StartClim2007.D

Effect of a climate-induced shift of the timberline on the release of greenhouse gases

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Contents

Abstract

Die Waldgrenze verschiebt sich durch die Klimaänderung und durch die geänderte Form der Landbewirtschaftung nach oben. Der Effekt ist seit mehreren Jahrzehnten gut dokumentiert. Durch Bodenanalysen an einem Standort, der in den 50er Jahren untersucht und gut dokumentiert wurde, konnten Auswirkungen des Überganges von Zwergstrauchheide zu Zirbenwald auf den Boden ermittelt werden. Der Versuchsstandort Poschach in Obergurgl, Ötztal, war in den 1950er Jahren Gegenstand detaillierter pflanzenphysiologischer und kleinklimatischer Messungen, die im Zuge von großflächigen Hochlagenaufforstungen von der damaligen Forstlichen Bundesversuchsanstalt durchgeführt wurden. Bei dieser Gelegenheit wurden die Vegetation, die Geomorphologie, und die Bodentypen exakt kartiert. Im Zuge einer Neu-Aufnahme der Vegetation und der Böden konnte die Veränderung der Fläche innerhalb eines halben Jahrhunderts gut festgestellt werden. In Obergurgl verdrängt der Wald Zwergstrauchheiden, die von Calluna und Rhododendron dominiert sind. Diese Zwergsträucher sind für ihre schlecht abbaubare Streu und für den extrem geschlossenen Nährstoffkreislauf bekannt. Die Böden unter Zwergsträuchern erwiesen sich als wesentlich kohlenstoffreicher als jene unter dem nunmehr 50 Jahre alten Zirbenwald. Dies hat weitreichende Implikationen für die Kohlenstoffbilanz: Zwar wird in der oberirdischen Biomasse im Wald ein großer Kohlenstoffvorrat aufgebaut, doch wird gleichzeitig der stabilere Kohlenstoffvorrat im Boden abgebaut. Der Befund wurde durch die geostatistische Auswertung bestätigt: Die Böden unter Zwergstrauchheiden haben einen tiefgründigen A-Horizont, der profilmorphologisch vom Auflagehumus kaum unterscheidbar ist. Die Kennzeichen der Podsolierung sind daher maskiert. Unter Zirbe ist hingegen eine deutliche Trennung zwischen Auflagehumus und dem kohlenstoffarmen Mineralboden erkennbar. Die Böden sind eindeutig Podsole, die bei der Erstaufnahme 1955 als Eisenhumus-Podsole bezeichnet wurden.

Repräsentative Bodenproben aus vier Positionen eines Höhengradienten wurden im Labor in fünf Temperaturstufen (5, 10, 15, 20, 25°C) inkubiert, um zu untersuchen, wie viel Kohlenstoff durch die Erwärmung als CO_2 emittiert wird. Die Böden unter Zwergstrauchheiden haben auf die Temperaturerhöhung kaum reagiert, d.h. die Kohlenstoffverbindungen auf diesen Standortseinheiten sind chemisch sehr stabil. Die gemessenen Werte waren auch weit unter den Werten, die für andere Wälder österreichweit gemessen wurden. Die Böden unter Zirbenwald haben hingegen deutlich auf die Temperaturerhöhung reagiert. Die Implikation für die österreichische Kohlenstoffbilanz ist, dass durch die Vegetationsänderung ein Bodenkohlenstoffpool aufgebaut wird, der stark auf Temperaturanstieg reagiert und leicht abbaubar ist. Eine bodenbiologische Charakterisierung mittels der Phospho-Lipid-Fettsäure-Methode (PLFA) zur Unterscheidung der dominierenden Bodenmikroorganismengruppen, der Aktinomyzeten, der Bakterien, der Mykorrhizen und der Pilze, sowie zur Abschätzung der gesamten Biomasse der Mikroorganismen ergab die gleichen Artenspektren, d.h. die gleiche prozentuelle Verteilung der Arten entlang des Höhengradienten. Grosse Unterschiede bestanden allerdings bei der mikrobiellen Biomasse. Die Böden unter Zwergstrauchheide sind offensichtlich als Substrat für Mikroorganismen extrem unergiebig und daher kaum besiedelt. Böden unter Zirbenwald sind hingegen biologisch deutlich aktiver. Kohlenstoff, der durch den Streufall (Nadeln und

Wurzeln) in den Boden gelangt, wird daher rasch mineralisiert und als CO_2 an die Atmosphäre abgegeben. Zusammenfassend gilt für den spezifischen Standort, dass der Anstieg der (Zirben-) Waldgrenze zu signifikanten Änderungen im Boden führen, die mit erhöhter Kohlenstofffreisetzung verbunden sind. Diese Ergebnisse werfen viele Fragen auf, die in Folgeprojekten abgearbeitet werden sollen.

The timberline shifts upwards due to climate change and changes in land use. The effect is well documented since several decades. The effects of the shift from dwarf-shrub communities to stone pine ((*Pinus cembra*) forest was investigated by soil analyses at a site that was intensely monitored and well documented during the 1950s. The experimental site Poschach near Obergurgl, Ötztal, has been subject to detailed plant physiological and meso-climatic research. The experiments were conducted in support of large scale afforestation projects in high altitudes and were performed by the former Forstliche Bundesversuchsanstalt Mariabrunn (now Forschungszentrum Wald [BFW]). At that occasion vegetation, geomorphology and soil typology were assessed on a small scale. Upon a repeat assessment of vegetation and soils the change of these site properties within half a century was documented. In Obergurgl the advancing forest replaces dwarf-shrub communities, dominated by *Calluna* and *Rhododendron*. These dwarf shrubs yield a poorly degradable litter and are renown for their closed nutrient cycle. Soils under dwarf shrubs were richer in carbon as soils under now 50 year old stone pine forests. That has far reaching implications for the carbon balance: Although a large carbon pool establishes in the aboveground biomass, the usually more stable carbon pool of the soil is reduced. The observation was supported by the geostatistical analysis: Soils under dwarf shrubs have a deep A-horizon that is hardly distinguishable from the litter layer. The indicators for podzolization are masked. In the stone-pine forest the litter layer and the carbon poor mineral soil are clearly separated. Soils are typical podzols, that were named Ironhumus-podzols in the initial survey of 1955.

Representative soil samples from four positions along an elevational gradient were incubated in the lab at five temperature steps (5, 10, 15, 20, 25$^\circ\mathrm{C}$) in order to quantify how much carbon is released as CO_2 as a consequence of the temperature increase. Soils under dwarf shrubs hardly responded to the temperature increase, indicating the high chemical stability of soil organic matter at these sites. The measured values were below the values of most other previously investigated forests in Austria. Soils under stone pine responded much stronger to the temperature increase. The implication for the Austrian carbon balance is that the changing vegetation implies the formation of a soil carbon pool that strongly responds to increasing temperatures.

A soil biological characterization by means of the Phospho-Lipid-Fatty Acid (PLFA) Method, distinguishing between the dominating taxonomic groups of soil microbes, *i.e.* the actinomycetes, the bacteria, the vasicular-arbuscular mycorrhizae, the fungi, and an estimation of the total soil microbial biomass showed similar spectra along the elevational gradient. Large differences were found with respect to the total microbial biomass. Soils under dwarf shrubs are obviously a poor substrate with a low microbial population density. Soils under stone pine are biologically active. Organic matter that enters the soil via litterfall (needles, roots) is quickly mineralized and released to the atmosphere as CO_2. In conclusion we state that the rise of the timberline leads to significant changes in the soils that are linked to a higher release of carbon. Our results open a wide array of hypotheses that will be addressed in future research projects.

