Each data point is the average of 18 measurements taken per visit per site. As seen in Table 1 and Figure 3, soil flux for the spruce site varied from a low of 3.4 μmol m^{-2} s^{-1} in January of 2001 to high of 6.3 μmol m^{-2} s^{-1} in September of 2000. At the Douglas-fir site (Table 1 and Figure 4) the lowest value was also in January 2001 at 1.9 μmol m^{-2} s^{-1} and the high was 5.2 μmol m^{-2} s^{-1} in September of 2000. The pine site (Table 1 and Fig 5) had its lowest value in May of 2000 at 2.9 μmol m^{-2} s^{-1}, and the highest measurement in July of 2000 at 4.8 μmol m^{-2} s^{-1}. Here I must note that there were no winter measurements for the pine or juniper sites in January of 2001 due to technical difficulties; if these measurements were available we would expect them to contain the lowest measurements, as in the other sites. The juniper site's lowest measurement (Table 1 and Figure 6) was in November 2000 at 0.27 $\mu mol\ m^{-2}\ s^{-1}$ and the highest was recorded in June 2000 at 2.2 $\mu mol\ m^{-2}\ s^{-1}$. These data can also be seen in the expanded data (Figures 14,15 a-d) covering all of 2000 and 2001.

To ensure that we were properly representing the actual flux rates, we measured diurnal CO_2 fluxes at each site as seen in figures 7a-d. These figures show vary little variation in Fs rates throughout the day and ensure our measurements appropriately represented the Fs rates at each site.

For the analyses, we used soil temperature data at 10 cm depth in the soil (Table 2 and Fig.10 and 12a-d). We found comparatively little seasonal variation in the soil temperature at the spruce site, more so at the Douglas-fir site and pine site respectively, and the greatest variation at the juniper site.

Above ground biomass, as seen in figure 8, was greatest at the spruce site and declined as follows; Douglas-fir, pine, and juniper.

Soil water potential as seen in figure 9 was correlated with Fs. In all but the juniper site, as the water potential became less negative the Fs dropped.

III. Discussion

Many factors may alter the rates at which CO_2 evolves from the soil. Depending on the conditions found at any given site, there may be one specific driving condition affecting Fs or several conditions driving Fs. This point becomes very apparent in this study as we move across the climatic gradient found in OTTER (Fig. 8).

The analysis of soil water potential (Fig. 9) in 2000 showed a relationship with Fs with an r^2 of 0.59 when data for all sites are combined. Analyzing the sites individually shows that at approximately –1.5 MPa and above, Fs begins to decline. This decline could be due to a possible correlation between higher water content and lower temperature. The juniper site is the only site where we measured water potential values below –1 MPa. In contrast to the other three sites, Fs declined at this site as moisture availability declined, suggesting that this is the only site where water availability limits Fs. From these data it appears there is a range of water potential at each site that harbors high Fs rates. Above or below that range Fs declines rapidly.

It has been shown that Fs is very responsive to temperature (Conant 2000). We found this to be true at two of the sites we studied, but not at all of them. As presented in Table 1 and Figures 3 and 4, we found a strong correlation between Fs and soil temperature at both spruce and Douglas-fir sites, with r^2 values of 0.88 and 0.62, respectively. As shown in Table 1 and Figures 5 and 6, this relationship becomes much weaker at the pine and juniper sites; in fact, at the juniper site, as temperature increased from June to July, Fs decreased (Tables 1 and 2, and Figures 6 and 10 and 11). In analysis of the 2001 data (Figs. 13,14 and 15a-d), there was a good relationship between temperature and Fs at the pine (Fig. 15 c) site as well as the spruce and Douglas-fir sites (Fig.15 a and b), while the juniper site (Fig. 15 d) continued to hold no relationship. The relationship probably improved at the pine site due to a larger amount of data collected. I believe that the reason temperature is not a good indicator of Fs at the juniper site is due to limiting conditions of other climatic variables. At this arid site, as the temperature increases in late summer, available soil water content decreases dramatically. As seen in figure 9, at low water potential, Fs declines rapidly. It has also been shown by both Burton *et. al.*, and Goulden *et al.* that soil respiration decreases with decreased soil water content. Therefore, at the Juniper site, soil water content could be what is limiting Fs. If this is true, it would explain why at the spruce and Douglas-fir sites, Fs increases almost linearly with soil temperature and high available soil water content. On the other hand, at the pine and juniper sites, where soil water content is limited, the relationship between temperature and Fs is strong only until the soils dry out in June, after which the relationship, as at the juniper site, is inversely associated.

The summation of the research to date (Figs. 8,16 and 17) strongly depicts the impact of climatic and vegetative variation on Fs. As is clearly evident, different forest types have different respiration rates and annual amounts.

In conclusion, temperature plays a very important role of Fs, but that role differs from one forest type to another. Soil water potential (Fig. 9) is also an important contributor to Fs across all forest types. But neither one can independently predict Fs. With the relationship of these two variables better understood and appropriately modeled to a specific aboveground biomass, strong models predicting annual Fs, can be developed.

There are two main weaknesses in this study that could affect the results. First, the winter of 2000 – 2001 was unusually dry in Oregon and this could alter the "normal" actions of the soil. Second, in the 2000 data, I have no measurements for either the pine or juniper sites during the coldest season. Only additional research will clarify whether this is a serious limitation.

With continuation of this study, a better understanding of the strengths and weaknesses of particular climatic variables will be established in comparison to what we currently know.

VI. Acknowledgements

- I thank Dr. Barbara Bond of the Department of Forest Science at Oregon State University for mentoring me through the logistics of this study, increasing my education in the area of Fs, proof reading many assignments, and providing me with the opportunity to do this research.
- I thank Nate McDowell of the Department of Forest Science at Oregon State University for development of the research idea and plan, for assistance in field work, statistical calculations, problem solving, and operation of technical equipment; for the 2001 data, statistics and regression models. In short, I thank Mr. McDowell for his tremendous help in all aspects of this study.
- I thank Dave Bowling of the University of Utah for his guidance in important aspects of this study, for writing letters of recommendation, and increasing my education in Fs.
- I also acknowledge the Undergraduate Research Innovation Scholarship Creativity (URISC) committee and grant
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Appendix

Table 1. Soil Flux (μmol $m^{-2}s^{-1}$)

	Spruce	Douglas-fir	Pine	Juniper
May-00	4.57	3.39	2.91	1.66
Jun-00	4.11	4.85	3.07	2.20
Jul-00	6.03	4.99	4.81	0.72
Sep-00	6.38	5.22	3.68	0.62
Nov-00	4.52	3.89	3.87	0.27
1-Jan	3.41	1.92		

Table 2. Soil Temperature (°C) at 10 cm

	Spruce	Douglas-fir	Pine	Juniper
May-00	8.6	8.1	9.1	12.3
Jun-00	8.9	9.4	12.0	18.2
Jul-00	12.4	13.1	14.8	20.7
Sep-00	11.4	11.9	13.4	17.2
Nov-00	9.4	9.1	7.8	3.5
1-Jan	6.4	4.9		

Fig. 1 Atmospheric CO_2 concentrations (Kimmins pg. 514)

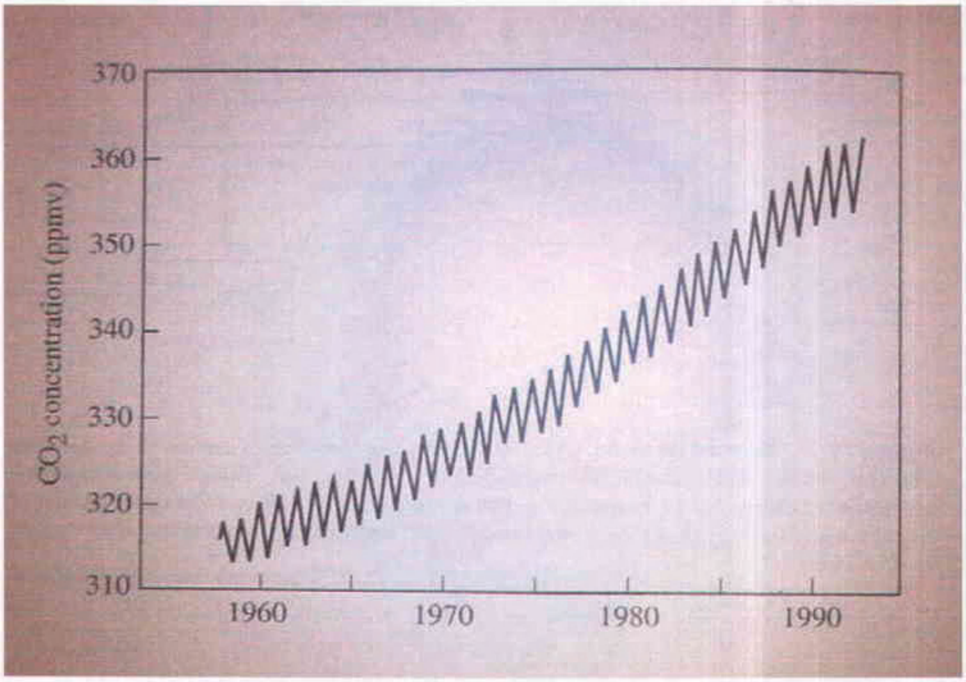
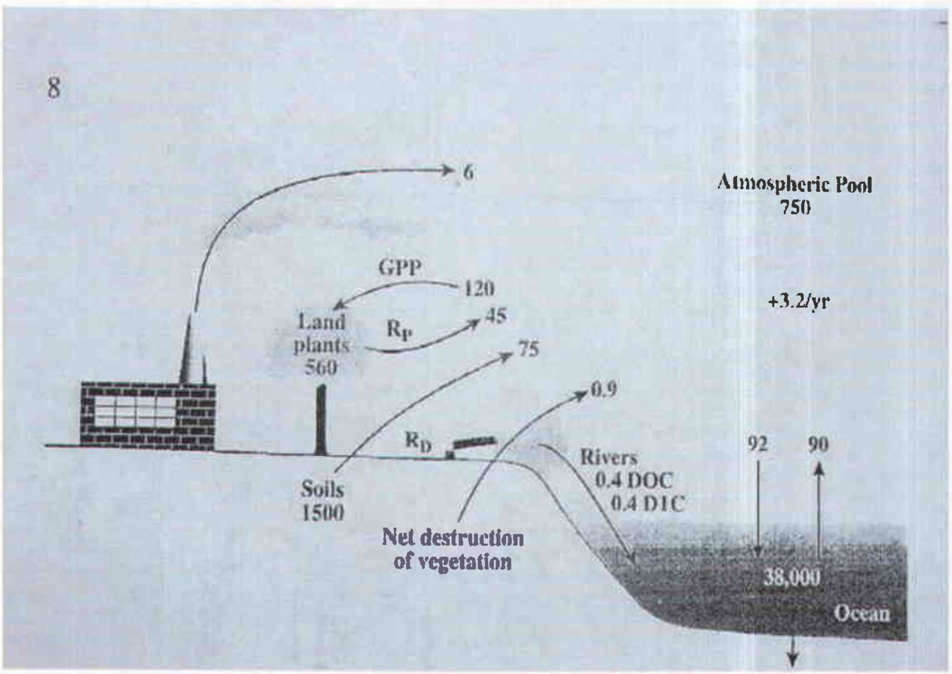


