Chapter 6

Spatial dependence of soil CO_2 efflux and the effect of clearfelling on temporal and spatial variability of soil CO_2 efflux

6.1 Introduction

Very often in field studies the problem of autocorrelation arises, that is samples collected close to one another are often more similar than samples collected further away, whether in space or time. In many field studies such autocorrelation can arise from subtle topographic features of a site and other environmental factors such as microclimate or soil nutrient status and temporal features such as diurnal trends in temperature (Robertson, 1987). In temperate forest soils spatial heterogeneity is a dominant and conspicuous feature (Bruckner *et al*., 1999). Soil CO_2 efflux rates show large spatial variations both within and among sites (Raich and Nadelhoffer, 1989; Norman *et al.*, 1997) as well as temporal changes (Borken *et al*., 2002). Singh and Gupta (1977) indicate that temperate habitats show great variability in soil CO_2 efflux, with values in temperate forests ranging from 2.4 to 12 g CO_2 m^{-2} d^{-1}, and maximum values up to 56.16 g CO_2 m^{-2} d^{-1}. This variability is due to the several factors that affect soil CO_2 efflux, such as soil temperature and water content (Raich and Potter, 1995; Davidson *et al*., 1998), soil microbial population levels (Klopatek, 2002), availability and quality of soil C substrates (Orchard and Cook, 1983), levels of plant root activity (Ewel *et al*., 1987, Bowden *et al*., 1992), and vegetation type (Raich and Schlesinger, 1992).

Land use changes, like the conversion of grassland to forest, may have considerable effects on the spatial variation of soil CO_2 efflux, due to the mechanical preparation of the site for the planting of trees. Forest management practices such as clearfelling may result, conversely, in changes in spatial variation of soil CO_2 efflux, since the removal of the trees alters dramatically the microclimate at the forest floor, while mechanical disturbance caused by the harvesting machines causes compaction of the soil and changes in its physical properties (Pritchett, 1979).

Spatial variability of soil CO_2 efflux has not been studied extensively, although it has been reported of being very high in some ecosystems (Raich *et al*., 1990; Hanson *et al*., 1993). It is important to estimate soil CO_2 efflux accurately in order to evaluate the carbon budget of an ecosystem. However, this may require a large number of sampling points for the estimation of a representative value within an ecosystem. This may be practically difficult to implement in the field.

Geostatistical analyses provide powerful analytical tools to capture the horizontal variability of a property and have received increasing interest by soil biologists in recent years. In its simplest form geostatistics define the degree of autocorrelation among the measured data points and interpolates values between measured points based on the degree of autocorrelation encountered (Robertson, 1987). Spatial patterns are usually described using the experimental semivariogram $\gamma(\mathbf{h})$ which measures the average dissimilarity (or inversely autocorrelation) between data separated by a vector **h.** Variograms can be derived from a few or from many thousands of data points**,** but those based on fewer than 50 data points are often erratic sequences of experimental values with little or no evident structure**.** The form of the variogram becomes clearer as the size of the sample increases (Webster and Oliver, 2001).

Another useful indicator of spatial variation of soil CO_2 efflux is the coefficient of variation (CV), resulting from the variability among different sampling locations, and it is useful for comparing the variation of different sets of observations of the same property (Webster and Oliver, 2001), e.g., in this case the variation of soil CO_2 efflux across the different dates of the study period.

Because of the paucity of information on the spatial variability of CO_2 efflux from the soils of the Sitka spruce stands and the total lack of data referring to disturbed areas such as clearfells, it was decided to conduct a systematic study in study sites in Harwood Forest. In particularly the objectives were: a) to investigate the spatial patterns of soil CO_2 efflux in mature Sitka spruce stands, b) to evaluate the contribution to soil CO_2 efflux from the different strata (ridges, furrows and plain ground) within a stand, resulting from the mechanical preparation of the original grassland soil for the drainage of the site and the planting of trees and c) to evaluate the adequacy of the number of sampling points adopted for the measurement of CO_2 efflux.

6. 2 Materials and methods

6.2.1 Site selection and sampling strategy

The study was conducted over two summers (2001 and 2002) in two 40-yr-old stands. One of the two stands was clearfelled during the winter 2001-2002 and further investigations were carried out after clearfelling (see Chapter 3 for further information on site characteristics).

In early June 2001, 90 collars (7 cm height and 10 cm diameter) were installed in a 30 x 30 m plot (A) located in the CF_{before} stand. Within the plot the 90 collars were placed at the intersections of a 3 x 3 m grid. The measurement of the 90 collars took place over two days, with approximately half of the collars measured on one day and the other half the next day. All of measurements took place between 9:00 and 15:00. Two complete sets of measurements were obtained on 23-24 June and on 4-6 July 2001. Additionally 66 of the 90 collars were also measured on 1 August 2001.