1. Introduction

1.1. Historical context

Due to livestock grazing in the Alps the timberline was severly lowered in former centuries. In several valleys such as the Ötztal in Tyrol the loss of forest since 1774 was estimated to be 50% and timberline was reduced by $\approx$ 400 m. The pastures were productive for several decades, but later were overgrown by dwarf shrubs. In consequence the livestock density was reduced and the revenue from agriculture and forestry was reduced by more than 30% until the 1950s. At that time the concern was considerable that the low forest density in high elevation ecosystems would compromise the protection against natural hazards in the valleys. In that time several high-elevation programmes, partly subsidized by the European Recovery Plan (ERP), were started. One of them was the afforestation experiment Poschach, conducted by the Forschungsstelle für Lawinenvorbeugung, Innsbruck [FBVA, 1961]. The research focused on micro-meteorolgy and plant physiology [Tranquillini, 1979] and that line of research was maintained [Wieser and Tausz, 2007].

Changes in land use and a general reduction of the relevance of the primary sector of the economy led to an encroachment of alpine pastures in the last 50 years. Soon the impact of climate change on the vegetation was identified and a line of investigations on its effect on alpine plants commenced [Grabherr et al., 1994]. The research was expanded to numerous mountain ranges in the Alps and around the globe [Dullinger et al., 2004, Körner, 2003].

1.2. Recent research

The observed encroachment of alpine pastures with stone pine (*Pinus cembra*) is expected to lead to an accumulation of carbon in the soils. This effect has been often authoritavely described [Lal, 2004a,b, Richter jr. and Markewitz, 2001, Schulze and Freibauer, 2005] and is in accordance with expectations: "...the development of a high quantity of aboveground biomass leads to a high flux density of litterfall. The steady high input of litter to the soil enriches it in the long term with carbon". That paradigm holds true for most forest ecosystems. However, dwarf shrub communities have a peculiar and particularly tight nutrient cycle. These properties have been described in the context of soil acidification in the past [Blaser and Reiser, 1975, Blaser, 1976].

During the preparation of an excursion in summer 2006 we observed that soils under stone pine have a litter layer of decomposing pine needles that is clearly distinct from the carbon poor mineral soil. Instead, the soils under dwarf shrubs were characterized by a deep dark upper horizon where the separation between litter layer and mineral soil was difficult. The impression was that this soil contains more C than the forest soil. That observation was supported by earlier soil surveys [Neuwinger-Raschendorfer and Czell, 1961]. The implication of that observation is considerable: If indeed former soils from alpine pastures and dwarf shrub communities are losing C upon encrochment, the soils are a long term C source. For a regional C budget the C loss of soils needs to be balanced against the C gain in the aboveground biomass. For considerations of the longevity of a C pool the stability of C in different pools in the ecosystem needs to be taken into account. Generally, the soil C pool is more stable than the C pool in the biomass because the majority of the constitutents of soil organic matter (”humic substances”) are less degradable than cellulose and lignin, the main building blocks of plant material.

1.3. Research approach

The intention of STARTCLIM2007.D is a re-investigation of the experimental site Poschach, Obergurgl. We digitized map material from the previous vegetation, geomorphology, and soil surveys [FBVA, 1961]. The vegetation and soil surveys were repeated in summer 2007 in a method that allowed an advanced data evaluation. Soil organic matter was quantified and the soil microbial community was characterized.

As a surrogate for the former detailed meteorolgical measurements we installed several soil temperature sensors along an elevational gradient. Soil temperature was previously recognized as the single variable that explains the most on the dynamic behavior of the timberline [Körner and Paulsen, 2004].

2. Methods

2.1. Experimental site

The experimental site Poschach, Ötztal (46° 53′N, 11° 3′E) is a long W-facing shoot (Figure 2.1). The lower end is at 2070 m, the upper end at 2150 m a.s.l. [Fromme, 1961]. The valley bottom is another 150 m lower. The geology is silicatic bedrock that is overlain by moraines. The entire landscape is shaped by glaciers. Due to the mass effect of the Alps the precipiation is low. At the meteorological station in Obergurgl (1927 m a.s.l.) the annual precipitation is 830 mm[1] [Turner, 1961]. Figure 2.2 shows the local situation.

An appreciation for the change that had occurred in the previously agriculture-dominated community to a booming tourist resort can be gained from figure 2.3.

2.2. Preparation of available surveys

The results of the previous experiment are all published [FBVA, 1961]. Records from previous field work and archived sampling material are not available.

Mapped material from the previous experiment was digitized. For field use an ortho-photo was put in the background (Figure 2.4).

The map derived from the published soil survey [Neuwinger-Raschendorfer and Czell, 1961] was digitized and is shown in Figure 2.5.

An integrated view to site properties and soil units is given by Figure 2.6. The graph combines vegetation, morphology, and soil information.

2.3. Geostatistics

An efficient method for vegetation and soil surveys is a nested design of sampling points [Webster, 1985]. The advantage is the assessment of the variability of site parameters at several scales. Accordingly, the experimental site of figure 2.4 was amended with several grids (Figure 2.7). The coarsest grid had a side length of 50 m. Within that grid the vegetation and the soil was assessed in 10 m-transects. At several grid points a finer grid was introduced with a side length of 5 m. Within that, a 1×1 m grid was used.

[1] A site in that elevation in the front range of the Alps receives more than twice that quantity of precipitation.

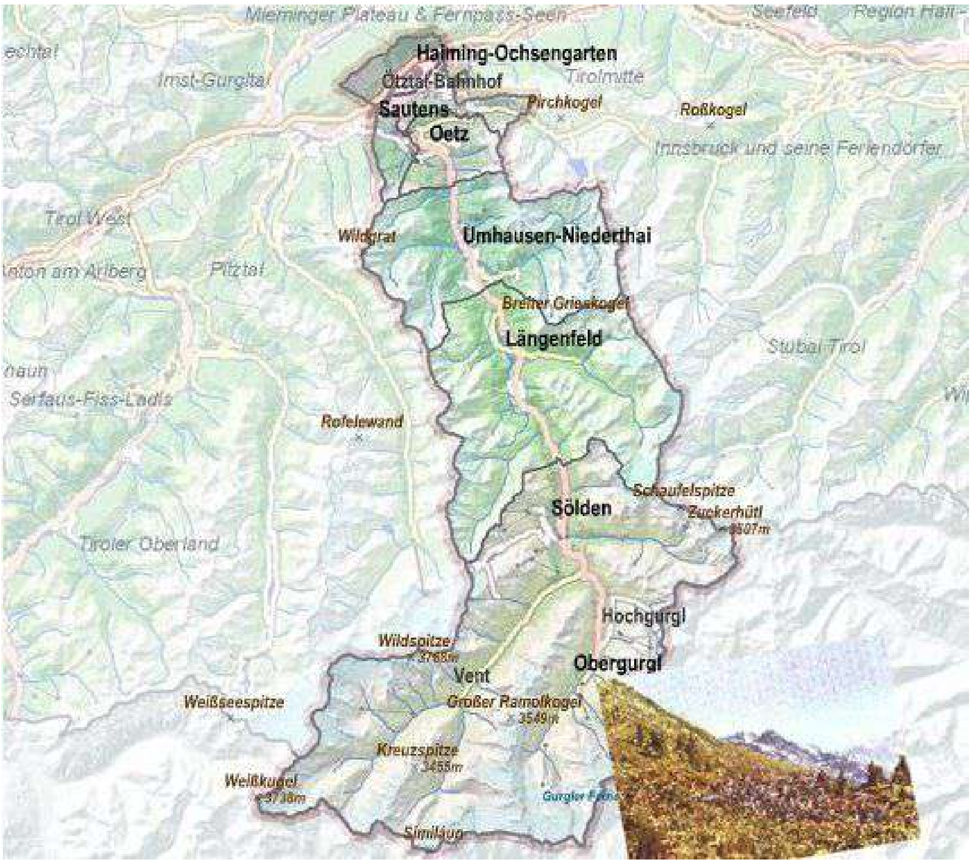

Figure 2.1-D: Experimental site Poschach, Obergurgl.

