Multiscale Soil Carbon Distribution

in Two Sub-Arctic Landscapes

Volume 1

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Declaration

I hereby declare that this thesis has been written by myself, that it embodies the result of my own research and that the work contained therein has not been submitted for any other degree. All research material has been duly acknowledged and cited.

Signature Date 30th of September 2011

Abstract

In recent years, concern has grown over the consequences of global warming. The arctic region is thought to be particularly vulnerable to increasing temperatures, and warming is occurring here substantially more rapidly than at lower latitudes. Consequently, assessments of the state of the Arctic are a focus of international efforts. For the terrestrial Arctic, large datasets are generated by remote sensing of above-ground variables, with an emphasis on vegetation properties, and, by association, carbon fluxes. However, the terrestrial component of the carbon (C) cycle remains poorly quantified and the below-ground distribution and stocks of soil C can not be quantified directly by remote sensing. Large areas of the Arctic are also difficult to access, limiting field surveys. The scientific community does know, however, that this region stores a massive proportion (although poorly quantified, soil C stocks for tundra soils vary from 96 to 192 Gt C) of the global reservoir of soil carbon, much of it in permafrost (900 Gt C), and these stocks may be very vulnerable to increased rates of decomposition due to rising temperatures. The consequences of this could be increasing source strength of the radiatively forcing gases carbon dioxide (CO_2) and methane (CH_4).

The principal objective of this project is to provide a critical evaluation of methods used to link soil C stocks and fluxes at the usual scales spanned by the field surveys (centimetre to kilometre) and remote sensing surveys (kilometre to hundreds of kilometres). The soil C distribution of two sub-arctic sites in contrasting climatic, landscape/geomorphologic and vegetation settings has been described and analysed. The transition between birch forest and tundra heath in the Abisko (Swedish Lapland) field site, and the transition between mire and birch forest in the Kevo

(Finnish Lapland) field site span several vegetation categories and landscape contexts.

The natural variability of below-ground C stocks (excluding coarse roots > 2 mm diameter), at scales from the centimetre to the kilometre scale, is high: 0.01 to 18.8 kg C m^{-2} for the 0 - 4 cm depth in a 2.5 km^2 area of Abisko. The depths of the soil profiles and the soil C stocks are not directly linked to either vegetation categories or Leaf Area Index (LAI), thus vegetation properties are not a straightforward proxy for soil C distribution. When mapping soil or vegetation categories over large areas, it is usually necessary to aggregate several vegetation or soil categories to simplify the output (both for mapping and for modelling). Using this approach, an average value of 2.3 kg C m^{-2} was derived both for soils beneath treeless areas and forest understorey. This aggregated value is potentially misleading, however, because there is significant skew resulting from the inclusion of exposed ridges (with very low soil C stocks) in the ‘treeless’ category. Furthermore, if birch trees colonise tundra heath and other ‘open’ plant communities in the coming decades, there will likely be substantial shifts in soil C stocks. This will be both due to direct climate effects on decomposition, but also due to changes in above- and below-ground C inputs (both in quantity and quality) and possibly changes in so-called root ‘priming’ effects on the decomposition of existing organic matter.

A model of soil respiration using parameters from field surveys shows that soils of the birch forest are more sensitive to increases in mean annual temperature than soils under tundra heath. The heterogeneity of soil properties, moisture and temperature regimes and vegetation cover in ecotone areas means that responses to

climate change will differ across these landscapes. Any exercise in upscaling results from field surveys has to indicate the heterogeneity of vegetation and soil categories to guide soil sampling and modelling of C cycle processes in the Arctic.

Acknowledgements

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This work is also part of the 2007-2008 International Polar Year project ABACUS (Arctic Biosphere Atmosphere Coupling at Multiple Scales). Led by Williams at the University of Edinburgh, ABACUS involves researchers from all over the United Kingdom in a study of the arctic ecosystem with the aim of modelling the complex interactions between the atmosphere and biosphere and forecasting the consequences due to climate change in the arctic region. Their field sites at Abisko (Swedish Lapland) and Kevo (Finnish Lapland) are used in this project. The work done there would not have been possible without the help and kindness of the people working at these field stations. I have had assistance on the field from fellow ABACUSs Iain Hartley and David Hopkins, and Iain McNicol was the cheerful Scottish lad that made a long summer of fieldwork run more smoothly and a very nice "future colleague" to work with. Some of the data used in this work have been used courtesy of other ABACUS team members, in particular Timothy Hill and Ana Prieto-Blanco and I thank them for their assistance.

Through SAGES and ABACUS, I have been part of the British postgraduate and research community and it was a really good experience. My fellow PhD students from these groups were a good support in times of doubt and the retreats at the Burn with SAGES students as well as the weeks on the field with the ABACUS's were a very enjoyable way to work! And a good way to discover the exotic countrysides of Sweden, Finland and England.

Stirling and its university were really a home from home these four years, so I will be back! SBES was a really nice and relaxed environment to work in and people made me feel welcome there. I would like to thank Bill Jamieson and Scott Jackson for rescuing me a number of times from technical nightmares and printing problems. My laboratory work was greatly eased thanks to Lorna English and Helen Ewen and the micromorphology was simplified thanks to George MacLeod and Paul Adderley. Stuart Bradley did suffer the GPS failures with me.

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Enfin je remercie ma famille et mes parents, qui m'ont laissé partir encore plus au Nord au pays du haggis et du tartan!

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Chapter 1 - Introduction

1.1 Climate change and the Arctic

In recent decades, climate change and the threat of global warming have reached the top of the environmental agenda and become a worldwide concern. As a result, numerous assessments of the present state of the environment have been undertaken and the prognosis for the future has been based on a suite of scenarios of climate change. These had to take into account a diversity of viewpoints and issues, amongst which are biodiversity, ecosystem services to society, economic resources and the current state of carbon (C) stocks and fluxes (for example The Intergovernmental Panel on Climate Change (IPCC) reports are an international reference on the topics of global warming; Prentice *et al.*, 2001; Christensen *et al.*, 2007; Denman *et al.*, 2007; Lemke *et al.*, 2007). A major preoccupation of many of these reports is to strengthen the scientific basis underpinning the knowledge of climate change and the likely ecosystem responses (e.g. Jonasson, 1982; Houghton *et al.*, 2001). Greenhouse gases, amongst which carbon dioxide (CO_2) and methane (CH_4), are named thus for their capacity to cause air temperature increase (Prentice *et al.*, 2001) and this puts them under particular scrutiny. For instance, one of the main debates is about finding the principal cause of their increased emission to the atmosphere. Another unknown is the strength of the associated positive or negative feedback loops between terrestrial, oceanic and atmospheric processes and of course within the C cycle (for example studies presented on soil winter-respiration (Chapter 4); Prentice *et al.*, 2001; Randall *et al.*, 2007). Understanding the global carbon cycle is vital to locating the sources of these fluxes and their likely responses to environmental, climate or management change. This project aims at characterising sub-arctic soil C stocks and their distribution at the field scale, as well as their relationships with soil and vegetation variables. This will guide future projects surveying arctic areas to estimate circumpolar soil C stocks.

The Arctic and in particular its C stocks are seen as particularly sensitive to any change in mean global temperature on a number of spatial and temporal scales (Wookey, 2002; Wookey, 2008; Post *et al.*, 2009). Over the past century, the Arctic has undergone a mean annual warming higher than the global mean warming and this trend is predicted to continue throughout the next century (Prentice *et al.*, 2001; Christensen *et al.*, 2007). Each small change results in a cascade of responses by other ecosystem processes. For instance, sea ice and snow cover decrease both in duration and in area covered, for any small change in air, soil or water temperature (Loeng *et al.*, 2005; Anisimov *et al.*, 2007). Changes in sea ice, snow cover and glacier volumes result in changes in albedo, favouring the absorption of more solar radiation and thus further warming the oceans and soils (Kittel *et al.*, 2000; Loeng *et al.*, 2005; Euskirchen *et al.*, 2006). Combined with the increase in air temperature, this increase in soil temperature causes earlier snow melting and further soil temperature increase (Larsen *et al.*, 2007; Jahn *et al.*, 2010). The winter duration decrease and snow-free periods extension affect directly the organisms living in these areas, as the more adapted to higher temperatures are favoured by the new climatic conditions. This may allow them to colonise new territories and compete with species already disadvantaged by the changing climate (Wilmking *et al.*, 2006; Millard *et al.*, 2007; Wookey *et al.*, 2009). At the end of the food chain, this ultimately has dramatic consequences for the people living in this landscape

(Huntington *et al.*, 2005a). However, it is important to understand that a cascade of processes such as the one described above is a simplification compared to the natural complexity of these systems. The circumpolar Arctic covers a large area and thus these reactions can differ in intensity and time, making the forecasting of climate change consequences less than straightforward and more time-consuming (Randall *et al.*, 2007). This concern was addressed directly in the organisation of an International Polar Year in 2007-2008, which promoted projects centred on the study of climate change and its impacts in the Arctic. This includes the ABACUS (Arctic Biosphere Atmosphere Coupling at Multiple Scales) project, which this project is a part of (ABACUS, 2010).