Spatial variability was also characterized at a lower spatial scale, by installing collars in a denser grid. Thus, in the same stand, 72 collars were installed in a 3 x 2 m plot

(B) at varying distances between 10 and 60 cm. This second set of collars was measured once on 25 October 2001. In the 40-yr-old control stand (40-yr) 52 collars were installed in a 2 x 2 m plot and at varying distances between 10 and 60 cm and they were measured once on 12 July 2002.

Soil CO_2 efflux was measured with a portable, closed dynamic chamber (EGM-3, with SRC-1, PP Systems, UK) equipped with a portable infra-red gas analyser (IRGA) (for a more detailed description, see Chapter 3). Soil temperature at 1 and 5 cm depth (from now on referred as T_1 and T_5 respectively) and soil water content (W) were taken adjacent to each collar at the time of the measurement.

6.2.2. Spatial dependence

The structure of the spatial dependence (autocorrelation) was studied by using the semivariogram, in which the semivariance is calculated for different distance intervals (lags). It is computed as the average squared difference between all the component data pairs:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{a=1}^{N(h)} \left[z(u_a) - z(u_a + h) \right]^2 \qquad (1)$$

where z is the measured variable (in this case soil CO_2 efflux) at location $\mathbf{u}_a$, and a= 1, 2,…. N(**h**) is the number of data pairs within a given class of distance and direction (Goovaerts, 1999). The shape of the plot describes the degree of autocorrelation present. The shape of the experimental semivariogram may take many forms, depending on the data and sampling interval used. Ideally, the semivariance increases with distance between sample locations, rising to a more or less constant value, the sill, at a given separation (lag) distance, which is called the range of spatial dependence, A_0. Samples separated by distances closer than the range are spatially dependent. The sill approximates the sample variance for stationary data. Semivariances may also increase continuously without showing a definite range and sill, thus preventing definition of a spatial variance, indicating the presence of trend effects and nonstationarity (Trangmar *et al*., 1985).

In theory, the semivariogram should start from zero, but experimental semivariograms generally do not. This non-zero -variance at zero distance is called the nugget variance or nugget effect, C_0, and it represents unexplained or "random variance", often caused either by measurement error or spatial variation that cannot be detected at the scale of the sampling grid (Trangmar *et al*., 1985). The difference between C_0 and the sill is called the structural variance, C, and represents the variance accounted for by the spatial dependence.

The sum of $C + C_0$ approximately equals the sill or sample variance for stationary data. The nugget variance can also be expressed as the percentage of the sill value to allow a comparison of the relative size of the nugget effect among samples. A nugget variance of 0 % of sill means that there is neither measurement error nor significant short-range variation present. Pure nugget effect (100% of sill) arises from very large point-to-point variation at short distances and indicates a total absence of spatial correlation at the sampling scale used.

6.2.3 Geostatistical and statistical analysis

The coefficient of variation is defined as:

$$CV = \frac{s}{x} \times 100\% \tag{2}$$

where: *s* is the standard deviation

and *x* is the mean of the population

The number of samples (n) needed to estimate the mean soil respiration of the plot within 20% of its actual value, at the 95% probability level, was estimated using the formula:

$$n = \frac{t_a{}^2 s^2}{d^2} \tag{3}$$

where t_α is Student's t value with degrees of freedom at the a probability level, s is the standard deviation, and d is the specified error limit (Petersen and Calvin, 1986).

The geostatistical analysis of the data was performed with the geostatistical program GS+, version 5.3b (Gamma design software). Repeated-measures ANOVA were used to test for the effect of location (furrow, ridge and plain ground) on soil CO_2 efflux across dates. The statistical analysis of the data was performed in SAS (1988), SPPS (1998), and Minitab (version 13.20).

6.2.4 Spatial variation

The data collected during the study period from all sites (CF_{before}, CF and 40-yr) were used to estimate the spatial variation present in the experimental sites and to evaluate the effect of disturbance, such as ploughing for the planting of trees and clearfelling. The full details of the sampling procedure and methods used can be found in Chapter 3. In brief, the methods used to estimate soil CO_2 efflux were:

Closed dynamic chamber method (DC): In the CF_{before} stand, from the 90 collars already installed for the geostatistical analysis, 10 were randomly selected for the continued measurements over the next year. In the 40-yr stand, 30 collars were randomly installed and after the first sets of measurements, 10 were randomly selected for the continued measurements during the rest of the study. The collars were permanently inserted in the soil at about 3 cm depth.

Closed static chamber method (SC): In each mature stand 12 chambers (inside diameter 40 cm and height 20 cm) open at the top and the bottom, were inserted into the soil in a depth of about 5 cm, in a stratified design (4 sets of 3 strata: plain, ridge and furrow). After clearfelling of one of the stands, 12 chamber were placed in the site, as close as possible to their old positions.