Figure 2.2-D: Dwarf shrub communities in the upper part of the slope (left) and mature stone pine forest in the lower part (right). Pictures taken in 2007.

Figure 2.3-D: Obergurgl, view from S → N in the year 1920 (left) and 2007 (right). The experimental plot is located on the right slope in the background.

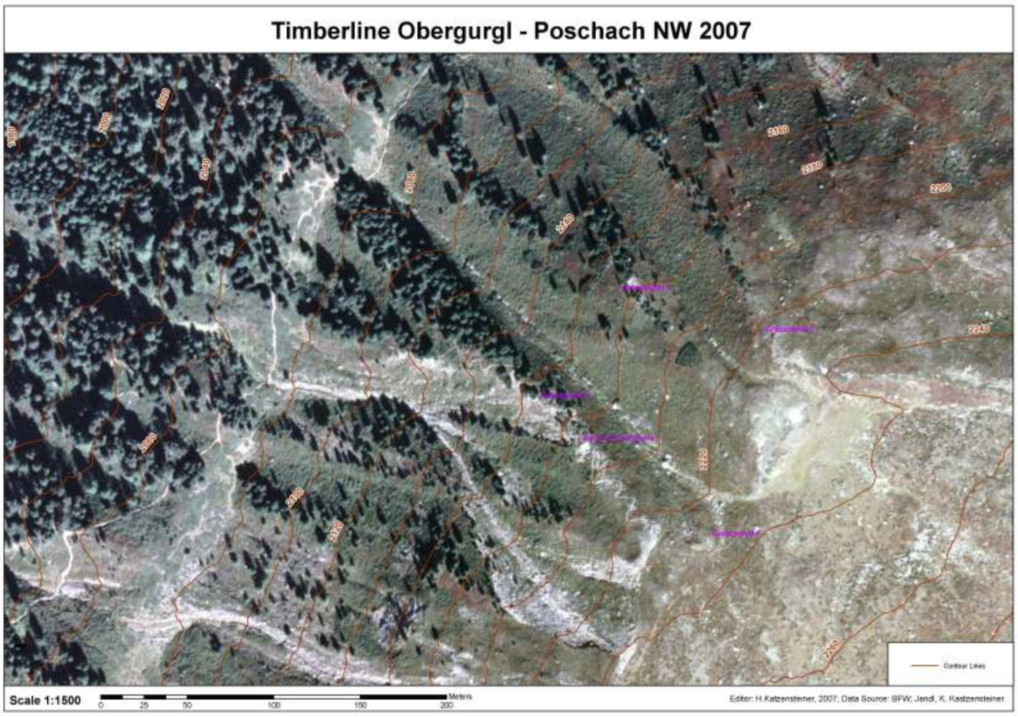

Figure 2.4-D: Elevation model overlaid to a recent orthophoto. The orthophoto displays the borders of the recent extension of forest cover.

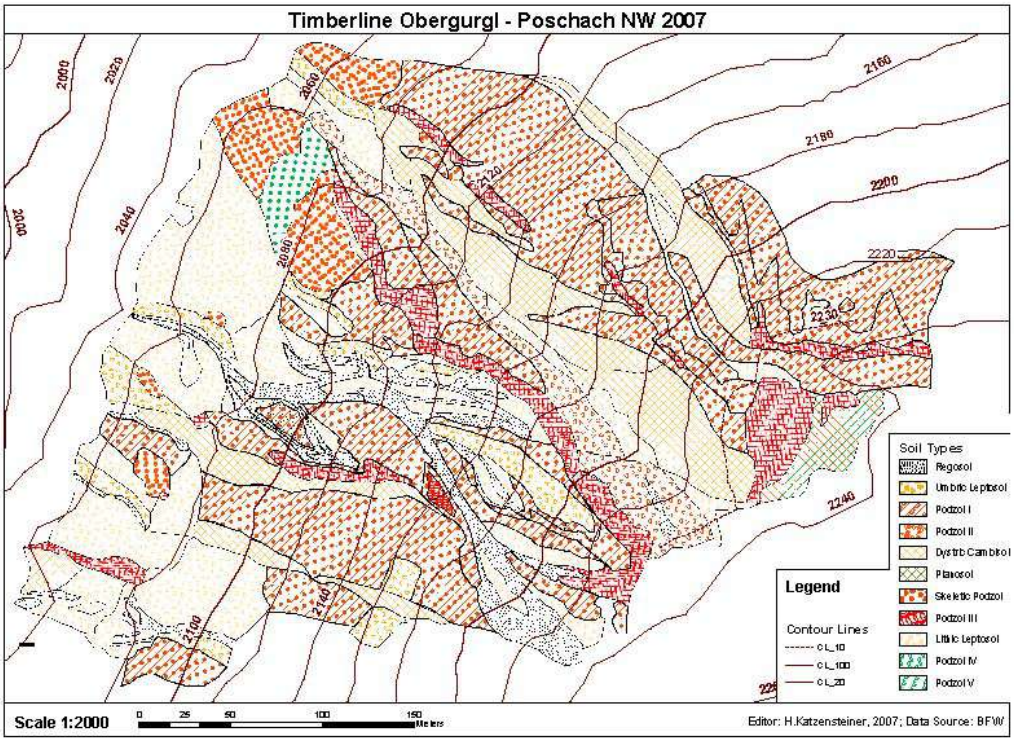

Figure 2.5-D: Soil survey in Poschach, Obergurgl; Survey after 1950 [FBVA, 1961].

The high resolution of the grid made a precise geo-referening of the sampling points. We used a GPS Trimble R8 GNSS/R6/5800 (Figure 2.8)[2]. The instrument receives data from at least 4 satellites. An exact reading of the location requires > 6 satellites. The received data are transmitted via a cell phone to the geo-data center in Vienna, processed, and corrected readings are transmitted back for storage.

Further support for a precise assessment of the site properties was provided from the results of a recent laser scan of the surface that was requested by the Province of Tyrol and that is archived at the GeoInfoCenter of Tyrol (TIRIS; Figure 2.9).

2.4. Vegetation and soil assessment in the field

At each point along the transects and grids of figure 2.7 the vegetation was assessed. A wooden frame of 1×1 m was placed on the surface and all plants were recorded according to Braun-Blanquet. In addition the height of the vegetation was recorded. The field expertise was amended with specimen from the plant collection of the University Center in Obergurgl.

In addition several recordings were taken from the stone pine stand in different elevations. We measured height of dominant trees (Vertex III; Haglöf, Sweden), stem diameter at breast height

[2] Courtesy: Dr Erwin Heine, Universität für Bodenkultur.