1.2 Background

Relevant thematic reviews are given in Chapters 2 to 4. The present chapter highlights some of the problems encountered when using C stocks data from previous studies and/or conducting field surveys as used in this project. The first problem is which definition of the Arctic to use, as the definition chosen for a study has a profound influence on the figure given for C stocks in the Arctic. The importance of the birch forest (*Betula pubescens* subsp. *czerepanovii* (Orlova) Hämet-Ahti) and tundra heath ecotone (i.e. transitional zone) at the margins of the arctic regions blurs the boundary between Arctic and Sub-Arctic (i.e. areas without trees and with trees). This ecotone is a key to understanding what consequences climate change can have at the margins of the ("biological") Arctic. Amongst these consequences, the changes in soil C stocks are of a particular interest since below-ground C stocks in these systems are often a large proportion of the total stocks

(Anderson, 1992), and so are globally important. However methodological and practical limitations lead to a broad range of estimates.

This project aims at characterising soil C stocks and their distribution at the field scale, in order to evaluate robust sampling approaches and appropriate spatial scales needed when surveying arctic areas to estimate circumpolar C stocks. The field sites chosen for this are presented subsequently.

1.2.1 Definition of the Arctic

Bliss and Matveyeva (1992) estimate the terrestrial realm of the Arctic as covering 360,000 km^2 in Alaska, 2,480,000 km^2 in Canada, 2,167,000 km^2 in Greenland and 2,560,000 km^2 in Eurasia; thus a total of 7,567,000 km^2. Of this area, arctic tundra covers 5.6 million km^2 (Wookey, 2002). However, the first parameter to consider when using data from arctic studies is how the authors defined the Arctic area (Fig. 1.1). Numerous global studies consider the Northern Hemisphere as a whole or take an area over a certain latitude, for example above 50°N (Kauppi, 2003; Biancamaria *et al.*, 2011), and the search for the “real Arctic” was already launched in the 1950’s (Polunin, 1951). Other definitions include the AMAP (Arctic Monitoring and Assessment Programme) area (Fig. 1.1; AMAP, 1998), the CAFF (Conservation of Arctic Flora and Fauna) boundaries and natural boundaries, such as the treeline and the 10°C July isotherm (for example AMAP, 1998; Sitch *et al.*, 2007). Taking territories above 50°N encompasses temperate, boreal and arctic regions and generally does not pretend to local results but only generalisations (Randall *et al.*, 2006; Bunn *et al.*, 2007). The Circumpolar Arctic Vegetation Map (CAVM team, 2003) indicates the different vegetation categories found in the Arctic north of the birch forest-tundra heath ecotone, amongst which several types of tundra heath. As the biological Arctic is defined as the area north of the treeline (Bliss and Matveyeva, 1992), the field sites used in this study, encompassing both treeless areas and birch forest (see sections 1.2.6., 2.3.1, and 3.3.4), do not appear on the CAVM or other maps based on the treeline. It is worth noting that they are situated several hundred of kilometres above the Arctic Circle (Fig 1.1 and 1.2; Walker *et al.*, 2005; Sitch *et al.*, 2007). However, the field sites do feature in the region included in the AMAP (Arctic Monitoring and Assessment Programme) area (see Fig. 1.1).

Figure 1.1: Map of the Arctic with the Arctic Circle, Arctic marine boundary, AMAP Arctic boundary and 10°C July isotherm, and location of the field sites area, modified from Fig. 2.1 in AMAP 1998, by Rekacewicz and Bournay, (GRID-Arendal), modified from Stonehouse, 1989

1.2.2 Birch forest and tundra heath

The Arctic region covers a vast surface (Fig. 1.1), and the spatial distribution of known data is very uneven. The short length of the growing season or of the thaw period means that measurements tend to be concentrated within a shorter period than studies of temperate environments. For ease, measurements are often taken around established scientific research stations, for example Abisko in Sweden (Sjögersten and Wookey, 2002a,b; Grogan and Jonasson, 2006; Rinnan and Rinnan, 2007), Toolik lake in Alaska (Oechel *et al.*, 1993; Mack *et al.*, 2004; Sitch *et al.*, 2007; Loranty *et al.*, 2011) and Ny-Ålesund in Svalbard (Robinson *et al.*, 2004; Callaghan *et al.*, 2005; Christiansen *et al.*, 2010). However, these environments can be perturbed by too many manipulations within a small area (Abisko, 2008). Large areas without any permanent human occupation are neglected due to the logistical problems of sampling. Nevertheless, precise measurements on fine scales are needed, as physical soil properties can vary a lot on a small distance (Callaghan et al, 2005).

The biological Arctic is defined as the area above the treeline (Bliss and Matveyeva, 1992), and so is separated from the sub-arctic forest. The transition area between tundra and forest is sometimes hard to define. Consequently, studies do not always encompass the arctic environment *sensu stricto*. Some authors deliberately consider boreal and arctic environments together, either for comparison purposes or as a single component of the Earth system, or because they are interested in the transition between the two (Gorham, 1991; Ping *et al.*, 1997; Beringer *et al.*, 2005; Grogan and Jonasson, 2006). Several estimates of arctic environments' C stocks are given: Sjögersten and Wookey (2002a) give a figure of 390 Gt C in tundra and boreal forests, whilst tundra soils are thought to contain 96 Gt C and boreal forest soils 138

Gt C (Callaghan *et al.*, 2005). The boreal forest and the arctic tundra are undoubtedly linked in the treeline area. The forest-tundra ecotone, as the transition between these two biomes, is generally hard to place precisely, and is considered as the area between the unquestionable tundra and the dense boreal forest. Examples of this ecotone can be found in the Abisko area in Swedish Lapland, which is used in the present study (Fig. 1.2 and 1.3; Jonasson, 1982; Bliss and Matveyeva, 1992; Wookey, 2002). The Torneträsk area near Abisko shows a transition between the birch forest and the treeless heath marked by isolated trees or thickets of birches on south-facing slopes and valleys (Jonasson, 1982).

Following the inventory of carbon pools by Schlesinger (1977), Anderson (1991) deduced that, as boreal forest and arctic tundra have similar biomass and Soil Organic Matter (SOM) pools, forest succeeding to tundra would result in little net change in carbon balances. This has to be verified in the field sites used in the present project (Chapters 2 to 4).

1.2.3 Limits of the inventories of total soil C in the Arctic

Despite the existence of several definitions for the Arctic boundaries, there is an agreement that the Arctic contains a great quantity of C in its soils and vegetation communities (Bliss and Matveyeva, 1992). However, the exact soil C stock size, its spatial distribution and organic matter ages are still uncertain, which creates challenges when trying to assess the potential consequences of this region switching from a C sink to a source (Oechel *et al.*, 1993; Mack *et al.*, 2004; Jahn *et al.*, 2010). Sometimes scarcity of data means synthesising and amalgamating data from very different sources, for instance in calculating global inventories (Schlesinger, 1977).

This aggregation leads to the problem of inexact representation of the Arctic in global studies, based on upscaling of only a small number of samples (Post *et al.*, 1982).

One of the reasons for the uncertainty in the size of soil C stock is that soil, as a C reservoir, is not always well defined. Global inventories provide estimates of global C stocks (Schlesinger, 1977; Post *et al.*, 1982). Soil is sometimes considered as one reservoir and heterogeneities in soil properties and plant cover are masked by averaging values of different vegetation communities for large areas. The figures used for global carbon stocks are of 1500 Gigatonnes of Carbon (Gt C or Petagram of carbon PgC) for soils and 500 Gt C for vegetation (Prentice *et al.*, 2001). The Fourth IPCC report (Denman *et al.*, 2007) puts the soil, vegetation and detritus in the same reservoir, detritus being formerly placed within the soil to give 1500 Gt C.