Fig. 2 Global carbon cycle (Schlesinger *et.al.* 2000)



Units 10^15 gC/yr

Fig. 3 Fs at spruce site from May 2000 to January 2001

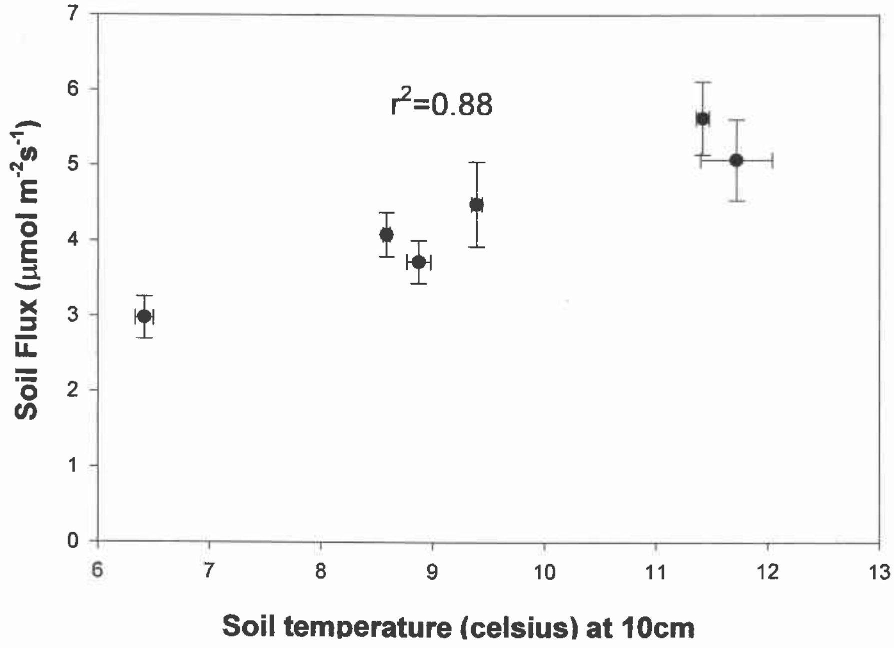


Fig. 4 Fs at Douglas-fir site from May 2000 to January 2001

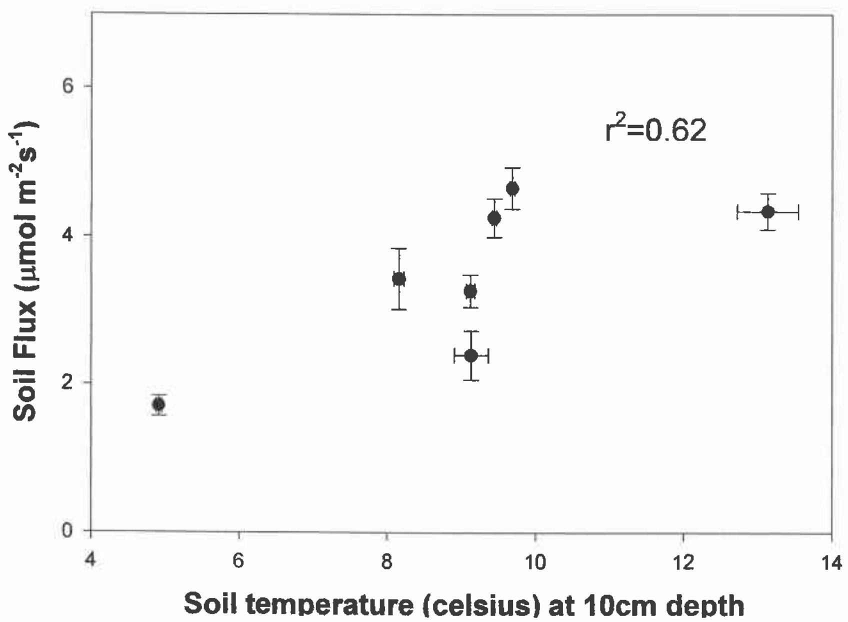


Fig. 5 Fs at pine site from May 2000 to January 2001

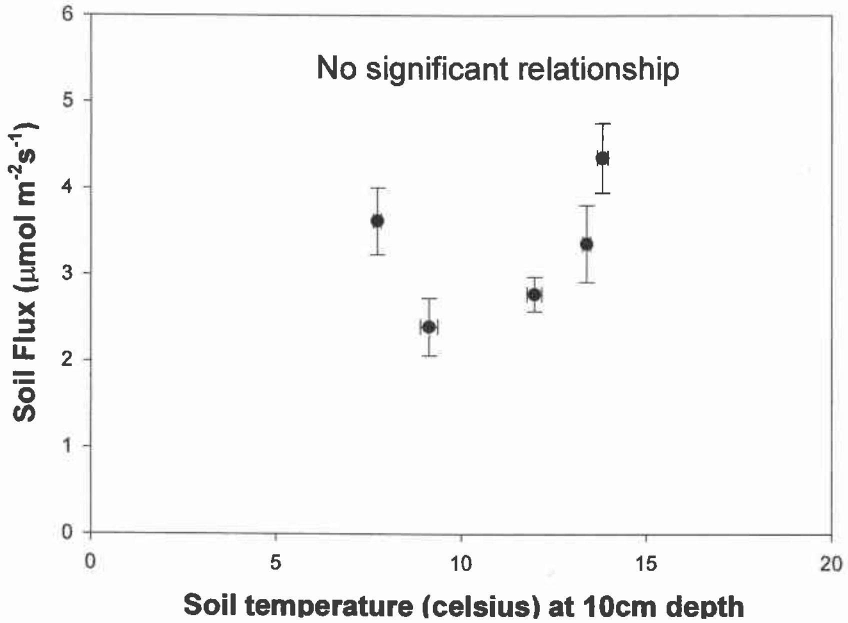
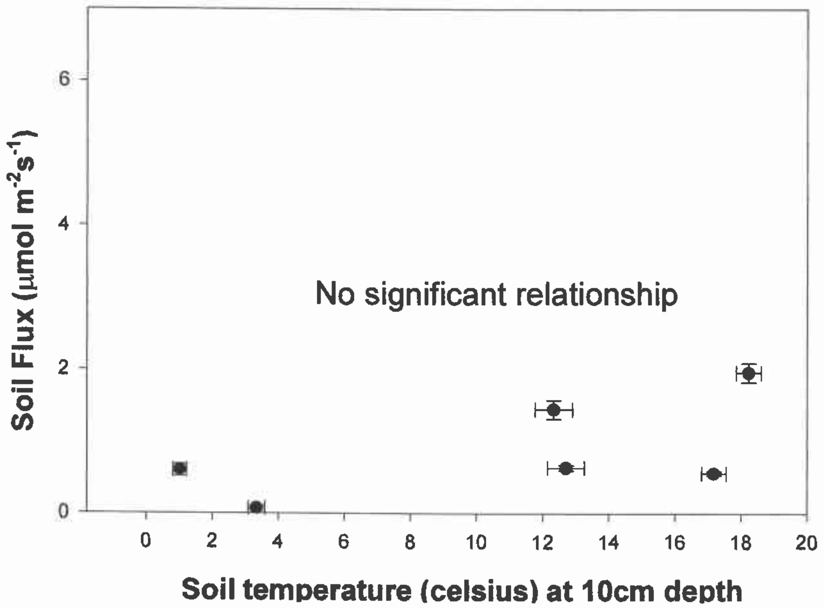