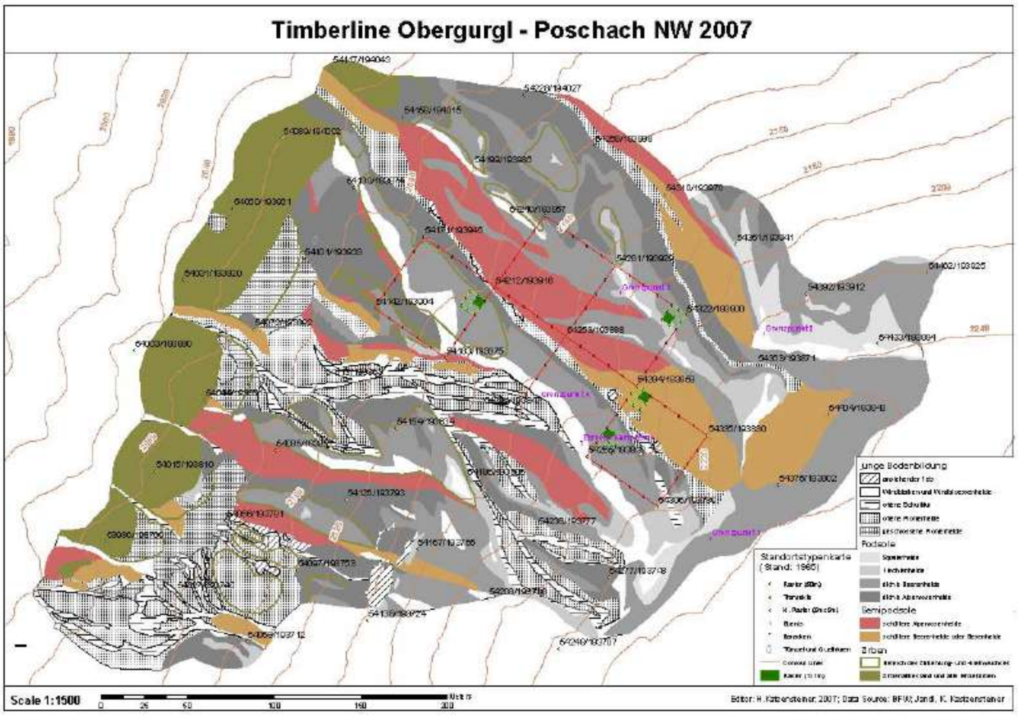

Figure 2.6-D: Site property map of the experimental field in Poschach, Obergurgl; Survey after 1950 [FBVA, 1961].

and the location of pine seedlings on a small subplot at the upper end of the slope.

At each point soils were assessed. Parameters were soil type, depth of litter layer, and depth of the A-horizon of the mineral soil. Samples for chemical analysis were taken at selected sites. Wherever possible the undisturbed soil profile was extracted with a corer. At places with a high rock content a soil pit was dug.

2.5. Soil temperature

The soil temperature is measured by a MINIKIN TT sensor (EMS Kucera; `http://www.emsbrno.cz`). This sensor type has a built-in battery that supplies energy for 2 years and is capable of storing data collected at a 10-minutes interval. No additional power source on-site is necessary.

Sensors were installed at three soil depths, at the boundary of the litter layer and the mineral soil, 5 cm and 15 cm deep within the mineral soil. The measurement interval of 1 hour was chosen.

The location of the temperature sensors is shown in Figure 2.12. Each location is geo-referenced, marked in the field with a wooden pole, and photographed. The site is inaccessible until early summer. Data will be collected after a full year of measuurements.

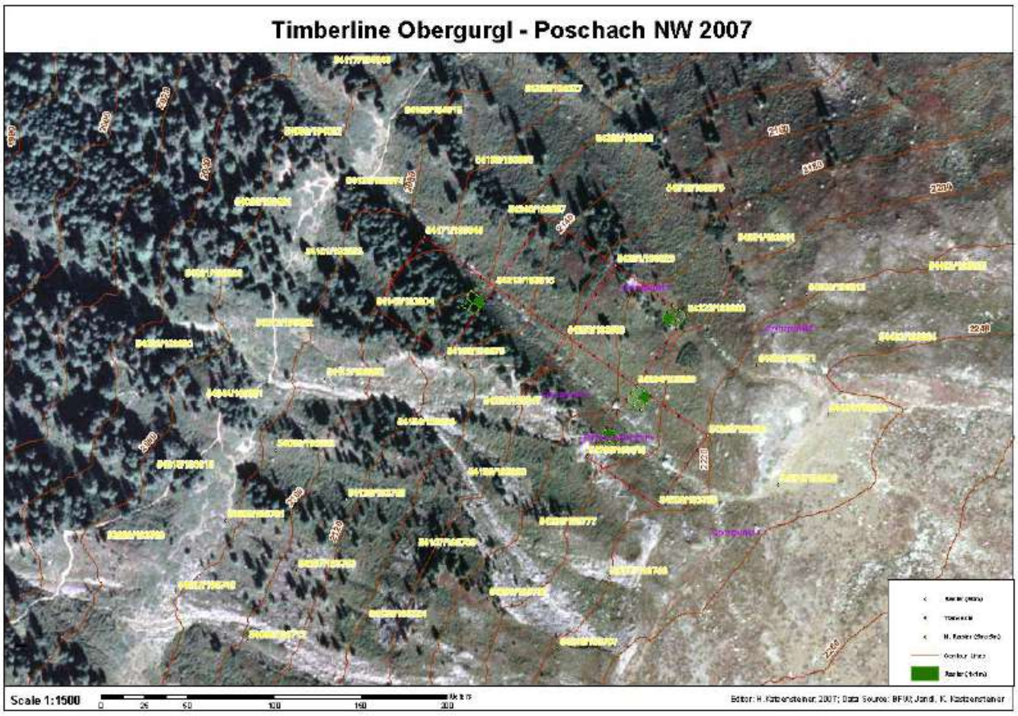

Figure 2.7-D: A variable grid was overlaid in order to identify spatial properties (vegetation, soil) at different spatial resolutions.

2.6. Soil analysis in the laboratory

D- 2.6.1. Chemical analysis

Soil samples were collected along a transect at 4 positions, B1–B3, B8 (compare figure 2.9). Samples were air dried and the C and N content was measured with a Carlo Erba CNS-analyzer. Total phosphorus was extraced in an acid digest (HNO_3/$HClO_4$). Exchangeable cations were extracted in an unbuffered $BaCl_2$-extract and measured in the Soil Chemistry Laboratory of the Forest Research Center, Vienna[3]. All applied methods are certified.

D- 2.6.2. Soil microbial community

The soil microbial community was assessed by the PLFA - method. The phospholipids of fatty acids extracted from the cellwalls of fungi and bacteria are biomarkers and can distinguish between two types of bacteria (gram positive, gram negative), actinomycetes, vasicular-arbuscular mycorrhizae and fungi[4] [Joergensen and Emmerling, 2006]. The analysis was done at the Soil

[3] Institute of Forest Ecology, BFW; Laboratory Dr Franz Mutsch.
[4] Alternative biomarkers that have not been used in that study are ergosterol and glucosamines.

Figure 2.8-D: GPS Instrument for a precise determination of the sampling locations.

Microbiology Lab of the Forest Research Center[5].

A typical chromatogram is shwon in figure 2.13. The peaks of the chromatogram are evaluated according to a still evolving protocol [Joergensen and Emmerling, 2006].