6.3 Results

6.3.1 Spatial dependence

As mentioned in the Materials and Methods section, sampling 90 collars required measuring from 9.00 to 15.00 over two consecutive days. This may have resulted in differences on soil CO_2 efflux due to variations in environmental conditions between different days or time of day. The coefficient of variation for soil T_5 was very low, 4% during all measurement days in July and August and 10 % for June (same for T_1), suggesting small day-to-day variability and spatial heterogeneity in soil temperature. However, the coefficient of variation for soil water content was much higher, with an average of about 35%, 44% and 27% for June, July and August, respectively. Soil CO_2 efflux was not related to soil temperature or water content during the days of measurements (for n=265, R^2= 0.06, 0.04 and 0.09 for T_1, T_5 and soil water content, respectively- similar R^2 values were obtained from the individual sampling days), suggesting that these factors strongly influence temporal variability but not spatial variability (Yim *et al*., 2003). Furthermore, the soil CO_2 efflux, measured in the 30-yr-old stand in the same forest over five continuous days, showed a diurnal coefficient of variation of only 2%-7% (with only one exception of 15%) for August 2001 (T. Ball, unpublished data), suggesting that changes in soil CO_2 efflux within individual days were small. Thus, no temperature correction was made to the soil CO_2 values collected during these campaigns at different times of the day.

6.3.1.1 30 x 30 m plot (3 x 3 m grid)

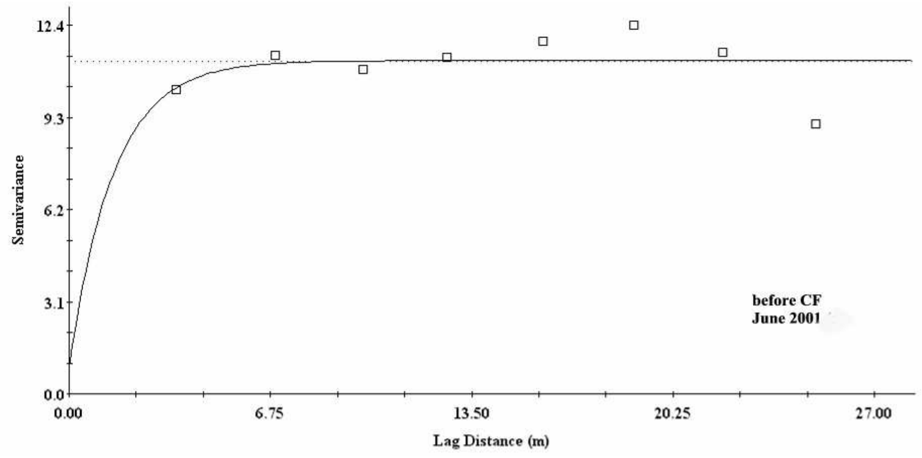
The soil CO_2 efflux data followed a normal distribution in June, but not in July and August. The variograms for June, July and August 2001 are shown in Figure 1. All variograms exhibit a clear sill.

The statistical models fitted and the relevant parameters are shown in Table 1. For the best fit of the models the Residual Sum of Squares (RSS) was used–the lower the RSS the better the model fits-as it is more robust than the regression coefficient (R^2).

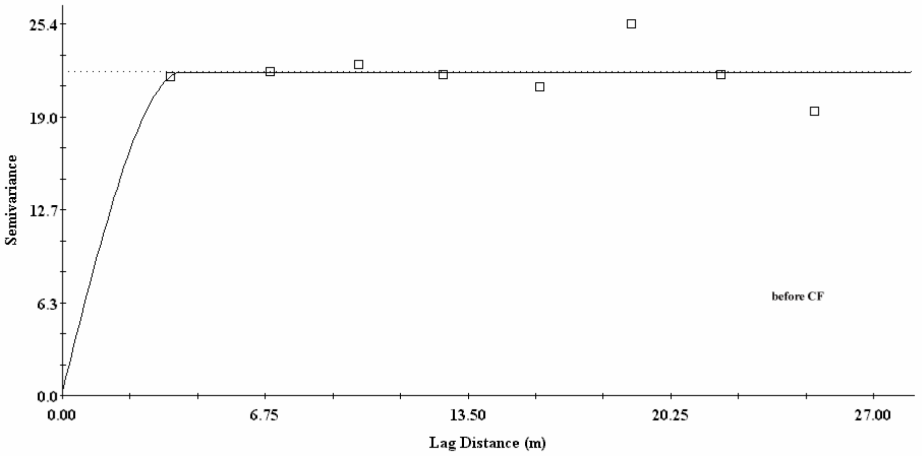
Table 1: The models used for the semivariograms and the fitted parameters of soil CO_2 efflux in the CF_{before} and 40-yr stands.