Fig. 6 Fs at juniper site from May 2000 to January 2001



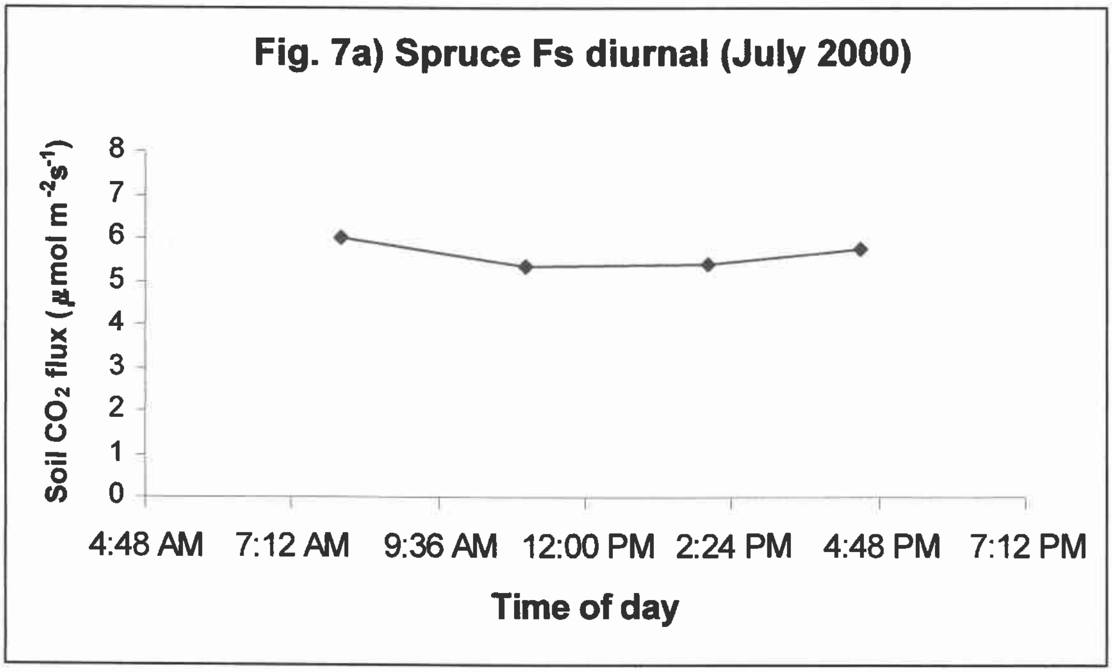


Fig. 7a) Spruce Fs diurnal (July 2000)
Soil CO2 flux (µmol m-2s-1)
8
7
6
5
4
3
2
1
0
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
Time of day

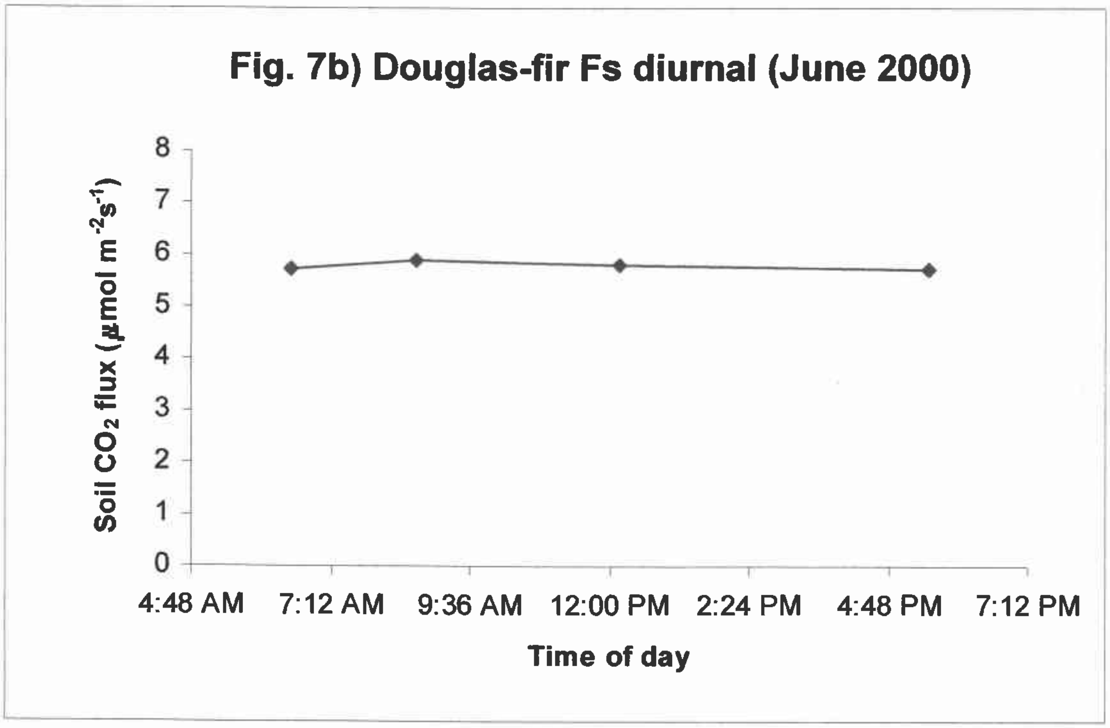


Fig. 7b) Douglas-fir Fs diurnal (June 2000)
Soil CO2 flux (µmol m-2s-1)
8
7
6
5
4
3
2
1
0
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
Time of day

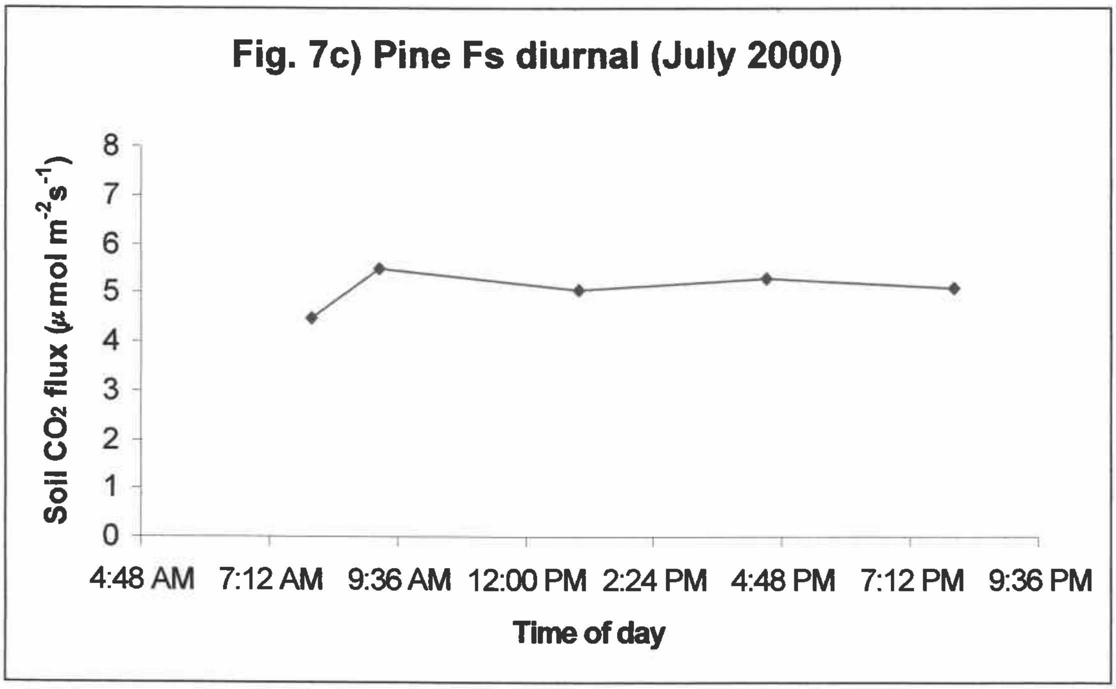


Fig. 7c) Pine Fs diurnal (July 2000)
Soil CO2 flux (μmol m-2s-1)
0
1
2
3
4
5
6
7
8
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
Time of day