D- 2.6.3. Degradability of soil organic matter

A direct measurement of the thermal stability of soil organic matter is possible in an incubation experiment. Soil samples from the locations B1–B8 (figure 2.9) were taken to the lab. The water content of the samples was adjusted to 35% and samples were incubated at 5, 10, 15, and 20°C. The experimental setup is located in the Soil Microbiology Lab of the Forest Research Center BFW. The equipment was previously used for the quantification of NO-emissions from soils [Schindlbacher and Zechmeister-Boltenstern, 2004]. In the present setup the emitted CO_2 was measured with a PP-Systems analyzer. Figure 2.14 shows a modified refrigerator that serves as a incubator for soil samples. Within 12 sample chambers and one reference chambers are assembled. Each chamber is connected with the gas analyzer. A PC controls magnetic valves that open the gas sampling stream between the individual chamber and the analyzer.

[5] Institute of Forest Ecology, BFW; Laboratory Doz Dr Sophie Zechmeister-Boltenstern.

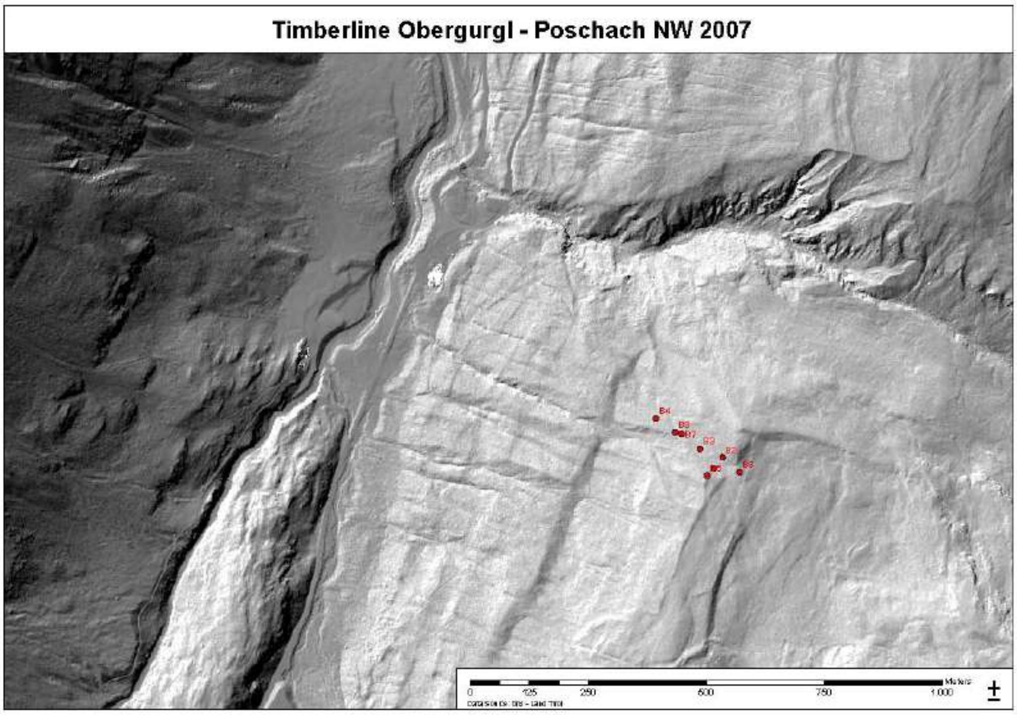

Figure 2.9-D: Surface scan of the surface of the experimental site Poschach, Obergurgl. The picture was provided by TIRIS. The red circles indicate positions of soil sampling.

The characterization of the chemical quality of soil organic matter by an incubation experiment is supported by theory [Davidson and Janssens, 2006]. The data of an incubation experiment allow the calculation of a Q_{10}-value. The Q_{10} for a reaction rate is defined as the factor by which the rate increases with a $10°\mathrm{C}$ rise in temperature.

The Q_{10} value is calculated from [Reichstein et al., 2005]

$$R_{\text{soil}} = R_{\text{ref}} \times Q_{10}^{(T_{\text{soil}} - T_{\text{ref}})/10°\mathrm{C}} \tag{2.1}$$

Nevertheless, mountain soils are spatially heterogenous [Stöhr, 2007]. Besides the temperature sensitivity other site and substrate quality factors play a role in the process of the biodegradation of soil organic matter (Figure 2.15). The prediction of soil carbon dynamics under field conditions depends therefore on a combination of information from lab and field experiments.

Figure 2.10-D: A wooden frame as sampling plot for the vegetation and three tools for soil work.

Figure 2.11-D: Soil temperature sensors of the type MINIKIN (left). The sensor itself is a regular Pt100, the head contains an energy source and a storing device. The data are retrieved with the MINIKIN-Software package `minikin32.exe` (right).

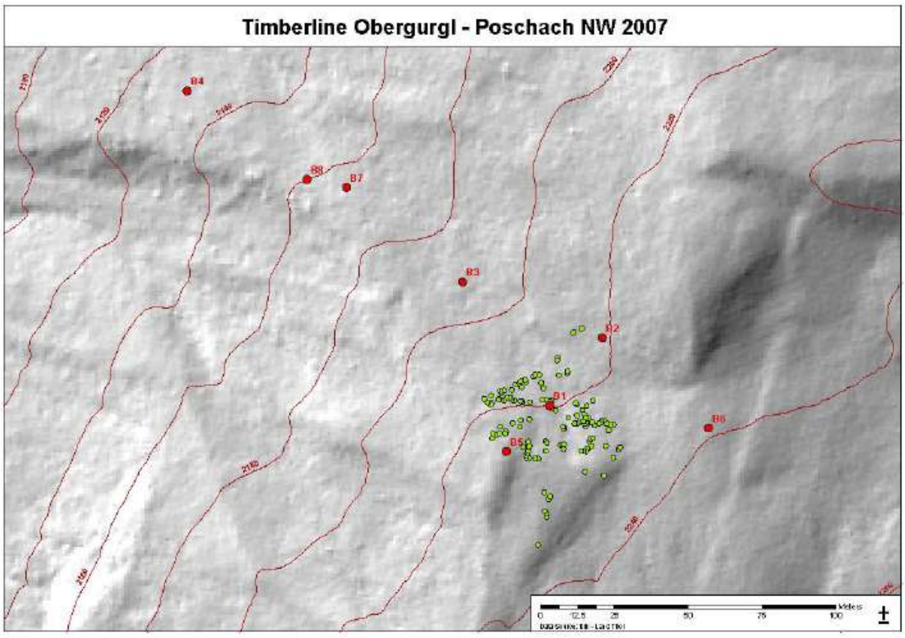

Figure 2.12-D: Location of soil temperature sensors along an elevational gradient.