Site (plot)	Model	Range (A_0) (m)	Nugget (C_0)	Structural variance (C)	Sill (C_0+C)	C/(C_0+C), %	RSS
CF_{before} June 01 (A)	exponential	1.48	0.88	10.33	11.21	99	6.63
CF_{before} July 01 (A)	gaussian	1.75	2.41	19.16	22.07	89	19.3
CF_{before} August 01 (A)	gaussian	1.54	2.53	22.46	24.99	89	58.7
CF_{before} (B)	spherical	0.44	3.15	3.16	6.31	50	1.56
40 yr	Linear to sill	0.55	10.47	14.1	24.45	58	14.3

i)



ii)



iii)

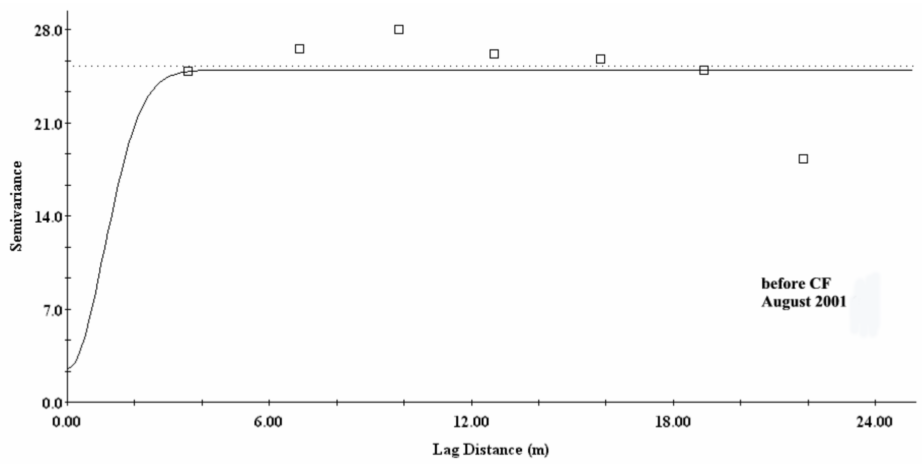


Figure 1: Semivariograms of soil CO_2 efflux in the CF_{before} (A) stand, for two sampling occasions in June (i), July (ii) and August (iii) 2001. The solid lines represent the models fitted in the semivariograms and the dotted lines the variance of the data.

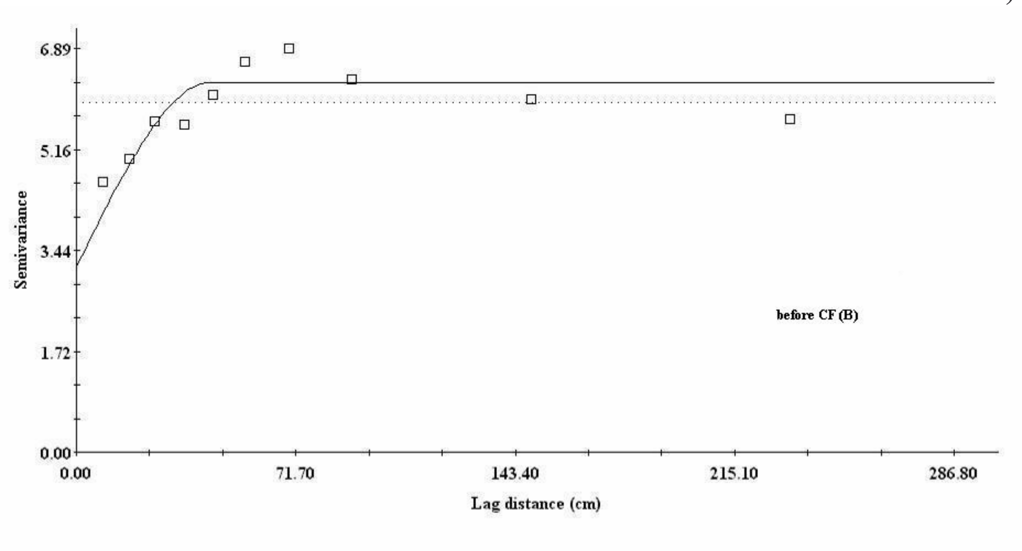
In order to evaluate the spatial dependence, criteria similar to those of Sun *et al*. (2003) were used. Soil CO_2 efflux was considered to have a strong spatial dependence if the proportion of structural variance (i.e. $C/(C_0 + C)$) was less than 25%, to have a moderate spatial dependence if the proportion was between 25% and 75%, otherwise it has a weak spatial dependence. In the 3 x 3 m sampling grid the average estimated range of soil CO_2 efflux was about 1.6 m (values between 1.48 – 1.75 m), and the proportion of structural variance ($C/C+C_0$) was very high (89-99%), indicating spatial weak dependence at the sampling scale used.

6.3.1.2 3 x 3 m and 2 x 2 m plots (10–60 cm grids)

Soil CO_2 efflux data followed a normal distribution in both the CF_{before} and the 40-yr stand. The variograms for these spatial analyses are given in Figure 2, while the regression models and their parameters are given in Table 1. Again, a clear sill was visible for both studies but differed from the larger plots, in those the estimated ranges were smaller, 0.44 m for the CF_{before} and 0.55 m for the 40-yr stands. The proportion of structural variance was also lower than at the larger sampling scale (50 % and 58% for the CF_{before} and 40 -yr respectively), indicating moderate spatial dependence at this sampling scale.