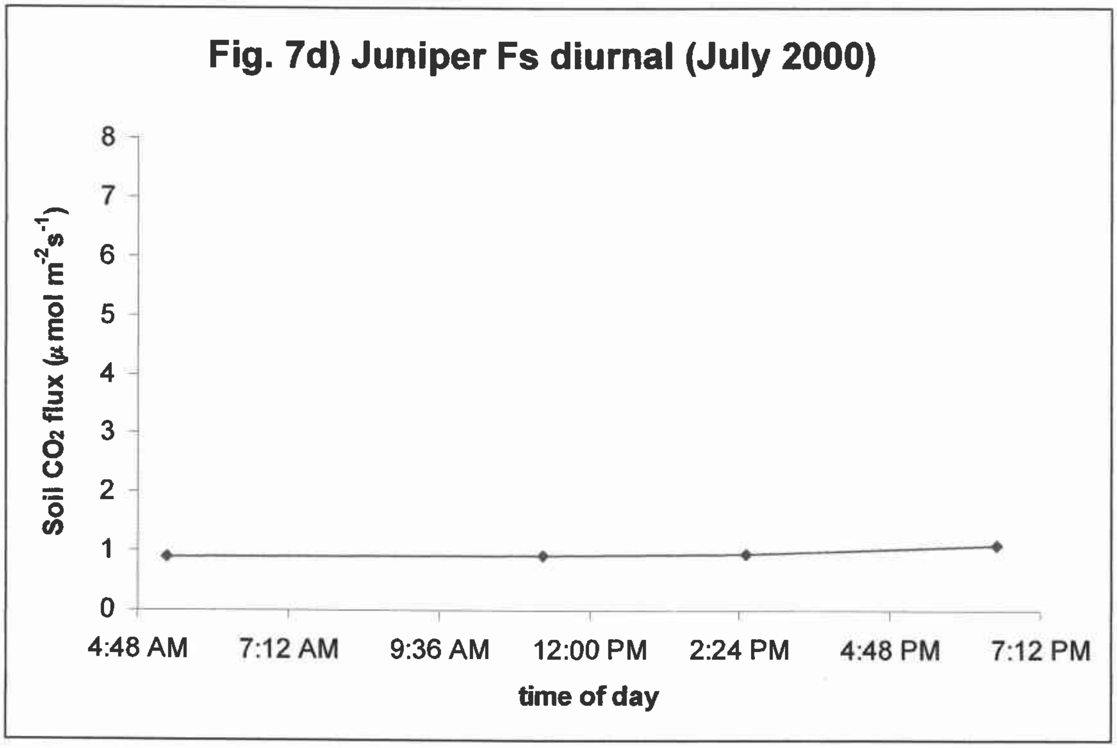


Fig. 7d) Juniper Fs diurnal (July 2000)
Soil CO2 flux (μmol m-2s-1)
0
1
2
3
4
5
6
7
8
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
time of day

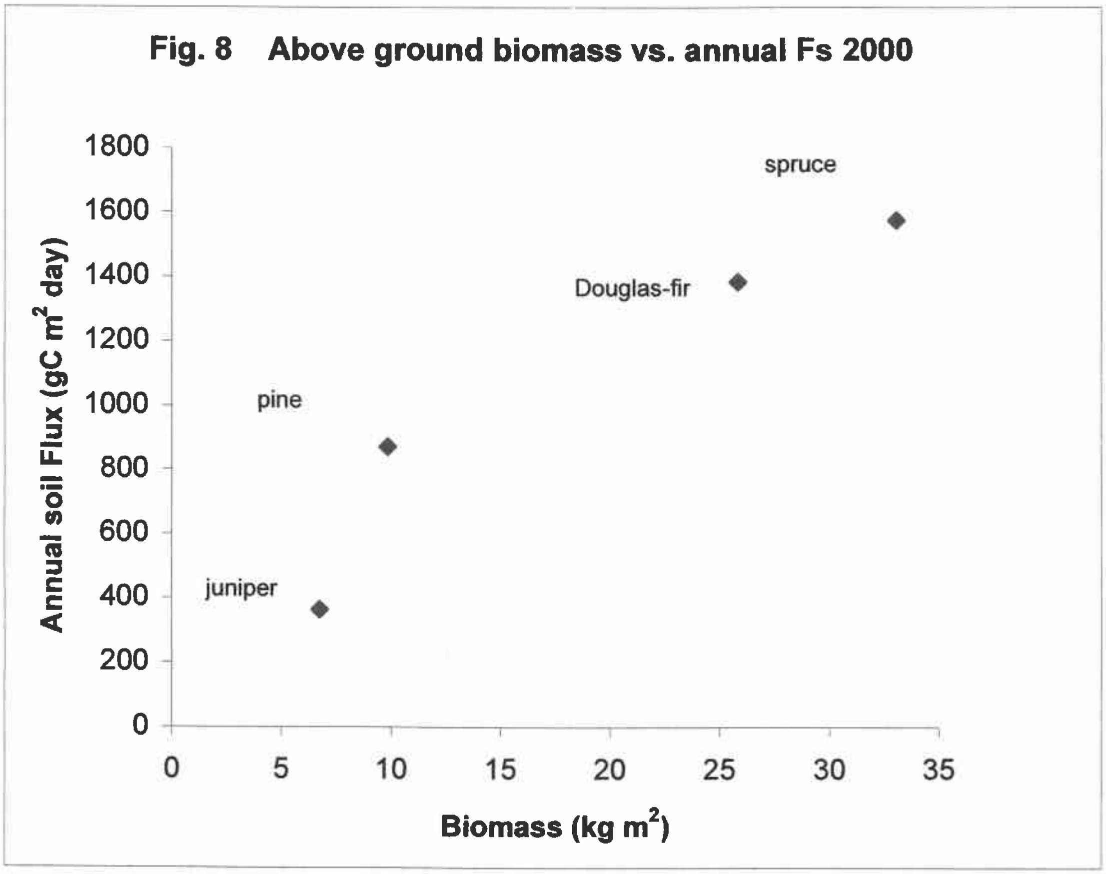


Fig. 8 Above ground biomass vs. annual Fs 2000
Annual soil Flux (gC m2 day)
1800
1600
1400
1200
1000
800
600
400
200
0
spruce
Douglas-fir
pine
juniper
0
5
10
15
20
25
30
35
Biomass (kg m2)

Fig. 9 Predawn water potential vs. Fs (2000)

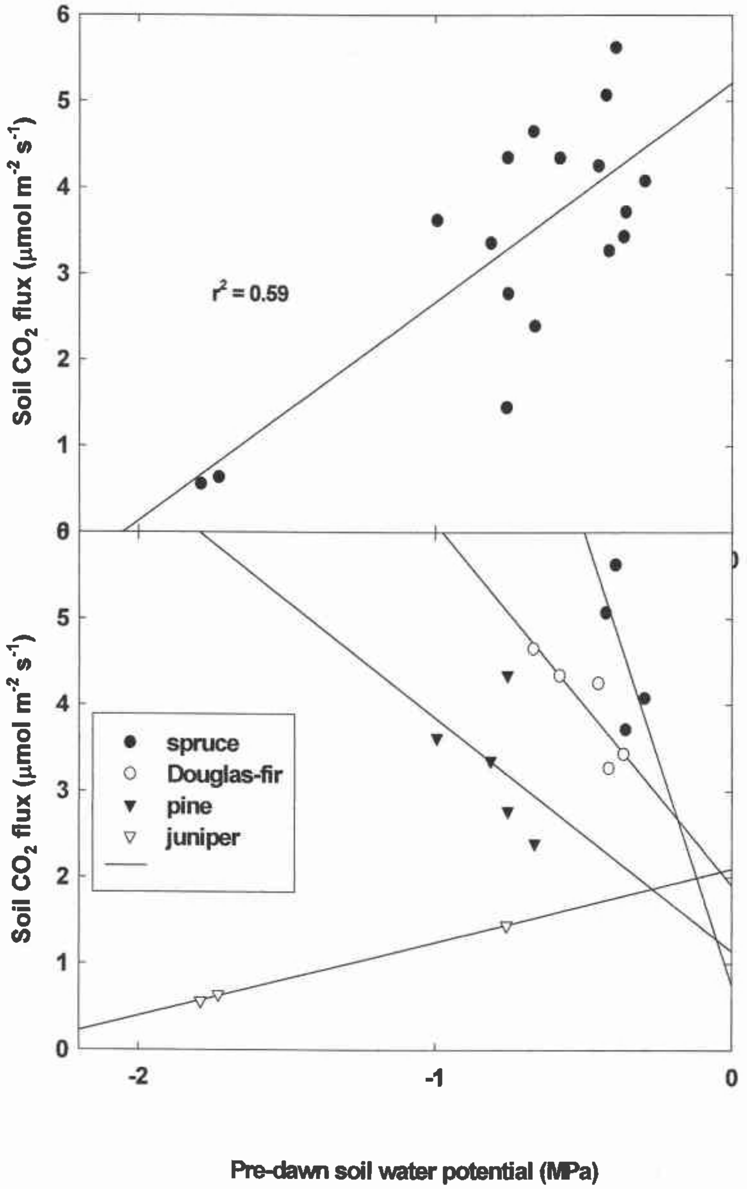
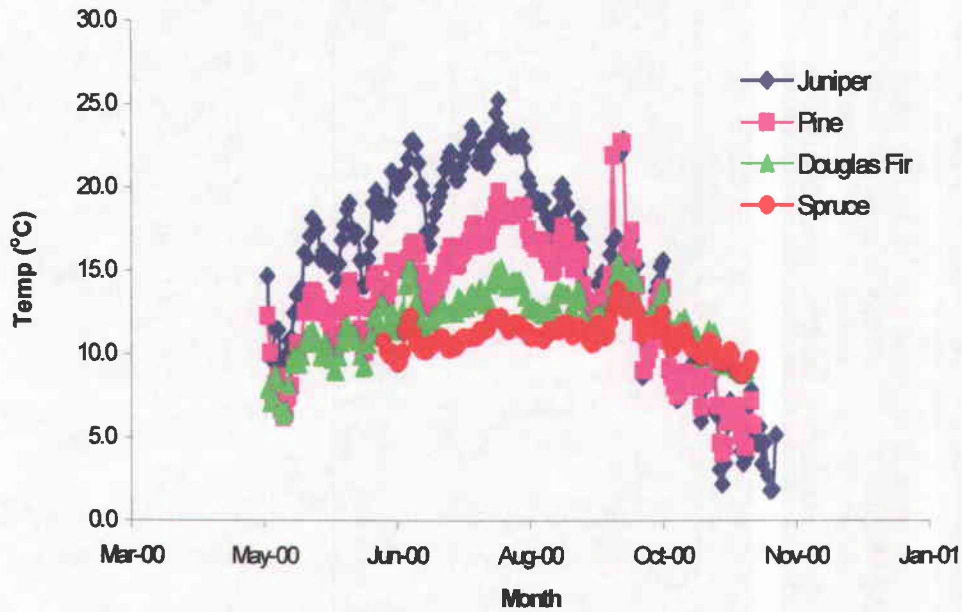