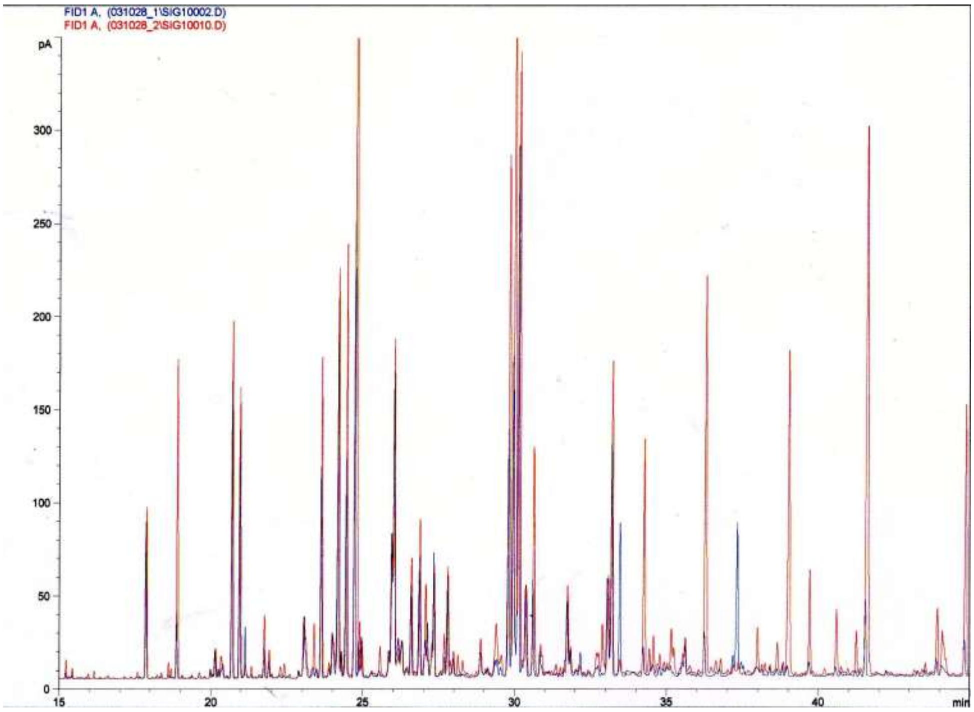

Figure 2.13-D: Template for a chromatogram of C-bondings. The evaluation of the data allows to distinguish taxonomic groups of soil microorganisms.

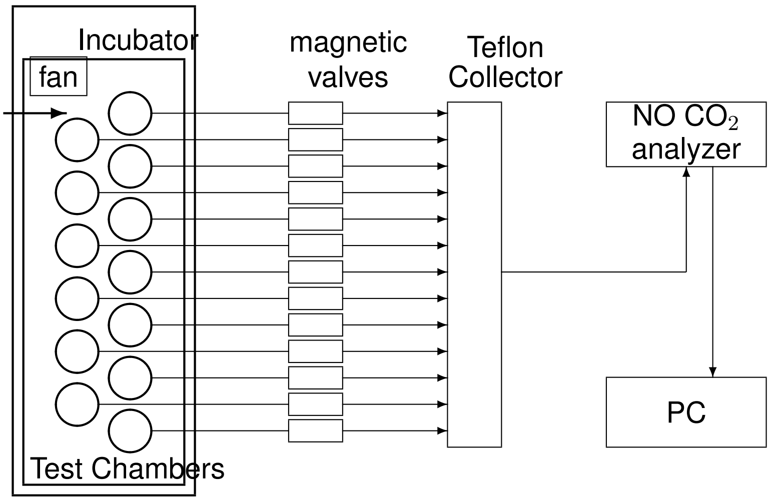

Figure 2.14-D: Soil incubator with automated measurement of the CO_2-evolution.

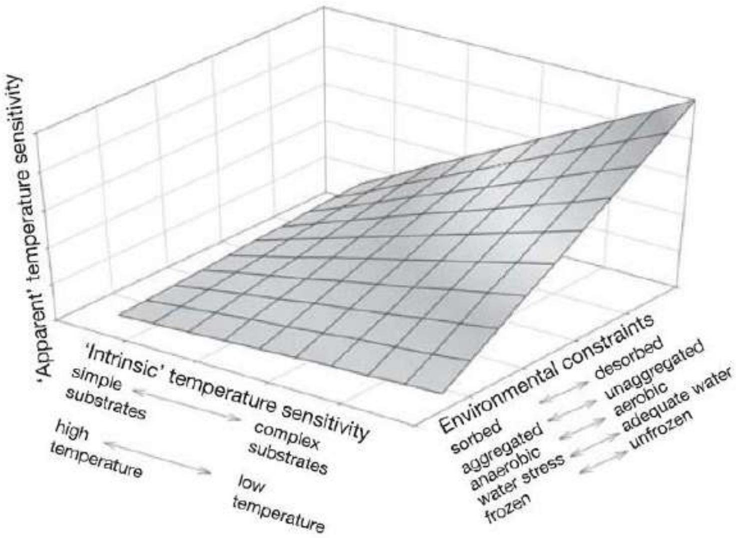

Figure 2.15-D: The mineralization of soil organic matter depends on temperature and several site factors[Davidson and Janssens, 2006].

3. Results

3.1. Geoinformation

From the surface model we derived the slope, the gain in radiation, several hydrological indices and the CTI for all sampling points. These data were further evaluated (see chapter 3.4).

3.2. Vegetation

The list of encountered species is given in tables 3.1, 3.2, 3.3

A detailed list of the vegetation survey is available on request.

Figure 3.1 shows the distribution of stone pine seedling (green dots) far above the present timberline. The map indicates that no germination constraint is active in that zone. Our observation agrees with the hypothesis of botanists, that the current timberline is at $\approx$ 2300 m, *i.e.* well above the elevation of current encounters of cembran pine. All of these specimen are between 5 and 40 cm high. The development of even higher trees may be simply a matter of time, or disturbances inhibit the quicker development of further pines.

3.3. Soils

The detailed soil surface confirmed the primary observation that the soils are extremly variabel. Indeed is the dominant soil formation under dwarf shrub and heath the deeply organic profile, whereas forest soils are primarily iron-humus podsols as described in textbooks [Duchaufour, 1982, Rehfuess, 1990]. Figure 3.2 gives visual evidence for the encountered differences. The differences with respect to the content of soil organic matter are obvious.

Differences in the depth of the litter layer are shown in figure 3.3. The graph shows the dominance of deep litter layers in podsols, which are dominant in the forest. In the other soil types more C is embedded in the A-horizon of the mineral soil. A statistical evaluation showed no significant differences in the depth of the litter layer and the A-horizon between types of vegetation

Table 3.1-D: Trees and woody species found at the experimental site Poschach, Obergurgl.

Larix decidua	Pinus cembra	Pinus mugo

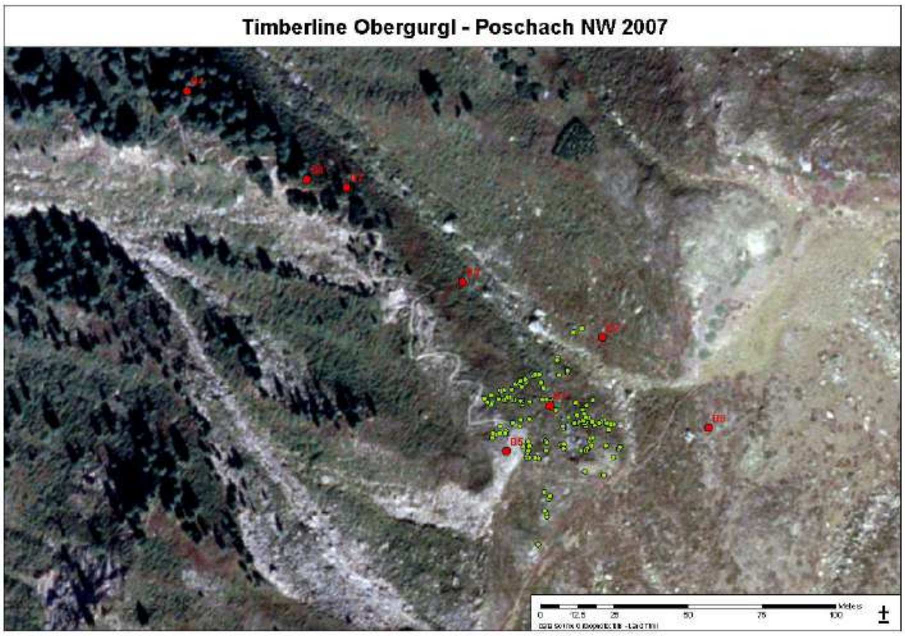

Figure 3.1-D: Distribution of stone pine seedlings well above the actual timber line (green dots).