Another reason for the lack of stocks data is the emphasis that has been placed on estimating C fluxes. In recent years, coordinated efforts have been made to facilitate the exchange of data and observations across the Arctic. SCANNET (Scandinavian/North European Network of Terrestrial Field bases) is a network of terrestrial field sites in the Arctic, and is part of the CEON (Circumarctic Environmental Observatories Network[1]). The sites used in this project, Abisko and Kevo (Fig. 1.2), belong to SCANNET. This network generates several thematic guide datasets, with climate change results and models, climate variability, biodiversity, phenology, and includes a societal aspect with the involvement of local

[1] http://www.scannet.nu/content/view/85/152/; last accessed August 2011

stakeholders[2]. However, its climate change scenarios report (Sælthun and Barkved, 2003) as well as the final report of one of its projects, the Land Arctic Physical Processes (LAPP; Lloyd *et al.*, 1999) give a relatively comprehensive account of the CH_4 and CO_2 fluxes and soil moisture data in the different field sites, but no soil C stocks values.

Modelling climate change relies heavily on global-scale models, such as the global coupled Atmosphere-Ocean General Circulation Models (AOGCMs), used in major studies such as the IPCC and ACIA (Kattsov *et al.*, 2005; Randall *et al.*, 2007). As their name suggests, these models deal mostly with atmospheric and oceanic processes, whilst terrestrial components are minor. In the ACIA 2005 report (Kattsov *et al.*, 2005), the terrestrial variables mentioned are the soil moisture, surface roughness, albedo, fluxes and river dynamics. However, soil properties as the C content and the C stocks are not taken into account (Kattsov *et al.*, 2005). This is corrected in the IPCC 2007 assessment, where the terrestrial C cycle is included; however, it is noted that this was not a common component of the AOGCMs at the time (Randall *et al.*, 2007). Nonetheless, one model used in these assessments, the Hadley Centre's climate-carbon cycle General Circulation Model (GCM) HadCM3LC is now coupled with the Rothamsted RothC model (Jones *et al.*, 2005; Arora *et al.*, 2009). To help integrating soil components into models, a model has been built on empirical soil data and is described in Chapter 4.

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[2] http://www.scannet.nu/content/section/6/155/, last accessed August 2011

1.2.4 Limits of field surveys

Arctic field surveys have their own spatial, temporal, practical and logistical limitations (Burrows *et al.*, 2002; Mikhailova and Post, 2006), which confound the uncertainties propagated by generalisation and scaling-up (Callaghan *et al.*, 2004a; Goidts *et al.*, 2009). Some of these difficulties arise from the limited access to some sites, the short field season, and logistics problems with sample transports from the field to the laboratory, as well as the time constraints imposed on processing a large number of samples. Therefore, field sampling is, of necessity, limited in scope and aims at retrieving the most robust information possible from parsimonious sampling.

In situ, several particularities of arctic soils (e.g. their high stone content, the presence – in some locations – of permafrost, and the protracted periods over which the active layer is frozen most of the year) make the measurements of C stocks difficult. Inventory methods involve repeated sampling, above- and below-ground, of different soil pools (Williams *et al.*, 2005). To the patchiness of soil C distribution is added the unevenness of the terrains, and sampling must take both into account whilst still having a good spatial coverage to keep some scientific value (Hugelius *et al.*, 2011a). A sufficient spatial coverage proves difficult because the transport of measurement material is not possible in all the sites and environments. As a result, biases in the choices of the sampling schemes and of the types of soil sampled can be introduced by the work conditions. Amongst arctic soils, drained soils are always easier to study and so have been more thoroughly researched, even if they contain less C in contrast to waterlogged and permafrost soils (Anderson, 1991; Harden *et al.*, 1992), which prove more difficult to sample due to their very nature (Christiansen *et al.*, 2010). This difficulty explains the shallow depth of most studies

(=<1m) on soils which can be several metres deep; hence there is a necessity to extrapolate to greater depths to complete data (Dutta *et al.*, 2006; Zimov *et al.*, 2006). Waterlogged soils are an important component of the arctic environment, and permafrost soils contain important C stocks. The difficulties in sampling mean that crucial data are lacking and resulting inventories are incomplete (Harden *et al.*, 1992).

The depth of sampling is important when quantifying soil carbon since the C content is generally not homogeneous throughout the profile. If the deeper soil horizons are neglected, it can lead to an underestimation of the C content. This error can later be amplified if the value for surface soil is used for extrapolating at depth or over large areas (Anderson, 1991; Zimov *et al.*, 2006; Ping *et al.*, 2008). In general the sampling depth is one metre (for example most data in Schlesinger (1977); Ping *et al.*, 2008). Sometimes in the Arctic even this depth can not be reached and requires approximations for bulk density or C content (Bockheim *et al.*, 1999). Some soils have deeper horizons comprised of coarse fragments or ice wedges, which will not be accounted for if only the upper horizons are sampled (Harden *et al.*, 1992). Though some studies (Schlesinger, 1977) deemed sampling in tundra and boreal forests as impractical, it is nevertheless necessary for a good comprehension of C distribution in these environments and regional scale inventories are realised with the data available (Ping *et al.*, 2008).

Furthermore, many *process* studies (for example of respiration, litter decay, and organic matter turnover) are based on laboratory work using materials sampled from relatively few locations or environmental contexts rather than experiments *in* *situ* (Knorr *et al.*, 2005; Hartley *et al.*, 2008). This leads to the problem of representativeness of the results compared to natural field processes, and they need to be validated before incorporation into models. Nevertheless, results obtained in the laboratory can help to gain an idea of the processes and controls existing for soil C stocks and fluxes, even if the environmental conditions are simulated and may not reflect the full suite of conditions (e.g. seasonal/diurnal conditions) intrinsic to the field (Schimel *et al.*, 2006).

1.2.5 Associated soil properties

To understand the relationship between soils and climate, knowledge of the soils' physical properties and other edaphic factors, especially C content, bulk density and water content of the soils, are necessary (Anderson, 1991). However numerous studies on plant biomass and soil respiration lack detailed data on soil composition and soil types on the study site (for example Jonasson, 1982; Lloyd *et al.*, 1999). In particular, bulk density and C content are essential for the calculation of C stocks and often are not cited (Schlesinger, 1977). Whilst critical to the calculation these soil data can seem irrelevant to the study itself if, for instance, it is concentrated on plant respiration mechanisms.

The bulk density and the C content of soils are not homogeneous along the profile depths or over landscapes (Schlesinger, 1977; Anderson, 1991; Bockheim *et al.*, 1999; Trumbore, 2000). The problem of geographical coverage is equivalent to the one of depth measurement in soil environments with highly variable carbon content. The spatial distribution of C stocks is difficult to measure precisely even when soil organic carbon (SOC) diversity is not taken into account (Harden *et al.*, 1992). For instance, the depth of the active layer above permafrost or of the frozen loess deposits in Siberia – which contain several layers of different C richness- can be highly variable too (Zimov *et al.*, 2006). Whilst frozen soil is difficult to sample, the available results show that it can contain more SOC than the active layer, especially in the near-surface permafrost, the zone most sensitive to thawing because of global warming (Bockheim *et al.*, 1999). In addition, ice content can be highly variable in permafrost, and local features can make mapping the carbon distribution even more complex, for example the ice polygons in patterned ground (Bockheim *et al.*, 1999). These variations in soil C content and bulk density have to be accounted for when forecasting soil C stocks and soil C fluxes.