Fig. 10 Soil temperature at 10cm across OTTER (2000)



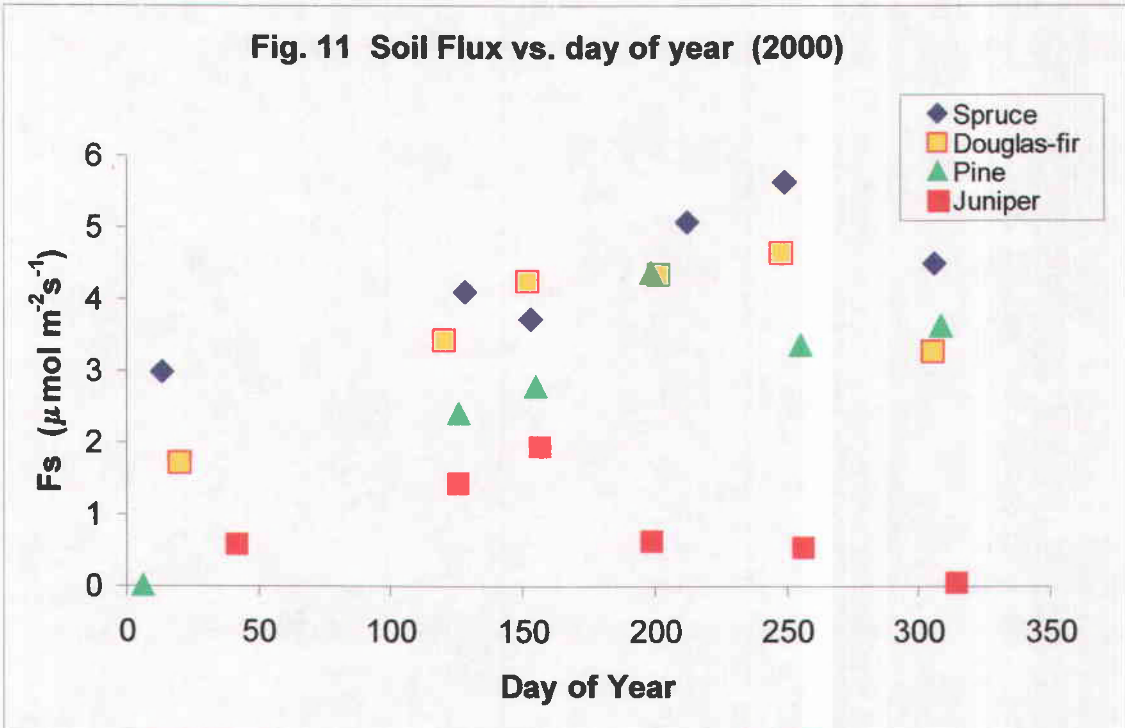


Fig. 11 Soil Flux vs. day of year (2000)
Spruce
Douglas-fir
Pine
Juniper
Fs (μmol m-2s-1)
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350
Day of Year

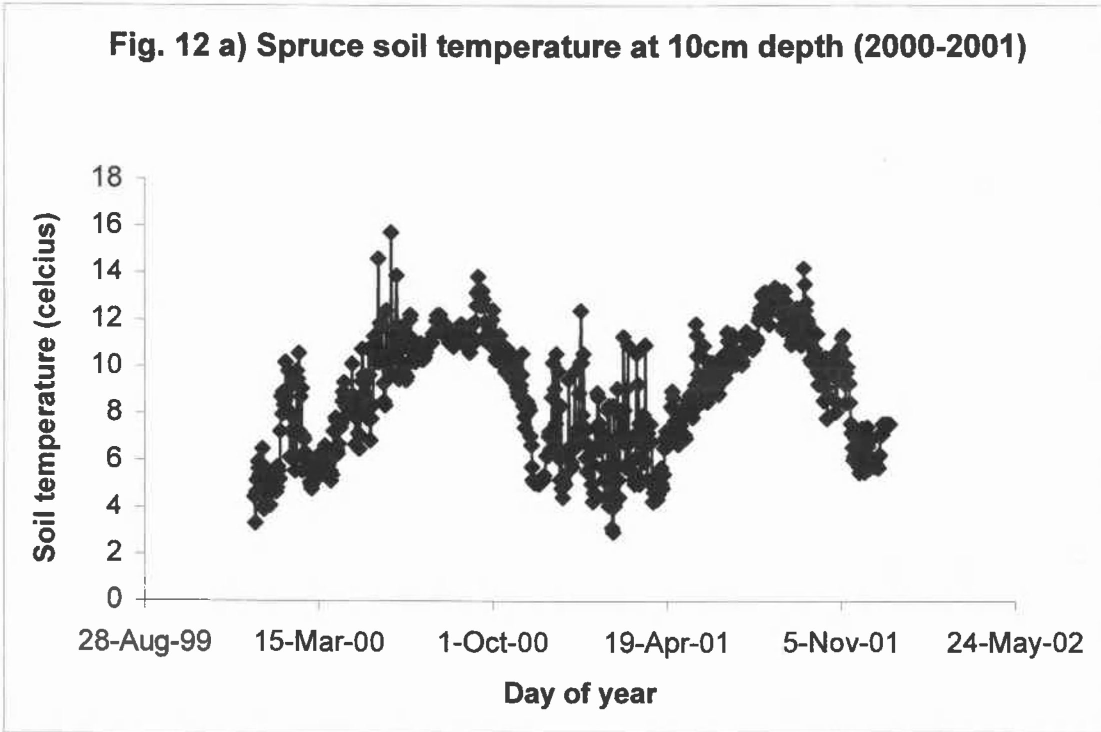


Fig. 12 a) Spruce soil temperature at 10cm depth (2000-2001)
Soil temperature (celcius)
0
2
4
6
8
10
12
14
16
18
28-Aug-99
15-Mar-00
1-Oct-00
19-Apr-01
5-Nov-01
24-May-02
Day of year

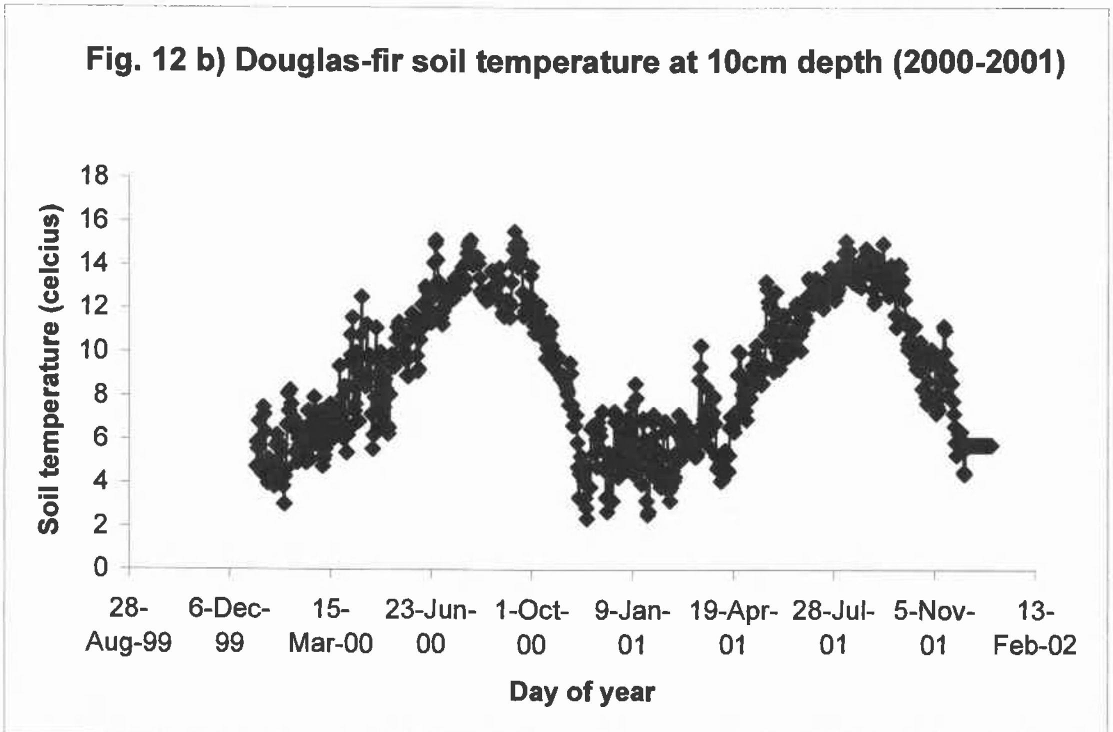


Fig. 12 b) Douglas-fir soil temperature at 10cm depth (2000-2001)
Soil temperature (celcius)
0
2
4
6
8
10
12
14
16
18
28-Aug-99
6-Dec-99
15-Mar-00
23-Jun-00
1-Oct-00
9-Jan-01
19-Apr-01
28-Jul-01
5-Nov-01
13-Feb-02
Day of year