Figure 3.2-D: A typical iron-humus podsol as found in the stone pine forest (left) and a cambisol/podsol/leptosol as found above the current timberline under the dwarfshrub communities.

Table 3.2-D: Dwarf shrubs and higher plants except trees found at the experimental site Poschach, Obergurgl.

Agrostis agrostifolia	Hieracium piliferum	Rhododendron ferrugineum
Agrostis rupestris	Hieracium sp.	Salix retusa (herbacea)
Anthoxanthum odoratum	Juniperus communis ssp. nana	Saxifraga bryoides
Arctostaphylos uva ursi	Ligusticum mutellina	Selene rupestris
Avenella flexuosa	Loiseleuria procumbens	Sempervivum tectorum
Botrychium lunaria	Luzula lutea	Senecio incarnus
Calluna vulgaris	Luzula luzulina	Silene vulgaris
Campanula scheuchzeri	Luzula multiflora	Soldanella pusila
Carex curvula	Luzula pilosa	Solidago virgaurea
Diphasiastrum alpinum	Luzula sp.	Trifolium sp.
Empetrum nigrum	Nardus stricta	Vaccinium myrtillus
Euphrasia sp. (pulchella)	Oreochloa disticha	Vaccinium uligunosum
Festuca halleri	Phyteuma betonicifolium	Vaccinium vitis-idaea
Geum montanum	Potentilla aurea	Veronica bellidioides
Helictotrichon versicolor	Primula glutinosa	

Table 3.3-D: Mosses and lichensen countered at the experimental site Poschach, Obergurgl.

Lichens	Mosses
Cladonia silvatica	Dicranum
Cladonia rangifera	Racomitrium
Cladonia alpestris	Polytrichum
Cetraria nivalis	Hylocomium
Cetraria islandica	Pleurozium
Alectoria ochroleuca	
Solorina crocea	
Thamnolia vermicularis	
Sterocaulon alpinum	

(forest versus dwarf shrubs) .

Tables 3.4 and 3.5 show the results of the chemical soil analysis. For the location of soil profiles refer to figure 2.9. Soils are fairly acidic, as expected, based on the geological setting. The C content in all four profiles is quite high. The C:N ratio from 18 to 24 is normal and gives no indication of an inhibition for the mineralization of the soil organic matter.

The cation exchange capacity of the soils is very low. Even the richest soil (B8 in table 3.5) has only less than 70 μmol kg^{-1}, that is approximately half of the average exchange capacity of Austrian forest soils (comparison: Austrian Forest Soil Inventory). The base saturation is very low, again with the exception of profile B8. The profile B8 may differ for the particular reason of being located in a small scale accumulation site. This is yet another indication of the observed small scale variability of mountain soils [Stöhr, 2007]. The majority of the cation exchange capacity derives from variable exchange sites of the soil organic matter. The low clay content of the soils determine that clay mineral contribute little to the cation exchange capacity. The

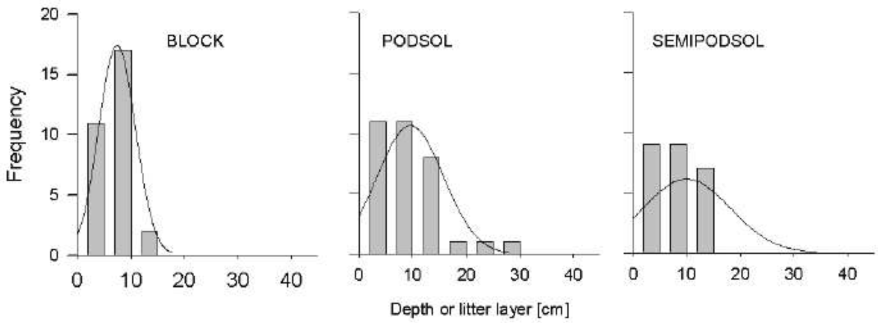

Figure 3.3-D: Depth of the litter layer under different soil types,

Table 3.4-D: Total content of carbon, nitrogen, and phosphorus and the *p*H of the soil.

	pH $CaCl_2$	C (%)	N (%)	C:N	P (%)
B1	4,1	39	2,0	20	0,70
B2	4,2	38	2,1	18	0,68
B3	4,1	44	2,0	22	0,41
B8	4,2	55	2,3	24	0,71

content of soil organic matter and its chemical properties are therefore a key variable for the biogeochemistry of that site.

The results of the incubation experiment are shown in figure 3.4. The soils show a very weak response to warming. Even a four-fold increase in temperature leads to a small release in CO_2. Again, profile B8 represents an outlier. The plot in the lowest position along the elevational gradient is most responsive to an increase in temperature. Nevertheless, the Q_10-values for all four sampling points are around 2 and therefore rather low, compared with many other studies [Davidson et al., 2006, Janssens and Pilegaard, 2003, Pavelka et al., 2007, Schindlbacher et al., 2008].

The composition of the soil microbial community is shown in figure 3.5. The relative contribution to the total microbial biomass differs only little between the sampling profiles. Major differences exist in the total soil microbial biomass (numbers in pie charts). The values for the total soil microbial biomass range from 24 to 130 nmol g^{-1}. Such values are extremely low. Some subtle differences are not obvious from inspection of figure 3.5: Soils B1, B2, B3 have less bacteria but a higher percentage of vasicular-arbuscular mycorrhizae. Especially the latter are highly important for carbon sequestration in soils [Langley et al., 2006].

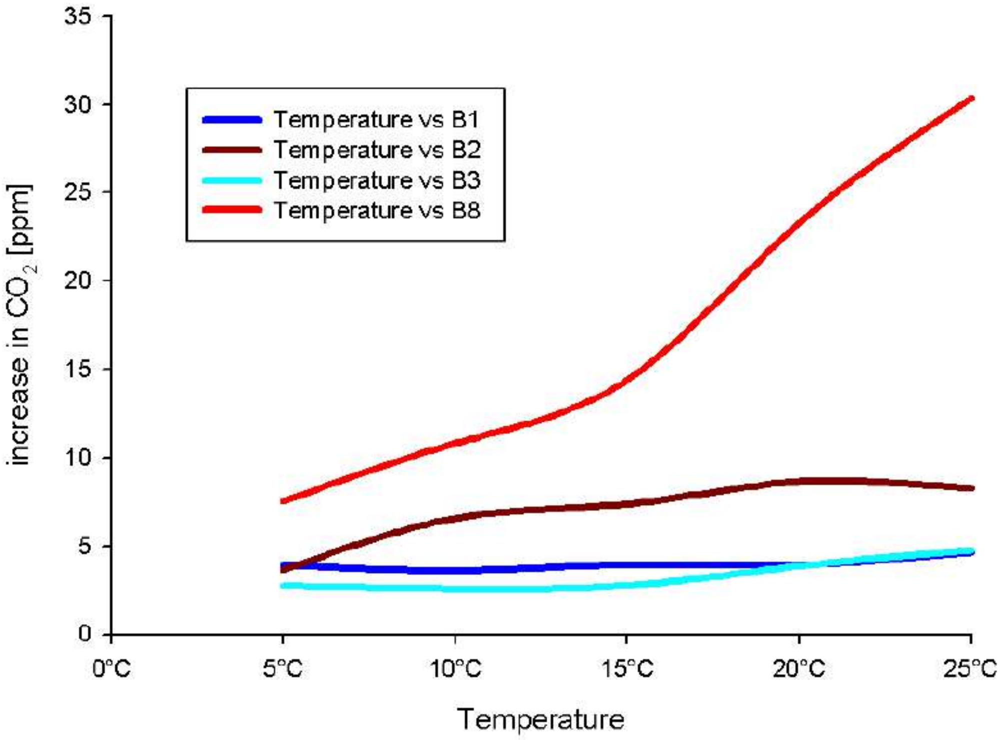

Figure 3.4-D: Basal respiration at four positions along an elevational gradient in Poschach, Obergurgl.