All sampling dates and plots showed a positive nugget, which can be explained either by sampling error, shorter-range variability, or random and inherent variability (Sun *et al*., 2003).

i)



ii)

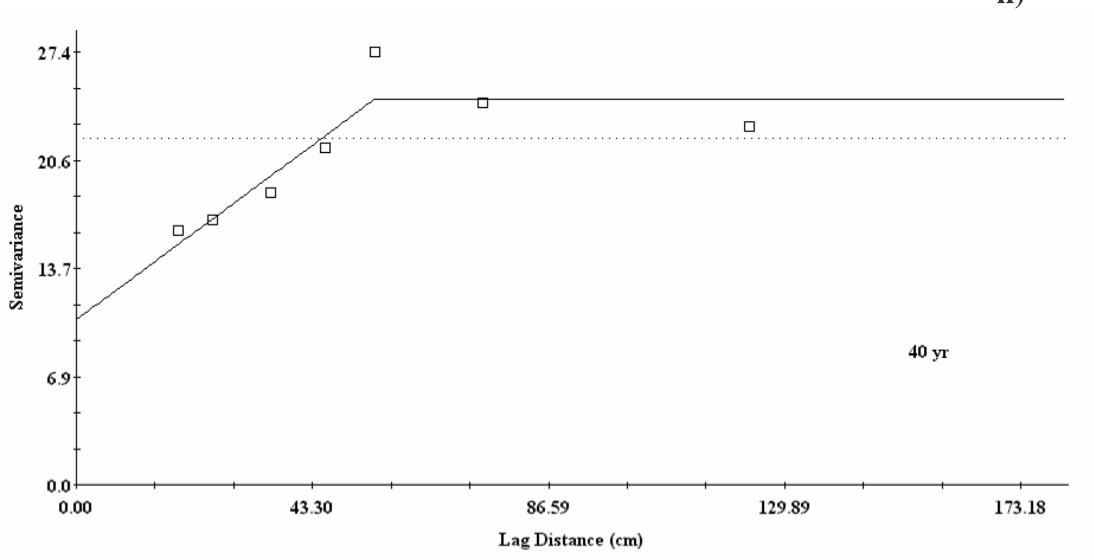


Figure 2: Semivariograms of soil CO_2 efflux in the smaller plots, in the before CF (B) and the 40 yr stands. The solid lines represent the models fitted in the semivariograms and the dotted lines the variance of the data.

6.3.2. Spatial variation

The variation in microtopography resulting from the ploughing that had taken place before tree planting 40 years before (ridge, furrow and plain ground) had no significant effect on the soil CO_2 efflux of the two stands. The data obtained from the DC method will be considered first. Figure 3 shows the average values of CO_2 efflux for furrow, plain ground and ridge during the measurement period for the 40-yr-stand (the trends for the CF_{before} stand were similar and are not shown here). Repeated-measures ANOVA showed no significant differences in the soil CO_2 efflux resulting from the different locations ($P > 0.05$ for the 40-yr and the CF_{before} stands). The coefficient of variation in the 40-yr-stand was generally between 21 and 50 %, with some very high values during winter when there was snow on the ground (115% on 31 December 2001 and 64% on 20 February 2002). For the CF_{before} stand, the coefficient of variation varied between 19 and 54%, again being highest during winter (94% on 31 December 2001 and 75% on 15 January 2001).

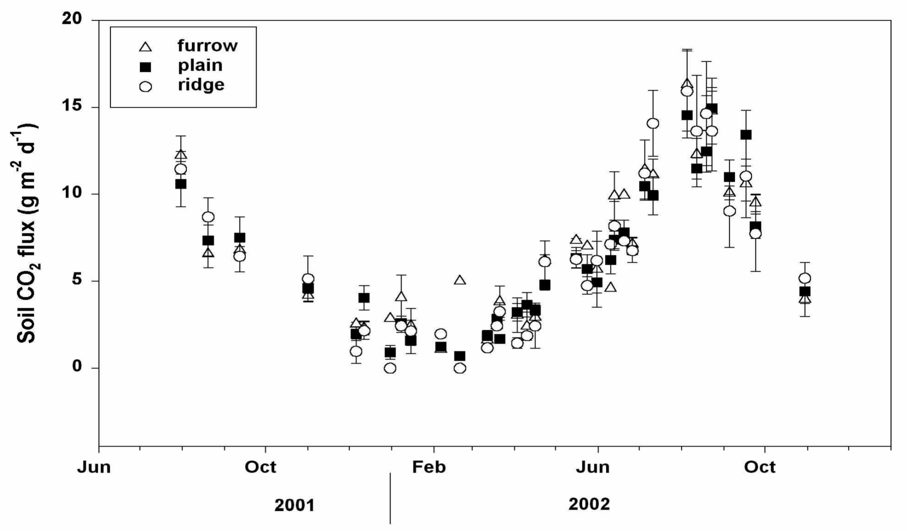


Figure 3: Spatial variability in soil CO_2 efflux from different microtopographic sites created by ploughing, in the 40-yr stand. Data obtained by the DC method.