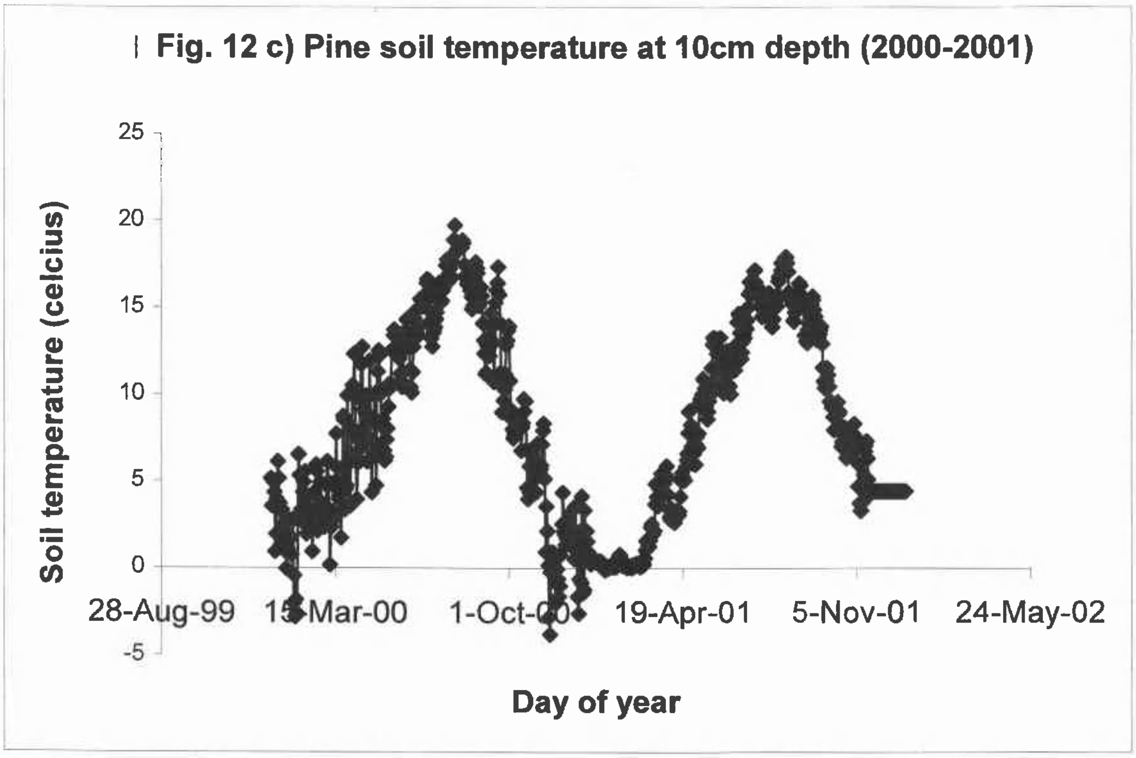


Fig. 12 c) Pine soil temperature at 10cm depth (2000-2001)
25
20
15
10
5
0
-5
Soil temperature (celcius)
28-Aug-99
15-Mar-00
1-Oct-00
19-Apr-01
5-Nov-01
24-May-02
Day of year

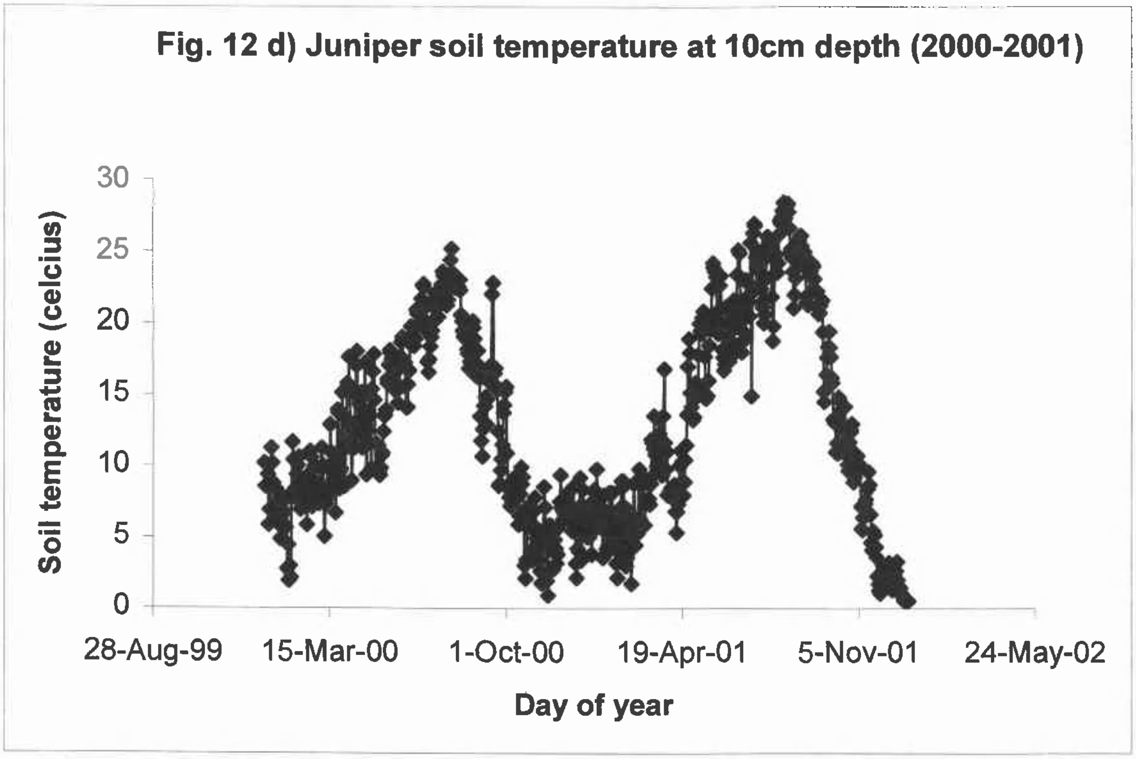


Fig. 12 d) Juniper soil temperature at 10cm depth (2000-2001)
30
25
20
15
10
5
0
Soil temperature (celcius)
28-Aug-99
15-Mar-00
1-Oct-00
19-Apr-01
5-Nov-01
24-May-02
Day of year

Fig. 13 Soil Flux vs. day of year across OTTER (2000-2001)

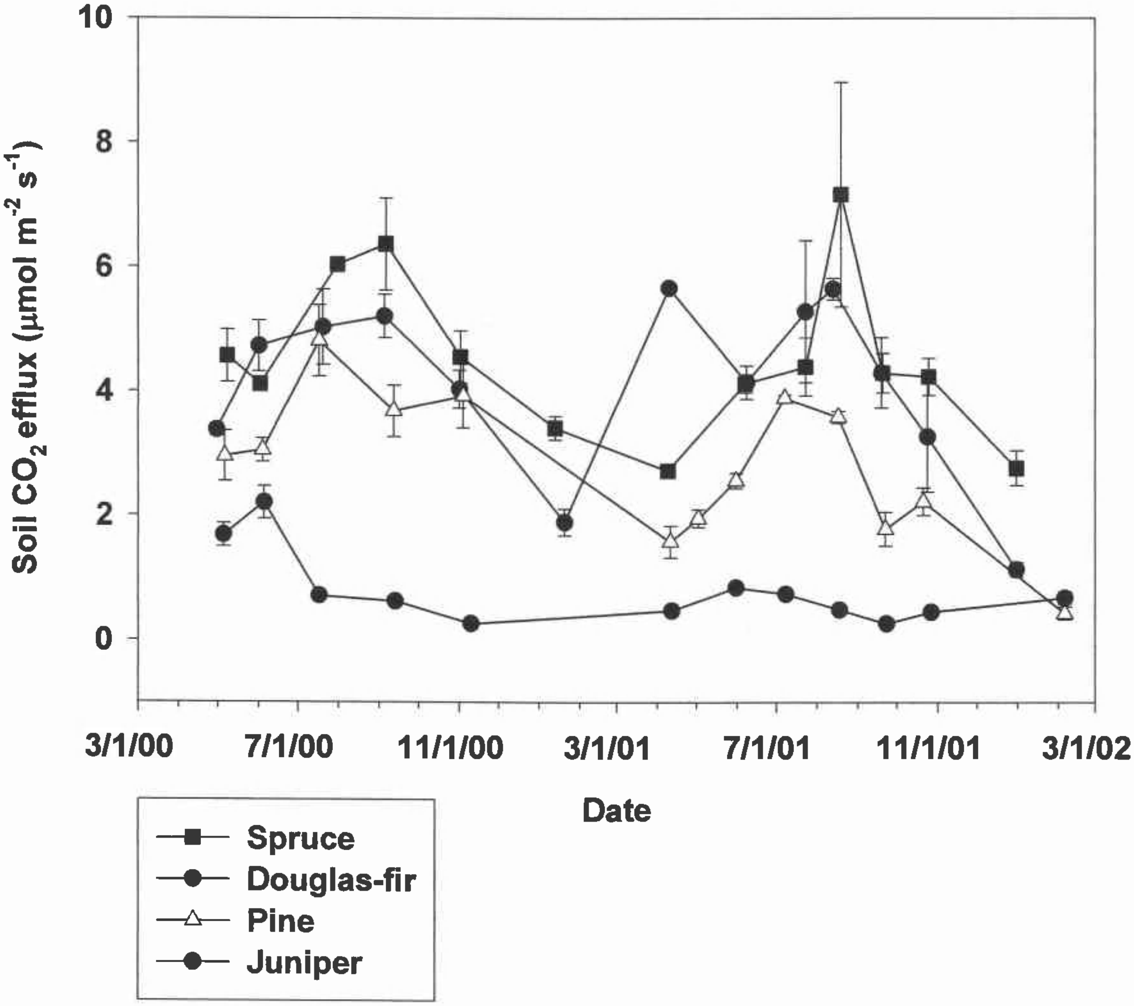


Fig. 14 Soil Flux vs. temperature across OTTER (2000-2001)