1.2.6 Some estimates of the soil C stocks in the Arctic

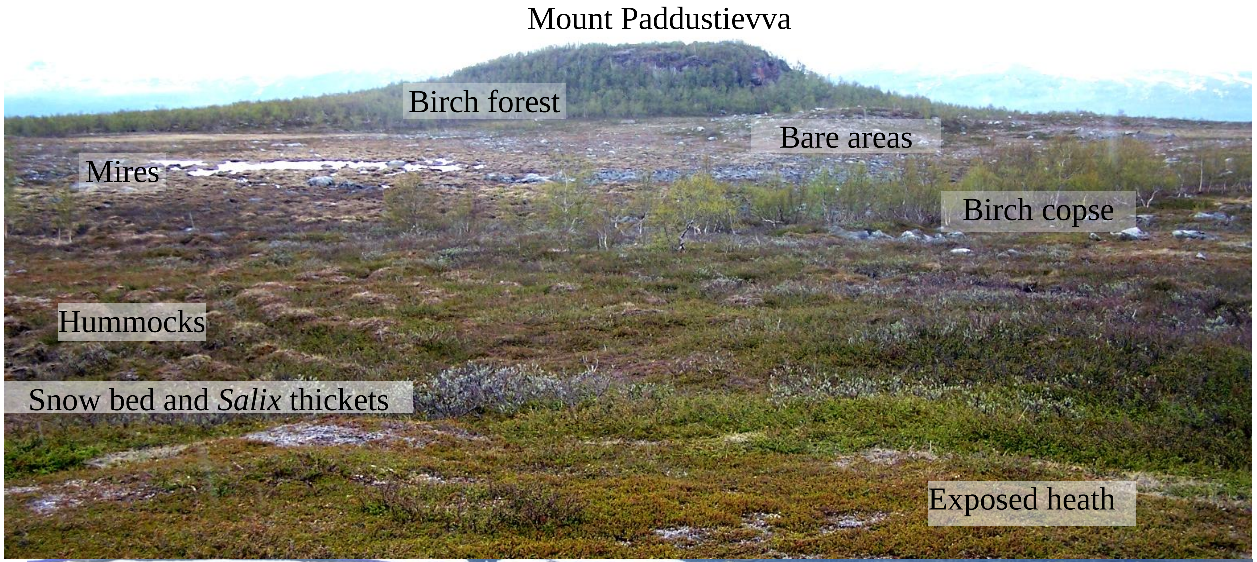
In spite of these constraints, estimates of the different arctic soil C stocks are available. In a global assessment of C stocks, Anderson (1991) gives estimates for all major types of vegetation and soils. Tundra soils' organic matter stock is estimated at 192 Gt C and boreal forests soils' organic matter stock at 182 Gt C. These figures are largely higher than the biomass estimates (84 Gt C for the boreal forest and 9 Gt C for the tundra). These stocks are linked to the surface extent of the vegetation or soil types to give estimates of the carbon content: more than 20 kg m^{-2} for the tundra and 17 kg m^{-2} for the boreal forest (8 kg m^{-2} for the boreal forest biomass, 2 kg m^{-2} for the tundra biomass; Anderson, 1991). Bliss and Matveyeva (1992) estimate arctic C reserves for unglaciated lands (5.60 x 10^{6} km²) to be of 26.33 Gt C for soils (soil organic matter) and vegetation (standing crops), with soils depths of 25 cm on average. This estimate uses data from other authors' works, per vegetation type. The Arctic Climate Impact Assessment report (Callaghan *et al.*, 2005) gives an estimate of 96 Gt C for tundra soils and 102 Gt C for tundra vegetation and soils for similar depths, taking data from McGuire and colleagues (1997) and Jonasson and co-authors (2001). They consider the forest tundra ecotone as being part of the boreal woodlands, and permafrost is limited to the seasonally thawed active layer. More recently, Ping and colleagues (2010) estimated the C stocks in the North American Arctic to be 98.2 Gt C for a depth of one metre.

Arctic soils are heterogeneous and the scope of this study does not encompass some of soils that are the richest in C. A significant fraction (900 Gt C) of this soil C is estimated to be stored in permafrost soils at a depth of 25 m, of which around 500 Gt C is found in the frozen yedoma (loess soils in ice-rich permafrost region) of north-eastern Siberia and Central Alaska (Dutta *et al.*, 2006; Zimov 2006; Ping *et al.* 2008). Other soils with a high C content are the boreal and sub-arctic peatlands (455 Gt C in total for a depth of one metre; Gorham, 1991; 50 to 70 Gt C in Western Siberia for a depth of 50 cm and expected to be higher if including deeper soils, Smith *et al.*, 2004), and sediments beneath ice-sheets (at least 46 Gt C at a depth of one metre; Zeng, 2003).

A detailed knowledge of the spatial distribution of C stocks on a circumpolar scale is necessary for understanding the possible responses of CO_2 and CH_4 emissions to environmental changes and the locations of sink and source areas. This will help identify where action can, and should, be taken to influence the future state of the arctic environment and C stocks. As mentioned above, this is done in the present project in the Fennoscandian sub-arctic sites of Abisko (Sweden) and Kevo (Finland) (Fig. 1.2).

Figure 1.2 Map of Fennoscandia showing the field sites of Abisko (Swedish Lapland) and Kevo (Finnish Lapland)

a)



b)

Figure 1.3: View of mount Paddustievva towards the North and its surroundings (a) and reindeer herd grazing on the Abisko field site (b)

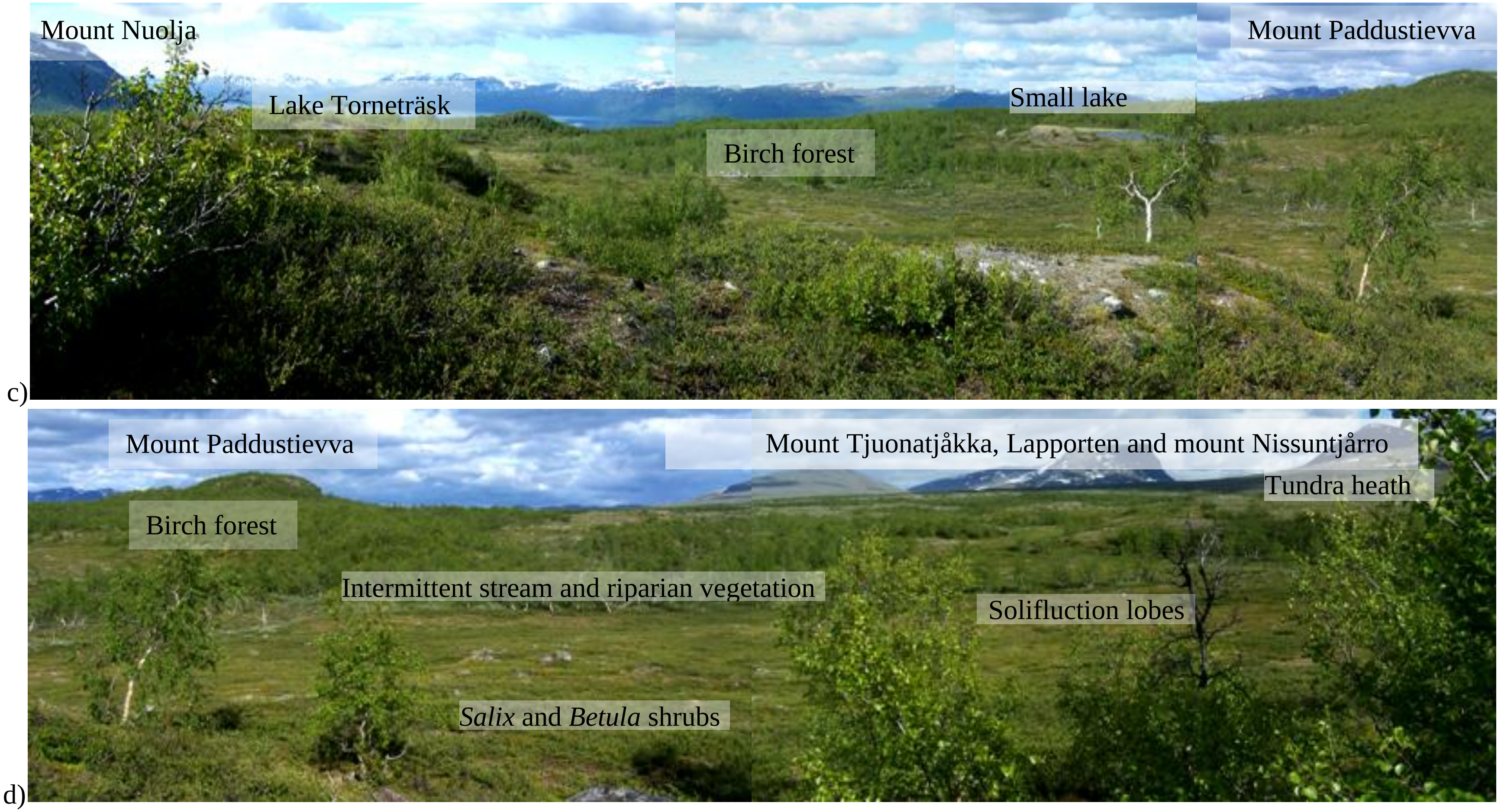


Figure 1.3: Two views of the Abisko field site, towards the North (c) and South-East (d) showing the landscape as a mosaic of birch forest patches and tundra heath