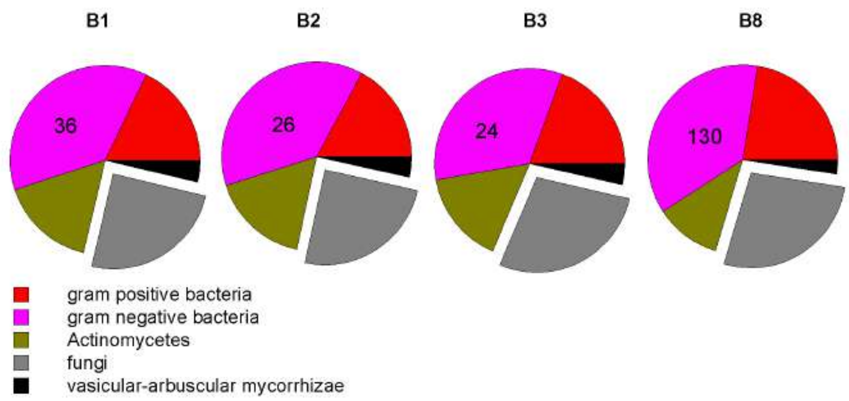

Figure 3.5-D: Composition of the soil microbial community at Poschach, Obergurgl. Pie chart gives relative contribution in % of total soil microbial biomass; the total microbial biomass is shown as number within the upper left part of the pie (biomasss: nmol g^{-1}).

Table 3.5-D: Content of exchange cations, cation exchange capacity (CEC), and base saturation (BSat) of the soil.

	K^+	Ca^{2+}	Mg^{2+}	Na^+	Mn^{2+}	Al^{3+}	Fe^{3+}	H^+	CEC	BSat
					[μmol kg^{-1}]					[%]
B1	0,7	2,1	0,9	0,00	0,08	42,0	0,48	1,04	47,3	8
B2	0,8	2,2	1,0	0,00	0,06	30,9	0,56	0,66	36,2	11
B3	0,8	3,5	1,5	0,00	0,02	36,6	0,63	1,03	44,1	13
B8	2,1	34,2	4,4	0,00	1,24	25,2	0,39	0,97	68,5	59

3.4. Relation between soil and vegetation

A correlation analysis showed a dependence of topography, soil, and vegetation. The unsurprising result is that deeper soils allow for a higher primary productivity. More productivity leads to more litterfall and consequently to the formation of a thicker litter layer and A-horizon, respectively. The thickness of the litter layer decreased with elevation. That spatial trend is also driven by differences in the productivity. An ANOVA with a subsequent comparison of group means (Duncan test) showed that the thickness of the litter layer depends on the vegetation type. The differences were even clearer when instead of plant communities (lumped information on all encountered plant species) only the dominant plant species was chosen as stratfier. Mapping the vegetation therefore yields information on the soil properties and allows conclusions on the current soil carbon pool. Even a rough characterization of the vegetation, *i.e.* identification of the dominant species, is valuable for inferences on soil C pools.

4. Discussion

Carbon sequestration in soils poses a challenge. Soil work is expensive because the field work is tedious, samples are bulky, and the chemical analysis in the laboratory is expensive. Therefore the information of a stationary soil C pool would save a considerable effort of soil C monitoring. Comprehensive experiments such as the LUSTRA project in Sweden [Berggren et al., 2004] yield inconclusive results on the long-term C dynamics. Soils may be considered as rather inert or at least slow in their response to global change. Nevertheless, some experiments give evidence to rapid changes in soil C pools. These dynamics are even accelerated when linked to land-use change [Bellamy et al., 2005, Heath and Smith, 2000, Kullman, 2002, Markewitz et al., 2002, Nowinski et al., 2007, Richter jr. and Markewitz, 2001, Trumbore et al., 1996]. Evidence for rather rapid changes in soil C is also given from modelling results [Cox et al., 2000, Powlson, 2005, Thürig et al., 2005].

An open question is the relevance of the C dynamics of unmanaged soils in future committment periods. It is one of the major critiques that the current reporting requirements apply only for managed land and therefore for only a small part of the global terrestrial carbon pool [IGBP Terrestrial Carbon Working Group, 1998]. Mountain soils have a poorly defined status. Abandoned pastures may or may not qualify as 'managed land'. A change in the soil C pool in that regions may affect national C budgets. On the other hand, the expansion of vegetation into previously unproductive land may go unnoticed under the current reporting requirements. The somewhat inconsistent treatment of soils and many other arguments are in support for a global full-carbon accounting scheme.

In our study we have gained further evidence that dwarf-shrub communities in the mountains are particularly slow in their C turnover. The differences in the soil microbial community that is in charge of the mineralization of soil organic matter may be an important factor. However, the differences in the taxonomic composition, as shown by the PLFA-techniques, support the hypotheses that the turnover of soil organic matter is functionally distinct in forest soils and soils under dwarf shrubs, respectively. Despite taxonomic similarities, the differences in the density of vasicular-arbuscular mycorrhizae may be crucial [Langley et al., 2006, Treseder and Allen, 2000]. - Our incubation experiment showed that the quality of the substrate is widely different. Even an increase of the ambient temperature to comfortable $20°\mathrm{C}$ led to only a small increase in the mineralization rate in soils under dwarf shrub communities. The indication that soil microorganisms could not dwell under favorable temperature conditions shows limitations in the substrate quality. That mechanism has been theoretically predicted [Davidson and Janssens, 2006].

A higher turnover of soil organic matter in forest soils as compared to dwarf shrub communities will invariably lead to the mobilisation of at least a part of the soil organic matter and consequently to a release of greenhouse gases. Most prominent will be the effect of the vegetation change on the CO_2-release. Presently, an experiment is conducted that will allow to narrow the estimated range of C release from soils [Schindlbacher et al., 2005, 2007]. A companion study focuses on nitrogen oxide emissions. Although they are much smaller than C-emissions, the effect of a regional greenhouse budget is potentially high [Härtel et al., 2002, Kitzler et al., 2006].

The experimenal site Poschach, Obergurgl, offers a unique opportunity to study the effects of global change (climate and land use, combined). Future research projects cannot only lean on the exquisitely published results of the Forest Research Center Vienna [FBVA, 1961], but also on the numerous interdisciplinary research activites conducted at the University Center Obergurgl.

The immediate consequences of the project are to derive a more complete picture on the carbon dynamics by

- assessing the growth of trees (time-series from 1950 on)
- further analysis of soil C & N
- characterization of soil organic matter, considering the diverging views on soil C stability [Knorr et al., 2005, Liski et al., 1999]
- assessment of the site history

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List of Figures

List of Tables