Similar trends for soil CO_2 efflux in ridges, furrows and plain ground, were obtained by the SC method. Repeated-measures ANOVA showed no significant differences resulting from the different locations ($P>0.05$ for the 40-yr-stand the CF_{before} stands).

The coefficient of variation in the 40-yr stand was generally low (range between 12 and 44 %) with the highest variability during the winter (44 % on 18 December 2002 and 42% on 31 January 2002). The CF_{before} had higher coefficients of variation (range between 13 and 92%) with the highest variability on 9 September 2001 (92%) and 15 January 2002 (75%).

Soil temperature varied little throughout the study period, with an average CV of 12% at T_1 and 6% at T_5 for the $CF_{before,}$ and 6%, 4%, and 5%, at T_1, T_5 and T_{10}, respectively, for the 40-yr stand. Soil water content showed a higher variation, with an average coefficient of variation of 32% for the CF_{before} and 40% for the 40-yr stand.

Clearfelling increased the variability in soil CO_2 efflux. The average coefficient of variation for both methods (DC and SC) was very similar (76 % and 74 % for the DC and SC respectively). The range was smaller for DC (43% to 124 %) than for the SC method (27% to 144%). Clearfelling also increased the variation in soil temperature, with an average coefficient of variation of 16 %, 10% and 9%, for T_1, T_5 and T_{10}, respectively, while the variation in soil water content decreased with an average coefficient of variation of 26%.

6.3.3 Sampling Statistics

Soil CO_2 efflux data from 23 and 24 June, 4 and 6 July and 1 August 2001 for the CF_{before} and 31 July, 20 August and 12 September 2001 for the 40 yr, were used to estimate the average number of samples needed (Equation 2) to estimate the mean soil CO_2 efflux within 20% of its actual value at the 95% probability level (Table 2).

Table 2: Temporal trends of spatial variability of soil CO_2 efflux at the study sites and number of collars needed to estimate the mean soil CO_2 efflux within 20% of its actual value at 95% probability level (data from DC). n, number of collars used; n-20% number of collars needed.

Date of measurement	Site	n	CO_2 efflux (± SD) ($g\ m^{-2}\ d^{-1}$)	CV (%)	n- 20%
23 June 2001	**CF_{before}**	42	9.02 ± 3.98	44	19
24 June 2001	**CF_{before}**	47	10.21 ± 3.99	42	15
4 July 2001	**CF_{before}**	30	13.1 ± 4.88	42	18
6 July 2001	**CF_{before}**	70	9.78 ± 4.11	42	18
1 August 2001	**CF_{before}**	65	9.965 ± 4.92	49	24
20 August 2001	**CF_{before}**	10	7.98 ± 2.49	31	10
15 January 2002	**CF_{before}**	11	1.01± 0.69	69	47
16 May 2002	**CF**	13	6.53 ± 4.86	75	56
31 May 2002	**CF**	13	4.54 ± 2.69	59	35
5 July 2002	**CF**	13	8.67 ± 9.11	105	111
11 July 2002	**CF**	13	6.56 ± 4.41	67	45
12 August 2002	**CF**	13	7.06 ± 4.18	59	35
31 July 2001	**40-yr**	30	11.57 ± 4.63	40	16
20 August 2001	**40-yr**	29	7.35 ± 2.95	40	16
12 September 2001	**40-yr**	30	7.5 ± 3.35	45	20
26 March 2002	**40-yr**	10	2.14 ± 0.69	32	10
23 April 2002	**40-yr**	10	5.34 ± 1.03	19	4
5 July 2002	**40-yr**	10	10.80 ± 1.69	16	2

For the CF_{before} the average number of samples needed across the study period was estimated to be 19, while for the 40-yr-stand it was estimated to be 17. Based on this evidence probably I over-sampled during the initial period and slightly under-sampled later on.

An examination of the number of sampling points required to estimate the mean soil CO_2 efflux within 20% of its actual value, revealed that the number of collars needed was not constant: a different number of collars (or chambers) was required for different periods (examples shown in Table 2). For all dates the average number of collars needed was 24 (range: 4 to 90) for the CF_{before}, and 14 (range: 2 to 132) for the 40-yr stand. After clearfelling the number of collars needed increased to 59 (range: 5-154). Similar evidence was obtained using the data from the SC method. It was estimated that the average number of chambers needed would be 14 (range: 2 to 56) for the CF_{before}, and 8 (range: 2 to 19) for the 40-yr stand. After clearfelling the number increases to 58 (7-136). On average more collars appear to be required than chambers. The number of collars needed was correlated to the mean soil CO_2 efflux for the mature stand; fewer collars are needed as soil CO_2 efflux increases (R^2=0.58 for the DC system, Figure 4, and R^2=0.43 for the SC method) but there was no pattern after clearfelling (Figure 5).