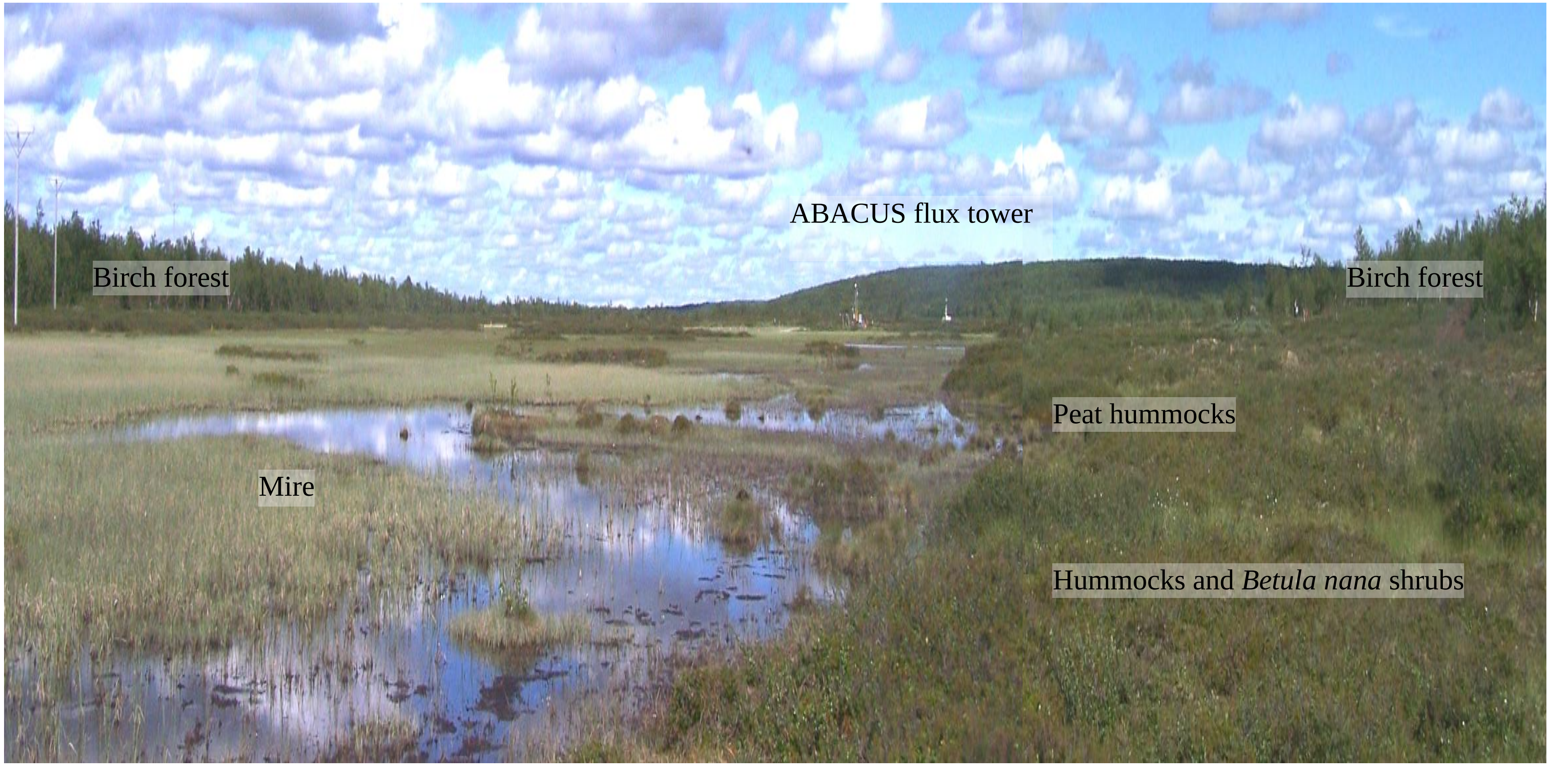


Figure 1.4: View of the Kevo field site (towards the North) with its central mire; peat hummocks with a heterogeneous vegetation cover mark the transition to birch forest

1.3 Field sites

1.3.1 Field sites in their scientific context

The field sites used in this study are Abisko (Fig. 1.2 and 1.3; 68º18’33’’N 18º50’42’’E) in Swedish Lapland and Kevo (Fig. 1.2 and 1.4; 69º29’33’’N 27º 13’39’’E) in Finnish Lapland. Both Kevo and Abisko have been used during the period of this project by the ABACUS (Arctic Biosphere Atmosphere Coupling at Multiple Scales) group amongst others, and so data are available to back up the soil and vegetation studies of the present work (e.g. Shaver *et al.*, 2007; Spadavecchia *et al.*, 2008; Williams *et al.*, 2001, 2006 and 2008). One of the ABACUS’s flux towers can be seen on the photograph of the Kevo field site (Fig. 1.4).

These sites have also important links to present scientific issues. Abisko is a base for several scientific teams and numerous projects, covering for example responses to climate change of the tree line and microbial respiration, ecosystem CO_2 production and photosynthesis during winter or the decomposition of leaf litter (Dorrepaal *et al.*, 2005; Grogan and Jonasson 2006; Larsen *et al.*, 2007; Hartley *et al.*, 2008; van Bogaert *et al.*, 2011). A comprehensive bibliography can be found on the Abisko Station website[3]. Kevo’s bibliography can be accessed through the SCANNET (Circumpolar Network of Terrestrial Field Bases) website[4]. It covers issues including the adaptation of the vegetation to climate change, seasonal variations of CO_2 exchange, properties of peatland for inclusion in a climate model

[3] http://www.linnea.com/~ans/bib.html, last updated in 2003; last accessed August 2011

[4] http://www.scannet.nu/content/view/42/141/, last accessed August 2011

or the upscaling of vegetation distribution (Heikkinen, 1998; Laurila *et al.*, 2001; Hall *et al.*, 2003; Karlsson *et al.*, 2003). Both Abisko and Kevo are participants in the SCANNET network which aim is exchanging and coordinating observations and data. They are close to sites of the LAPP network, Abisko close to Stordalen and Kevo close to Skalluvaara (Lloyd *et al.*, 1999). Works conducted in both sites have been included in the Arctic Climate Impact Assessement and in reports by the Intergovernmental Panel on Climate Change (Houghton *et al.*, 2001; Callaghan *et al.*, 2005).

Both sites are situated in the centre of Sápmi, inhabited by the Saami people (also spelled Sámi or Sami) and covering Swedish and Finnish Lapland as well as Northern Norway and parts of the Kola peninsula (Huntington *et al.*, 2005b). These are the Saami reindeer *(Rangifer tarandus tarandus*) herders' territories (Sonesson, 1987). Reindeer pens can be found near Paddustievva and reindeer groups graze on the Abisko field site during summer (Fig. 1.3 a and b). Both sites have been used to study the effects of reindeer grazing on the local vegetation (Gordon *et al.*, 2002; Nieminen, 2009). Any finding on the C cycle, future of C stocks and local vegetation can have an impact on the life of the herders and local economy. Though the possible consequences of C cycle change on local population are acknowledged, they are beyond the scope of the present work; Huntington and colleagues (2005a) give a good perspective of these impacts. The grounds of the Abisko scientific station as well as the nearby Stordalen mire and the Kårsavagge valley have been extensively studied (e.g. by Holdar, 1959; Clymo, 1983; Christensen *et al.*, 2003; Dorrepaal *et al.*, 2005; Truong *et al.*, 2006). A Strict Nature Reserve near the Kevo Scientific Station (Kevon luonnonpuisto; 32 km north of the field site) is studied for its rare vegetation species. The Kevo area is known for the moths' outbreaks (*Epirrita autumnata*), which regularly decimate the birch forests (Heikkinen, 1998; Kozlov *et al.*, 2010).

1.3.2 Contrasts between the field sites

If three photographs or more are needed to encompass some of the diversity in topography and vegetation cover in Abisko (Fig. 1.3), the Kevo field site can be presented in one photograph (Fig. 1.4). Though both sites are situated in Fennoscandia and only 360 km apart, their topographic features, vegetation covers and climate differ markedly (these are described in details in Chapters 1 to 3; vegetation species are listed in Appendix 1 of Chapter 3). The Abisko field site is situated in a well-drained valley (Van Wijk and Williams, 2005), with some wet soils in landscape depressions. In contrast, Kevo features broader elongated wetland areas surrounded by birch forest (Fig. 1.4). Kevo's birch forest occupies gentle slopes while Abisko's birch trees are grouped with contrasting densities between the expanses of continuous birch forest, smaller birch copses and isolated trees in the exposed parts of the landscape (Fig. 1.3). Abisko presents an altitudinal gradient from the margins of Lake Torneträsk (358 m asl) to the exposed heath on the slopes of mount Nissuntjårro (highest part of the field site around 800 m, summit at 1738 m) (Abisko-Björkliden, 2008). Kevo presents a hydrological gradient from the waterlogged mires to the mesic soils (average water content) of the birch forest (Fig. 1.4). Both these ecological gradients have been studied by the use of transects crossing them (Fig. 2.1). These sites complement one another as the apparent simplicity of Kevo can highlight relationships masked by the complexity of Abisko's land cover.