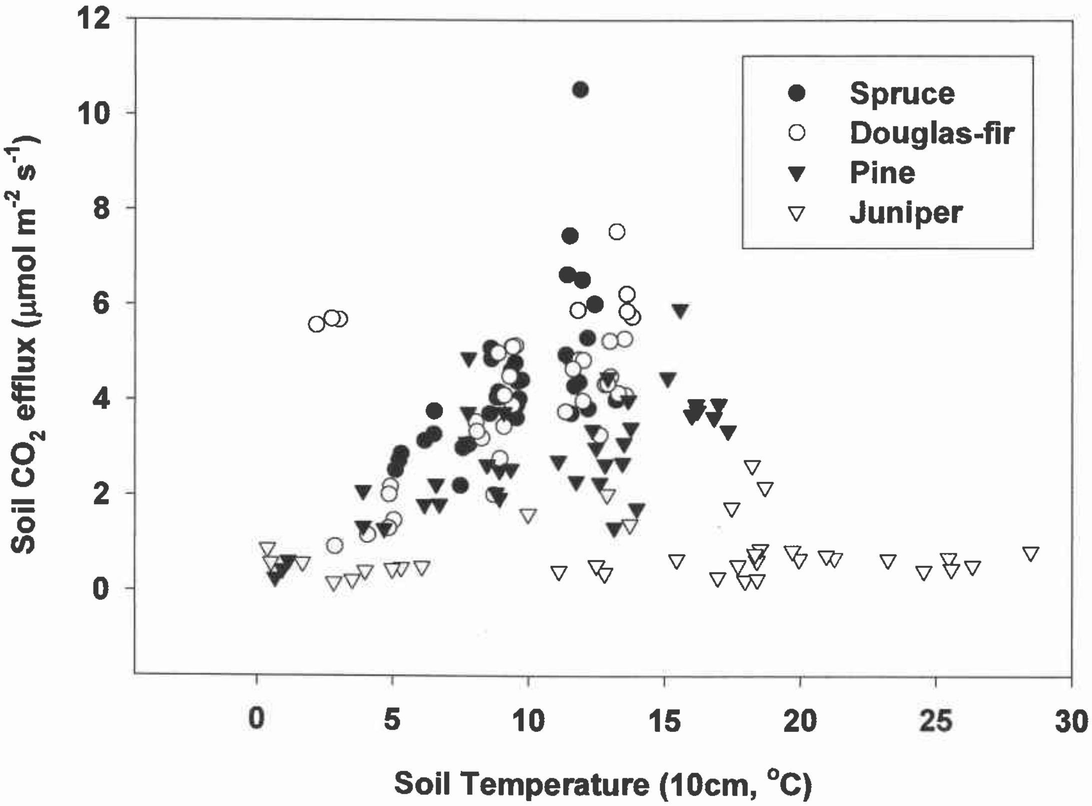


Fig. 15 a. Spruce soil flux vs. temperature (2000-2001)

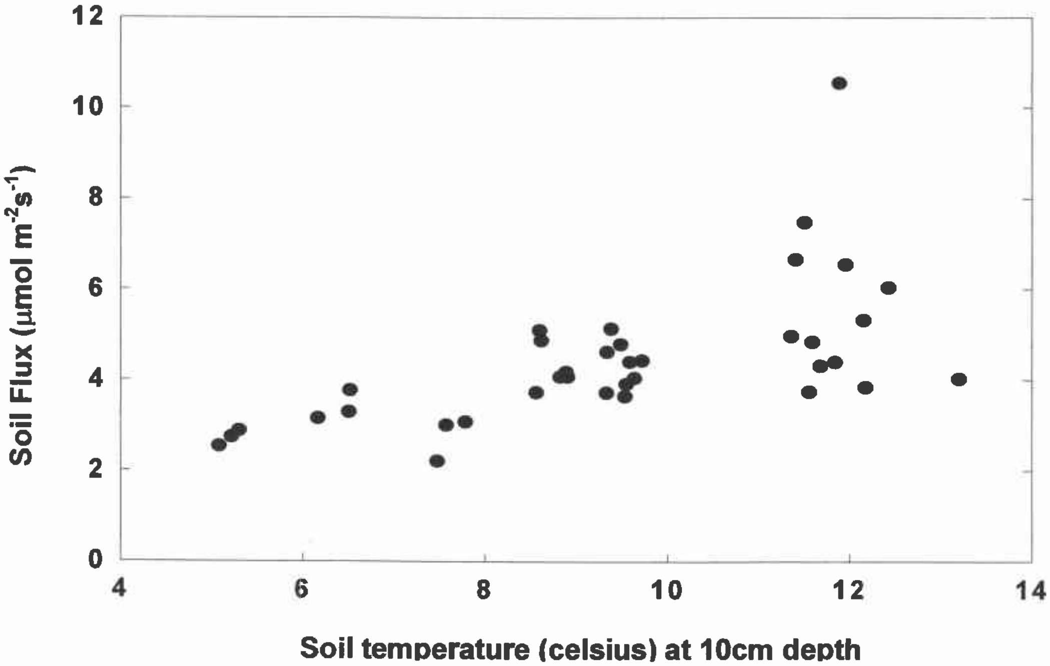


Fig. 15 b. Douglas-fir soil flux vs. temperature (2000-2001)

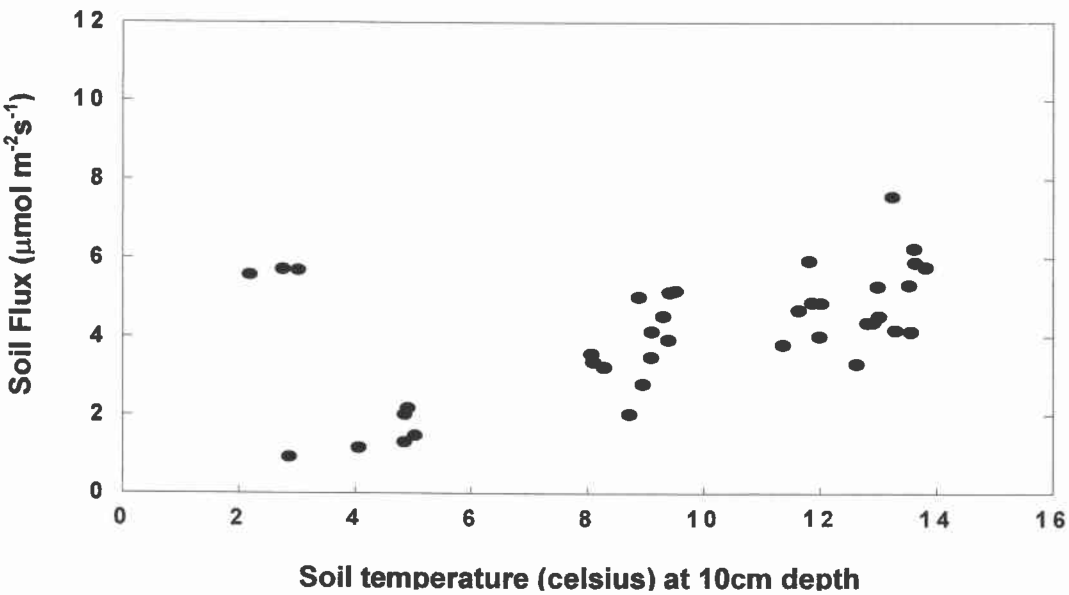


Fig. 15 c. Pine soil flux vs. temperature (2000-2001)

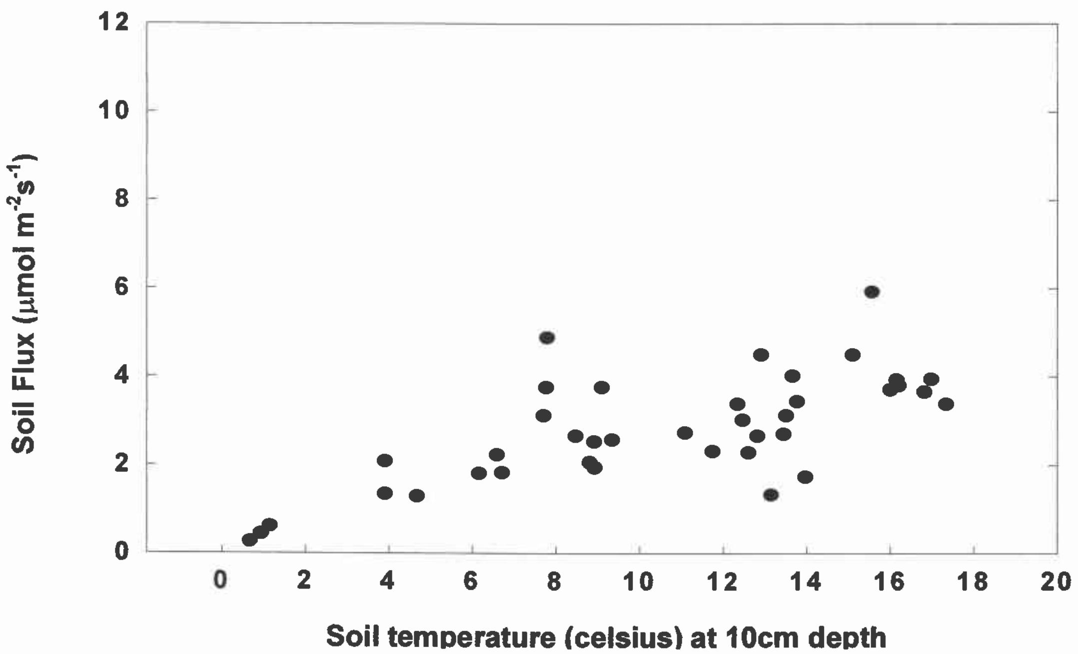


Fig. 15 d. Juniper soil flux vs. temperature (2000-2001)