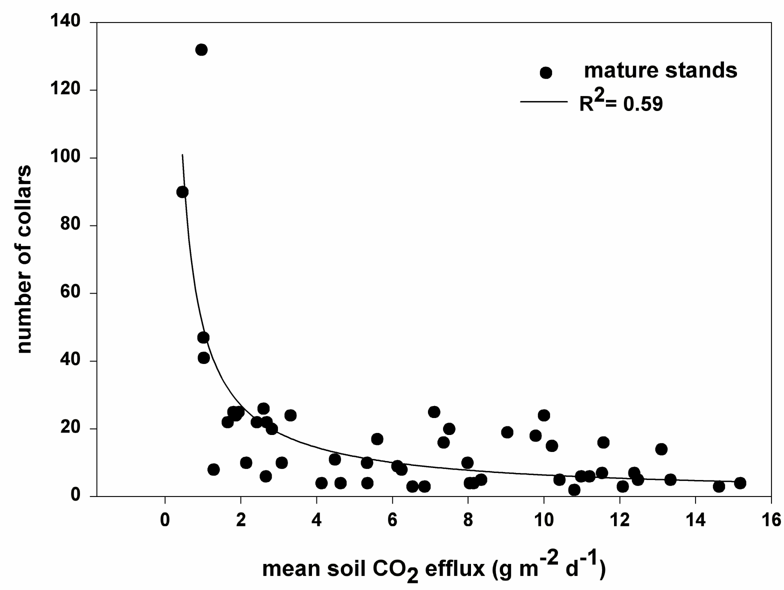


Figure 4: Relationship between the mean soil CO_2 efflux and the number of collars needed to estimate soil CO_2 efflux within 20% of the true population mean for the mature stands (CF_{before} and 40-yr) (data obtained with the DC method).

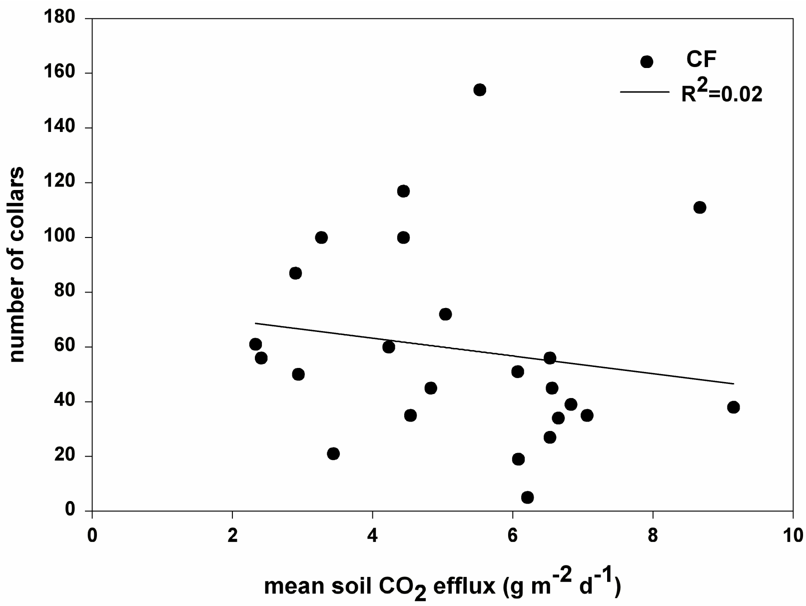


Figure 5: Relationship between the mean soil CO_2 efflux and the number of collars needed to estimate soil CO_2 efflux within 20% of the true population mean for the CF site (data obtained with the DC method).

6.4 Discussion

There are only a few published studies on the spatial and temporal variability of soil CO_2 efflux. Additionally, it is difficult to compare the spatial variability of soil CO_2 effluxes among different studies, because of differences in the size of the experimental plots and the number of sampling points (Fang *et al*., 1998).

In this study it was found that soil CO_2 efflux in a mature stand of Sitka spruce (CF_{before}) exhibits spatial autocorrelation at distances less than 1.6 m. More specifically, soil CO_2 has a higher degree of autocorrelation at locations separated by less than 0.5 m (CF_{before}, 40-yr stands). The spatial dependence of soil CO_2 efflux of about 1.6 m in this study is in agreement with the results by Rayment and Jarvis (2000) who estimated a high degree of autocorrelation between values of basal CO_2 (R_0) at locations separated by less than 1 m, in a boreal forest of *Picea mariana*. Russel and Voroney (1998) did not observe spatial autocorrelation in soil CO_2 efflux at 2 m spacing in an aspen forest. Raich *et al*. (1990) found no spatial autocorrelation in soil CO_2 efflux along a 20 m transect in red pine forest, where chambers were placed 0.5 m apart from each other.