1.3.3 Sampling sites in Abisko and Kevo

The two aforementioned transects cover scales from the metre to the kilometre along an altitudinal gradient (Abisko Transect, AT) and hydrological gradient (Kevo transect, KT) and are presented in Chapter 2. The other main site in Abisko is a 500 m by 500 m area referred to as the Intensive Valley, as already mentioned above (IV; from works by Spadavecchia *et al.*, (2008) and Williams *et al.*, (2008)). This sampling area is on the forest-tundra ecotone and thus a transition area between the two main vegetation types present on the Abisko field site. It represents some of the diversity of the Abisko field site in terms of topography and vegetation cover. A grid, positioned so that one of the main directions follows the main landscape slope from birch forest to tundra heath (See Chapter 2 and Fig. 2.1), covers it. The Abisko Transect (200 m away from the IV) covers the more “typical” birch forest and tundra heath soils. The IV field site permits to study soils under the same climatic conditions at similar altitudes, thus showing the influence of vegetation cover and topography at field scales (m – 100 m) on soil properties and soil C stocks.

1.4 Summary of the methods used in this project

The methods used are presented in more details in the Chapters 2 to 4. The first phase of this work was the data collection in the field. Four sampling campaigns were conducted in Abisko from mid-June to the beginning of July 2008, a week in March 2009, end of June 2009 to end of July 2009 and the last one at the end of June 2010. The Kevo campaign was conducted from mid-July to the beginning of August 2008.

The principal objective of the field work was the sampling of soils along linear or grid sampling schemes (Chapter 2) as well as targeting some of the vegetation and soil types not directly "captured" by these sampling programmes, for instance the sedge wetland soil in Abisko. The sampling plots were also used to estimate vegetation cover and vegetation properties such as Leaf Area Index (LAI) (Chapter 3). Other data obtained in the field were hourly temperature and moisture series for some of the Abisko plots (Chapter 4).

In the laboratory, soil samples were processed to measure bulk density in the different soil horizons as well as C content, rock content and carbon to nitrogen (C/N) ratios. From these measures are derived the C stocks datasets (Chapter 2).

For the finer millimetre and centimetre scales, micromorphology analyses allow the mapping and characterisation of soil organic matter (Chapter 3). The soil samples for this analysis are taken in parallel with some of those taken for the estimation of soil properties and so can be matched with them (Chapters 2 and 3). Therefore, the principal outputs of micromorphology analysis are maps of the distribution of different soil components, as for example the organic matter fragments or minerals present in the soils. Soils properties can thus be characterised in more details than by only describing soil horizons (Chapter 3).

Geographic Information Systems (GIS) software was used to map these soil data together with the vegetation data obtained on the same plots. Missing data in the grid were estimated with geostatistical techniques such as ordinary Kriging (Chapters 2 and 3). It is based on estimating the correlation between the values of two points to estimate the values of the points separating them (Isaaks and Mohan Srivastava, 1989). This technique is used to study the patterns of soil C distribution across the landscape (Chapter 2). Aerial photographs can be overlain in these systems to generate maps of the vegetation cover, here by delineating polygon shapes around each vegetation patch (Chapter 3). Areas for each polygon and for each class of polygons (here representing vegetation types) can be calculated.

To link soil C stocks, fluxes, vegetation types and soil properties, a model was built based on data collected in the field (Chapter 4). This empirically-based model simulates respiration during the year for different soils (amongst which tundra heath and birch forest) and the evolution of C stocks for mean annual temperature increase up to 2°C.

1.5 Aims and hypotheses tested in this project

The terrestrial Arctic is at the heart of the aforementioned climatological changes (see section 1.1). It has been seen as a C sink, taking CO_2 out of the atmosphere, with the potential to mitigate, to some extent, the changes occurring in other regions of the Earth (Hobbie *et al.*, 2000; Kaplan *et al.*, 2003). This status is uncertain and numerous studies have endeavoured to quantify the strength of this C sink and its potential to switch to a net C source because of temperature increases, still accompanied by numerous uncertainties (Oechel *et al.*, 2000; Callaghan *et al.*, 2005). As mentioned before, the Arctic is a heterogeneous area as reflected in its soils and vegetation types (Walker *et al.*, 2005), thus any change can happen at different rates in different parts of the Arctic, leading to numerous complexities and uncertainties. This thesis addresses some of the issues and challenges related to this heterogeneity and to the complex interactions between components of the Earth System. Some of the interactions and processes are illustrated in figure 1.5:

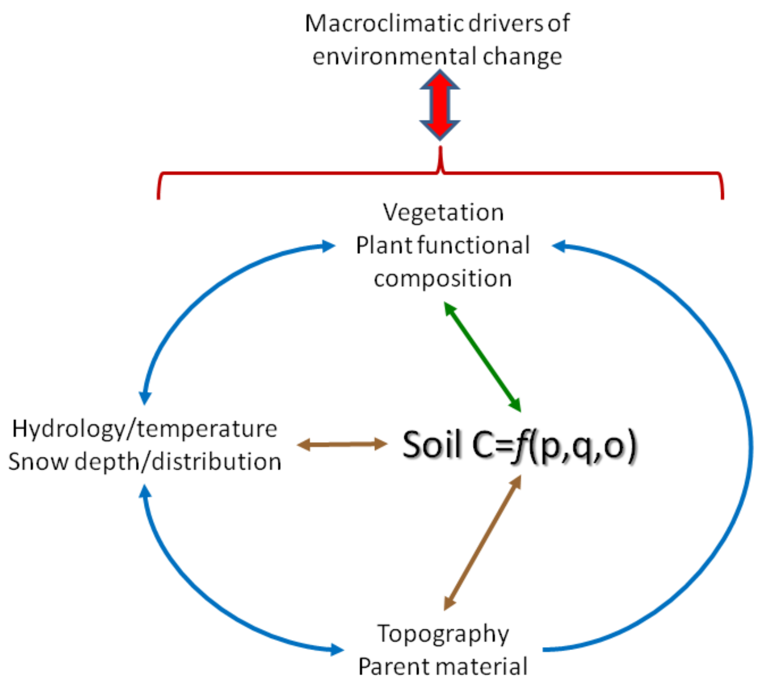


Figure 1.5: Diagram of the relationships between soil, topography, vegetation and hydrology, paraphrasing the equation by Jenny (1941) and based upon Swift *et al.* (1979a)'s controlling factors on decomposition in soils

Soil C stocks, both in quantity and "quality" (integrating lability, C content), are a function of *p* (physico-chemical environment; soil moisture and temperature regimes, pH etc.), *q* (quantity, quality and depth location of organic matter inputs), and *o* (the activity of the decomposer organisms) (paraphrasing the equation by Jenny (1941), and based upon Swift *et al.* (1979a)'s controlling factors on decomposition in soils). Figure 1.5 illustrates the interdependence of ecosystem and abiotic environmental components driving the fluctuations of soil C stock. Most linkages are self-explanatory, but the double arrow at the bottom left (in blue) illustrates that hydrology, temperature and snow can influence slope processes, while topography/parent material have an obvious reverse effect. Soil C can influence topography/parent material by altering weathering/erosion rates and influencing surface topography through, for example, peat formation. All components are coupled to macroclimate (the weakest direct connection being with topography/parent material), and surface/near surface processes and patterns influence local and regional climate through biophysical feedbacks (for example contrasts in albedo, surface roughness etc.) and biogeochemical ones (for example fluxes of radiatively forcing gases).

This work focuses on soil C stocks, however a complete study covering all the linkages presented in figure 1.5 is not possible due to logistical and temporal constraints. More information can be found in the reviews of the C cycle processes in soils and in the Arctic. The ACIA report presents the summary of current knowledge on Arctic tundra ecosystems (Callaghan *et al.,* 2005); King (2011) reviews the studies linking soil microbes and C storage; Andrén and colleagues (2008) analyse the current advances and issues with soil biology studies; decomposition processes in soils are presented in Schlesinger (1977) and Swift and co-authors (1979 a-c). The model used in Chapter 4 tests the effect of warming on the soil C stocks via soil respiration, moisture and temperature, thus testing a small part of this C cycle (Fig. 1.5).

The case studies presented in this work are based on two field sites in Fennoscandia (Fig. 1.2 and 2.1). Abisko in the Swedish Lapland is divided in two study areas, a square area of 500 m by 500 m referred to as the Intensive Valley and a 2.9 km long transect (Abisko Transect). Both areas sample the birch forest and tundra heath ecotone. Kevo in the Finnish Lapland has only one field area, the Kevo Transect covering a 475 m distance over a sedge mire to birch forest transition. Their differences, for instance in climate regime, continentality and landscape structure, are discussed before in section 1.3 and in the following Chapters 2 and 3. These field stations permit investigation of processes in regions that encompass areas with limited accessibility.