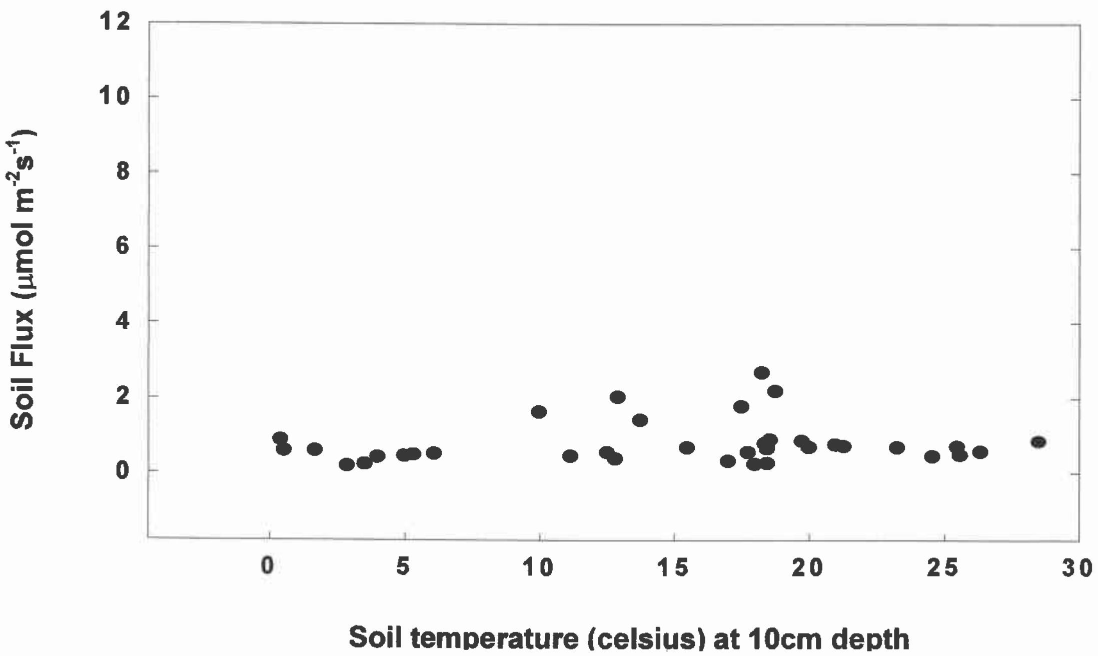
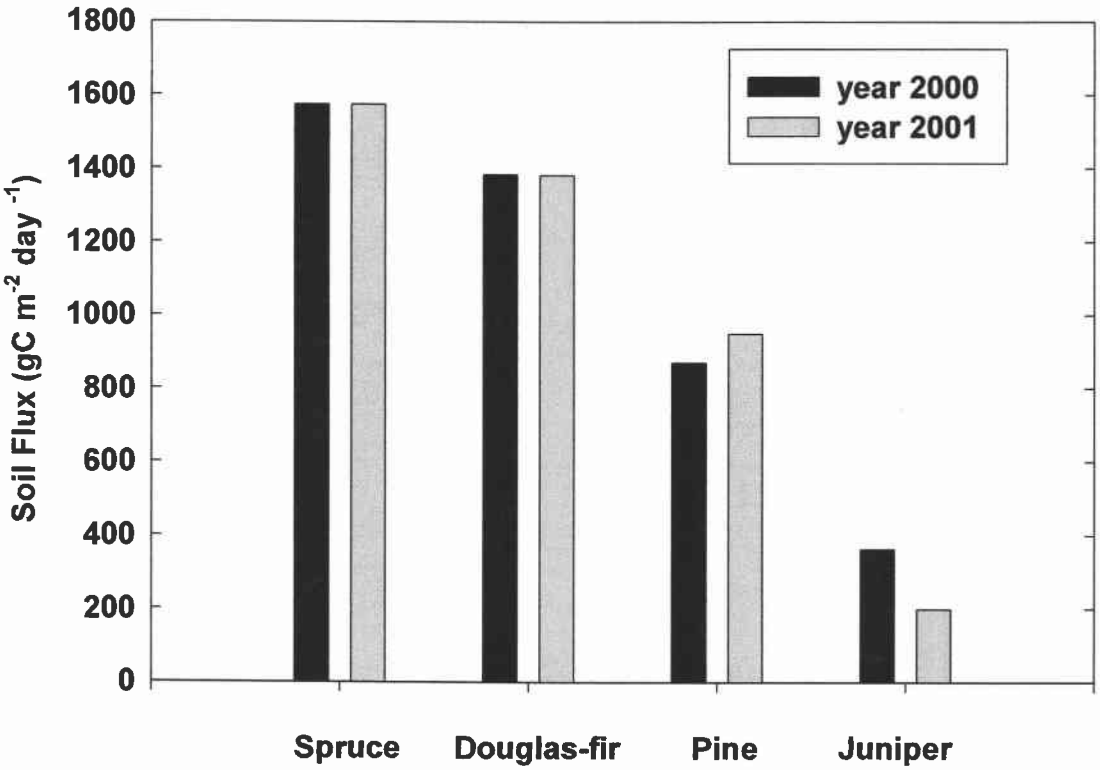


Fig 16. Annual soil respiration flux across OTTER



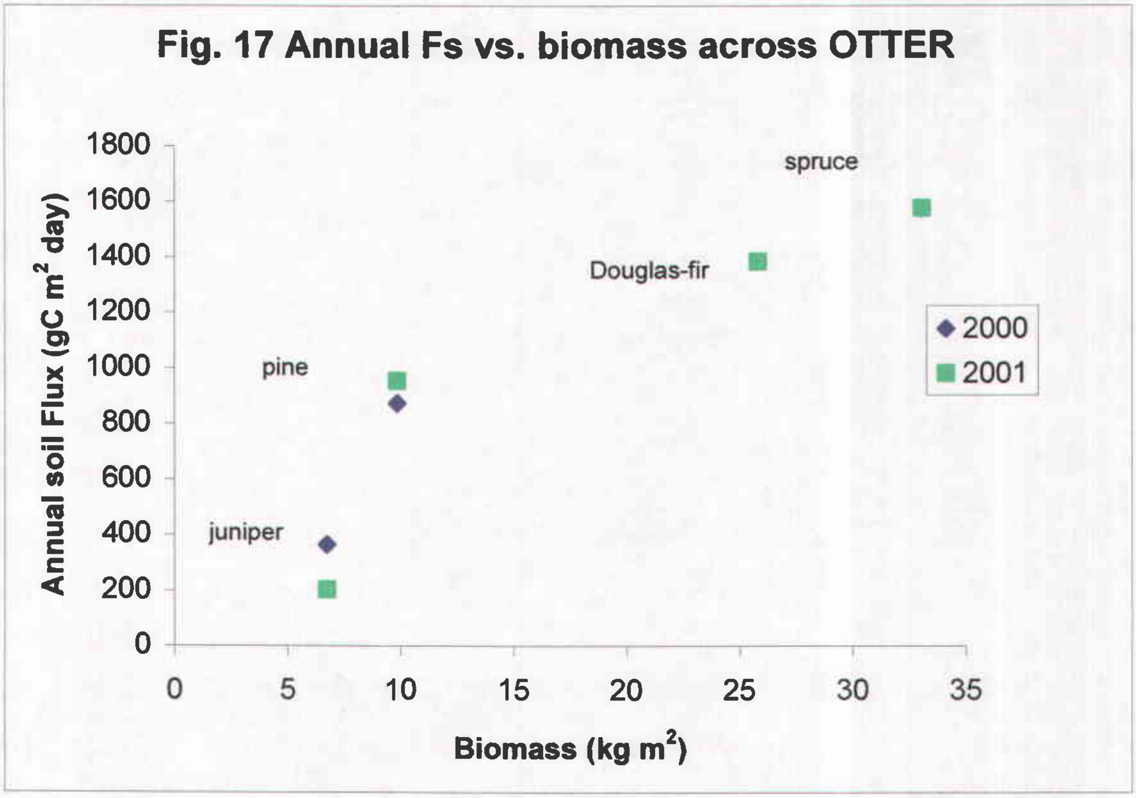


Fig. 17 Annual Fs vs. biomass across OTTER
Annual soil Flux (gC m2 day)
1800
1600
1400
1200
1000
800
600
400
200
0
spruce
Douglas-fir
pine
juniper
2000
2001
0
5
10
15
20
25
30
35
Biomass (kg m2)