The site preparation for the planting of the trees did not affect soil CO_2 efflux variability, since the emissions from ridges, furrows and plain ground were not significantly different. This could be due to the long time since site preparation took place (approximately 41 years) which contributed to reducing and smoothing the variability in soil microtopography. In a younger (20-yr-old) Sitka spruce stand in Scotland, spatial variability was more apparent ($P<0.05$) between ridges, plain ground and furrows, and the CO_2 efflux decreased in the order ridge>plain ground>furrow, although higher CO_2 efflux from the furrow was also observed on one sampling occasion (Wingate, 2003). The high variation observed in soil CO_2 efflux is probably due to the absence or presence of roots at the sampling points, rather than the disturbance that was caused before tree planting. The coefficient of variation was quite high in the CF_{before}, even when a large number of sampling collars (90) was used. The coefficient of variation was higher for the DC method (46%) compared with the SC method (40.6%). In the 40-yr stand the average coefficient of variation was lower, 33% for the DC system method and 26 % for the SC method. The lower variation from SC is probably due to the larger area covered (area=0.126 m^2) when compared with the small collars (area=0.008m^2). The difference in the coefficient of variation between the two mature stands could be explained by the different periods and duration of sampling. When the coefficients of variation were compared for the same period for both stands, they were similar (47% and 51% for the CF_{before} and 40-yr stand, respectively, data from DC method). Clearfelling caused an increase in the variability of the soil CO_2 efflux. The coefficient of variation was on average about 76% for the DC method and 74% for the SC method, with also a wider range (43%-124% and 27%-144% for each method, respectively).

High variations in soil CO_2 efflux have often been reported in the literature. Fang *et al*. (1998) reported an average coefficient of variation of 55% between 12 sampling locations, with a range varying from 38 to 173 %. Janssens and Ceulemans (1998) reported high variability in a mature (69-yr-old) patchy plantation with Scots pine and pedunculate oak as dominant species, with a coefficient of variation of 49% for the pines and 46% for the oaks. Buchmann (2000) found an average coefficient of variation of 25% in *Picea abies* stands, with higher variability (of about 40%) during the summer, although soil temperature varied less than 5% at each site.

Striegl and Wickland (1998) studied the effects of clearfelling on soil CO_2 efflux in a jack pine-lichen woodland, and found a coefficient of variation of 30.1% for the CF and 31.3% for the mature stand (control). Fernandez *et al*. (1993) found lower variability in a clearfelled site compared to an uncut mixed forest, with coefficients of variation of 26 % and 34 %, respectively. However, the above studies do not report variation in soil CO_2 efflux prior to clearfelling and treatment and site differences are confounded.

Clearfelling slightly increased the variability in soil temperature (about 4%) probably because of the removal of the canopy and direct exposure of the soil. However, the variability in soil water content decreased by about 6%. This decrease in soil water content variability can be explained by the rise of the water table. Londo *et al*. (1999) found a narrower soil water content range in a clearfelled site (15.4%) than in their control stand (19.1%) in a bottomland hardwood forest. A possible explanation they suggested, was the very rapid regrowth of woody and herbaceous vegetation in the clearfelled site, resulting in greater canopy interception of precipitation as well as a transpirational drying influence.

The soil CO_2 efflux data from the preliminary measurements in the mature stands were used in order to estimate the number of collars needed for the soil CO_2 efflux to be within 20% of the true population mean. On average, the number obtained was larger than the number that could actually be measured in the field on a weekly basis. However, the number of sampling points required is not constant and changes during time; for example the number of collars needed is less when soil CO_2 efflux is high, in the summer than in spring or winter. Russel and Voroney (1998) estimated that a larger number of sampling points was required for spring than for summer in order to estimate the population mean within 20%, and concluded that this seasonal trend in spatial variability of soil CO_2 efflux seemed consistent with a shift from random heterotrophic hot spots on the soil surface to more uniform emissions from the presence of actively growing roots and the diffusion of CO_2 from greater depths. This seems to apply to the 40-yr stand, with the coefficient of variation being generally lower in summer than spring 2002 (16%-30% from June to August and 18% -47% from March to May). The same does not apply for CF where tree harvesting increased the variability of soil CO_2 efflux. Laporte *et al*. (2003) estimated much higher coefficients of variation for scarified soil, where organic material had been removed or mixed with mineral soil by harvesting (49%-59% from May to October) compared to undisturbed soil (30%-39% for the same period) in a hardwood forest ecosystem in Ontario. Raich *et al*. (1990) estimated that 13 chambers were needed in order to estimate the mean soil CO_2 efflux with no more than 10% error in a red pine forest. However, their estimations were based on measurements on a single day during the growing season. It is consequently difficult to make comparisons among different studies where different sampling schemes have been used. More attention should be given to the actual number of sampling points needed for accurate estimation of soil CO_2 efflux.

6.5 Conclusions

The main conclusions drawn from this study are: a) spatial variability of soil CO_2 fluxes in mature Sitka spruce stands is very high, although the spatial scale of this variability is small. Spatial variability of soil CO_2 efflux can be large even in what appear to be relatively homogeneous stands. b) Clearfelling of the trees and disturbance of the soil by harvesting machines increases spatial variability of soil CO_2 efflux. c) The number of sampling points required to accurately sample soil CO_2 efflux within 20% of the population mean is not constant and changes in relation to the flux itself. In a mature undisturbed stand fewer samples are required for periods of high soil CO_2 efflux.