Quantifying the variability in the C distribution in this area is a guide to doing so over larger areas. Estimating whether C stocks are similar across this area is an indication of the validity of upscaling results from a field site of a few km^2 to landscapes covering hundreds of km^2 with similar soils and vegetations communities. If, however, we find a significant heterogeneity in soil C stocks and responses to warming, this is a *caveat* to upscaling sparse results over large areas, and could be a strong argument in favour of using more field studies to support modelling efforts. The aim of this work is to link remote sensing, field survey and modelling based on the same empirical datasets. The methods used simulate remote sensing and modelling approaches as a proof of concept study of these methodologies. This is done in the context of soil C stocks mapping and upscaling. This covers important issues such as:

- The variability of soil C stocks over small areas is masked when upscaling to cover larger areas, for example the circumpolar scale. Moreover, these estimates are based on a limited number of sampling locations. The variability of soil C distribution over small areas (field sites compared to the Arctic) has to be low to permit a good representation of present and future responses to climate change for large terrestrial areas.

- Remote sensing quantifies above-ground variables, however soil properties vary underground. The upscaling of soil results by remote sensing requires a link between the soil properties and one or several variables easily surveyed from the atmosphere. Soil properties have been quantified along vegetation properties to identify a strong relationship between soil C stocks and a possible proxy for upscaling results with remote sensing. The tundra heath and birch forest ecotone defines the boundary between boreal areas and arctic areas. The treeline zone is of particular interest, as one of the predicted consequences of a warming climate is the colonisation of tundra heath areas by birch trees (Fig. 1.3). Therefore, an aim of the field survey is the description of soil profiles under these vegetation categories to highlight the consequences of a transition from tundra heath to birch forest.

These issues are currently addressed with different approaches:

- Field studies sample soils at different scales with contrasting sampling schemes to estimate the variability of soil C stocks. They map the C stocks together with vegetation and soil types (Kaplan *et al.*, 2003; Hugelius *et al.*, 2011a).
- Measurements of C stocks via remote sensing have been attempted but are usually limited to the surface soil layers (Sitch *et al.*, 2007; Mulder *et al.*, 2011).
- Soil measurements in global climate models form part of the terrestrial component of the C cycle (Randall *et al.*, 2007).

This work connects the methods described above using data that can be easily collected and processed, keeping the same field sites and sampling plots. The thesis' methods range from soil sampling for C stocks estimation by carbon analysis, micromorphology analysis and geostatistics, to basic modelling. To guide this study, through the three data chapters, hypotheses test the links between soil C stocks and fluxes, soil properties and vegetation properties.

1.5.1 Heterogeneity of soil C stocks and soil profiles

The heterogeneity of topographical features, parent materials and vegetation cover in arctic landscapes creates a spectrum of contrasting soil-forming environments. It can therefore be hypothesised that this heterogeneity will also be reflected in the variety of soil profiles developing in these regions. This should hold particularly in topographically and geologically complex areas, such as the Abisko/Torneträsk region of Swedish Lapland, even across fine spatial scales (dm^2 to km^2). By contrast Kevo is marked by a simpler transition between mire and birch forest. These differences between the field sites should be reflected in their soils' properties and C stocks, as well as in their C fluxes and vegetation properties. The results for the Intensive Valley area in Abisko, in the middle of the birch forest-tundra heath ecotone, should differ from those of the Abisko Transect, which spans larger expanses of birch forest and tundra heath.

1.5.2 Variability of soil C stocks across spatial scales

Following from the previous hypothesis, the variability of soil C stocks at fine scales is linked to the diversity of vegetation cover and topographical features. This variability in soil C stocks at fine scales is hypothesised to disappear over larger areas, and thus averages of the complete datasets for the field sites can be used for upscaling if they span a sufficient range of the vegetation and topographic components present. If the microscale distribution is too heterogeneous, it is necessary to assess the relevance of averaging and upscaling these results.

1.5.3 Links between C stocks and vegetation

It can be hypothesised that each vegetation category (tundra, birch forest) should be associated with a "signature" range of C stocks. If this holds then it should permit soil C stocks and their dynamics to be estimated based on analysis of vegetation communities and landscape position. Similar vegetation types (physiognomically and structurally, for example different types of tundra heath), might, however, be associated with more similar soil profile characteristics and organic matter dynamics which are therefore more difficult to distinguish. If no clear differences can be defined for the main vegetation categories (for example different types of tundra heath), the distinction between forested and treeless areas should still remain.

1.6 Chapters' aims

The present chapter introduces the aims, objectives and methodology of this study. Chapter 2 deals with the multiscale variation in soil carbon distribution over two sub-arctic landscapes. Links between soil properties and C stocks are presented in Chapter 2 with the aim of finding which soil variables have the greatest influence over the soil C stocks. This will help in designing efficient and time-saving sampling schemes and protocols, as well as finding the scales that must be considered when trying to represent the natural C stock variabilities in these field sites and by extension across the Arctic.

Mirroring the study of the links between soil properties and C stocks in Chapter 2, Chapter 3 aims at linking vegetation distribution to soil carbon distribution in two sub-arctic landscapes with a “proof-of-approach”. If above-ground vegetation provides a robust proxy of below-ground C stocks, then the use of remote-sensing for estimating C stocks over large areas might be feasible. For both these chapters, the comparison is made between Abisko and Kevo, as well as different parts of the Abisko field site.

The study of the present distribution of soil C stocks in these sites and its links with other vegetation and soil variables is useful to understand the present state of these soils. However, it does not provide information on the future of these stocks in the context of a warming Arctic. This needs to be done through a study on the potential for C flux release from these soils in the coming decades. Chapter 4 presents the modelling of soil respiration in a sub-arctic landscape. Emphasis is placed on Abisko for its topographical and vegetal diversity, and to test the broad hypothesis that soil properties and landscape/vegetation context will significantly modulate the effects of climate warming on the magnitude of soil C losses through heterotrophic (decomposer) respiration. Moisture and temperature loggers were deployed from 2008 to 2011 in different landscape positions and under contrasting vegetation units. Soil sampling was done in parallel in the same plots. Thus, by use of an empirically-based respiration model including the moisture, temperature and soil data, scenarios for different moisture and thermal regimes as well as soil respiration patterns can be characterised.

Chapter 5 is a synthesis bringing together the themes treated in the Chapters 2 to 4. It first summarises the methodology used in the different chapters. Then it highlights some of the difficulties that similar field survey could encounter and should prevent if possible. Finally, the main results from this project are discussed and recommendations for further research in these areas follow them.

Chapter 2 - Multiscale variation in soil carbon distribution over two sub-arctic landscapes

2.1 Abstract

1. Arctic soil carbon (C) stocks are a key variable in the modelling of the consequences of climate change for arctic ecosystems and the broader Earth system. However, the distribution of the soil C stocks is challenging to quantify at a regional scale (10 km^2 - 100 km^2). Therefore, the distribution of soil C stocks has been mapped in two sub-arctic field sites.

2. A cyclical sampling grid encompassing various vegetation communities and landscape positions covers more variability than stratified sampling or other spatial sampling schemes. The choice of the vegetation sampled is less important than the choice of the scale and type of sampling design.

3. The results show that the heterogeneity of the soil C distribution at the surface is matched by heterogeneity at depth. Some minor landscape components cover more important stocks per area than major vegetation categories.

4. The relationships between soil variables differed between the two field sites, for example, the C stock is more influenced by the soil bulk density in Abisko and by the soil C content in Kevo. This can hinder upscaling from one site to the other. The variability of soil C distribution is larger for finer scales; however, other soil C variables follow different patterns.

5. *Synthesis:* The stock estimates of 0.82 to 1.49 kg C m^{-2} in three sampling areas place them below the global mean estimates for soil C density in tundra heath

and birch forest, but more akin to mountain tundra soils in the North American Arctic and Swedish tundra. The cyclical scheme used samples the natural variability of this area, however the results are sensitive to the position and geometry of the scheme. The design of a sampling scheme should be based on the sampling depth chosen and the importance of the vegetation components in the landscape. The soil variables should be coupled to vegetation variables and modelling of soil conditions to underpin predictions of changes in soil C stocks.

2.2 Introduction

The terrestrial Arctic region north of the tundra-boreal forest transition covers 7 567 000 km^2 (Callaghan *et al.*, 2005). The Arctic is a major store of soil carbon (C), and soil C dynamics are key to understanding the possible consequences of climate change in this sensitive region for net C fluxes between land, atmosphere and fresh waters (Prentice *et al.*, 2001; Callaghan *et al.*, 2004b). Tundra soils are thought to contain 96 Gt C and boreal forest soils 138 Gt C (Callaghan *et al.*, 2005). Quantities of soil C have to be known, as arctic soil C content shows a linear correlation with the C release from arctic soils (Dutta *et al.*, 2006). The soil C distribution is not homogeneous across this region and models must take into account variability at finer scales (Stendel *et al.*, 2007).

Understanding the distribution of the variability of soil C stock at finer scales (m - km) will facilitate upscaling and modelling at the regional scale (10-100 km) as is already done for vegetation variables such as the Leaf Area Index (LAI) (Williams *et al.*, 2008; Stoy *et al.*, 2009a; Chen *et al.*, 2010). Carbon stocks in North America have been estimated from field sampling and the use of a vegetation map (Walker *et* *al.*, 2005; Ping *et al.*, 2008). Remote sensing of soil C still depends heavily on validation by field survey (Fuchs *et al.*, 2009; Inoue *et al.*, 2010). Tools are being developed to estimate organic carbon content by using Near-Infrared Reflectance Spectroscopy (NIRS) coupled with multivariate analysis, however they are still limited to the surface (for example 2 cm for Summers *et al.*, 2011) and can be poor in mapping soil properties such as the bulk density and soil depth (Cécillon *et al.*, 2009). NIRS is an analysis of the reflectance signals of soils in the near-infrared region, whether in laboratory, by proximal sensing or by remote sensing measurements (Cécillon *et al.*, 2009; Summers *et al.*, 2011). Multivariate geostatistics are necessary to analyse the datasets generated with these techniques, as the multiple constituents of the soil confuse too much the signals to generate a simple spectrum (Cécillon *et al.*, 2009).

The development of these new techniques can be completed by improving existing field survey methods. The measurement of soil C stocks by soil survey can benefit from a judicious choice of sampling strategy according to scale and range of distribution. Soil C distribution data from field surveys can be obtained from the microscopic to the landscape scale (Sjögersten *et al.*, 2003). To achieve this, it is important to know which variables account for the variation in soil C distribution over arctic landscapes and which sampling scheme will be most successful in capturing and recording this. A wider range of data can be obtained from soil survey but for maximum efficiency, it is important to understand each variable’s relevance to the soil C distribution and choose a practical sampling strategy.

Stratified sampling can be biased towards the main landscape, soil and vegetation components and ignore the transition areas or minor components of the landscape, as greater precision is achieved if classes contain similar samples (Chen and Wei, 2009). Concentrating sampling principally on the main vegetation categories or soil types in the area can be a hindrance for later data modelling if the soils' reactions to climate change involve components that were not integrated to the model at the initial stage (Vaughan and Ormerod, 2003). Thus, key choices of the sampling strategy are the components and variables to sample, the selection of field sites, sampling areas and techniques used in the field, in the laboratory and to analyse remote sensing data. Another key parameter is the scale necessary to represent the distribution of the soil C variability in the landscape while getting the most data in the shortest time. Data collected across a suite of several spatial scales (for example 10^{-2}-10^{1} m^2 in the field) should be amenable to upscaling (for example to the spatial grain of satellite remote sensing from 10^2 to 10^6 m^2) while retaining key fine-grained ecological information (Stoy *et al.*, 2009a). The choice of a soil sampling strategy must therefore reflect the scale and range of the soil C variability of the study site.

Cyclical sampling provides a possible solution: it is based on sampling over increased intervals repeated as cycles and is used to ensure coverage over a larger range of vegetation and soil types, and to ease the processing of data (Burrows *et al.*, 2002). Soils variables of particular interest are the soil depth, horizon development/differentiation, bulk density, C to nitrogen (N) ratio, and soil C content/stock (McKane *et al.*, 1997; Bockheim *et al.*, 2003; Mikhaloiva and Post, 2006; Ping *et al.*, 2008).

To study the importance of these parameters, the quantitative soil C distribution was characterised in two arctic landscapes in three dimensions and at different scales. A first hypothesis states that the variability of the soil C stock will differ between scales, being more homogeneous at the landscape scale as finer scale variabilities will average out over coarser scales (***H_1***). If this is verified, data collected over larger areas need less support from field survey results. A second hypothesis ***(H_2)***, is that the use of cyclical sampling for soil variables at the field scale (1-100 m) adequately accounts for the variability of the soil C distribution and thus avoids both over and under-sampling. The sampling scheme used here is based on obtaining samples according to pre-calculated spatial coordinates, independent of their place in the landscape. Not targeting the main vegetation and landscape components may mean that more of the natural variability of the soil properties is sampled.

Testing these hypotheses helps in linking field survey methodology and possible study by remote sensing. A third hypothesis is that the surface soil variability is paralleled by changes of soil C distribution at depth as seen in chernozems and permafrost soils (***H_3***) (Mikhaloiva and Post, 2006; Zimov *et al.*, 2006). To ease modelling, soil is sometimes simplified to a homogeneous column or limited to the humus layer (Clein *et al.*, 2000; Kittel *et al.*, 2000; Stendel *et al.*, 2007). Using several layers of soil has proven to enhance the modelling of hydraulic and thermal properties in arctic peatlands (Hall *et al.*, 2003). Knowing the importance of the variability of soil properties at depth is essential to validate the use of remote-sensing methods to estimate soil C distribution.

Kevo in Finland and Abisko in Sweden were chosen for their contrasting geomorphologic settings, allowing for a comparison of the soil variables' relationships with the soil C stocks in differing sub-arctic field sites. The bedrock underlying Abisko comprises mica-schist nappes while Kevo's consists of gneisses (Hall *et al.*, 2003; Gordon *et al.*, 2002). Along the altitudinal gradient in Abisko, numerous landforms at different scales form an irregular microtopography while Kevo is dominated by gentle slopes under the birch forest. Abisko is drier and warmer than the surrounding mountain ranges while Kevo mainly features a hydrological gradient, from the saturated mire border to the mesic Birch forest soils. It is hypothesised that contrasts in relationships between soil variables could reflect these physical and climatic differences in settings ($\boldsymbol{H_4}$).

To test these hypotheses, sampling areas were chosen in two arctic sites. In Abisko, two sampling schemes were implemented: (i) a regular transect (equidistant between sampling plots) and (ii) a cyclical grid in a heterogeneous area. In Kevo, by contrast, a cyclical transect spanned the catena between mire border and birch forest. Soil samples were collected for all the plots' surface 4 cm layer and at depth for some profiles. C and N analysis was conducted on these samples as well as a measurement of sample bulk density. Overall scales from the metre to the field scale (100 m) are covered and the application of cyclical sampling to soil C stock variation can be assessed.

2.3 Material and methods

2.3.1 Site characteristics

The sub-Arctic region is recognised as an important transition area between the trees dominated boreal forest and the arctic tundra heath (Callaghan *et al.*, 2004c). The main site of study is Abisko (68º18’33’’N 18º50’42’’E), situated between Lake Torneträsk (385 m) and the Nissuntjårro mountain, in the Swedish Lapland part of the Scandes mountains (Fig. 2.1 a). The closest summits reach altitudes of 1737 m (Pallentjåkka) and 1738 m (Nissuntjårro). The bedrock consists of mica-schists overlain by sedimentary and magmatic nappes (Gordon *et al.*, 2002). The temperature range for 1961-1990 was of -11.9°C to 11.0°C (minimum in January, maximum in July), and the mean annual temperature (MAT) at ANS (365 m asl) was -1.0°C (Alexandersson *et al.*, 1991).

The field site is situated a few kilometres upslope from the Abisko Natural Sciences Research Station (Abisko Naturvetenskapliga Station: Abisko, 2010). The main slope rises over a distance of a few kilometres from the predominant mountain birch (*Betula pubescens* subsp. *czerepanovii* (Orlova) Hämet-Ahti) forest cover at the border of the lake to the mosaic of birch copses, tundra heaths, willow snow beds, sedge meadows and sparsely-vegetated ridge-tops bordering the uplands. The tundra heath is the other dominant vegetation cover around 620 to 770 m of altitude. *(Further characterisation of the vegetation can be found in Chapter 3.)* Fluvial and glacial deposits remaining after the last glaciation (Niessen *et al.*, 1992) provide intermediate scale relief. Some of these deposits appear as bare patches and rocky outcrops. Esker slopes protect birch copses as well as deep snow beds that can last until mid – June each year. Quaternary deposits are reworked by weathering and freeze-thaw processes and the resulting features form part of the microtopography at the metre scale (Ridefelt *et al.*, 2009). Patterned ground, terraces and solifluction lobes on the slopes are covered by lichen crusts. Some calcareous outcrops can be found nearby. The main streams to the west and east of the field site flow in the Nissunjåkka and Miellejåkka valleys, and on the field smaller streams fed by the snowmelt in spring are semi-permanent and disappear during summer. Numerous lakes of varied sizes and extended wet areas are scattered in the transition area and the birch forest. The Abisko Valley is drier than the surrounding mountains with 322 mm annual precipitation against 1100 mm on the west side of the mountains, and warmer than sites at the same latitude (mean temperature -1°C) (Gordon *et al.*, 2002).

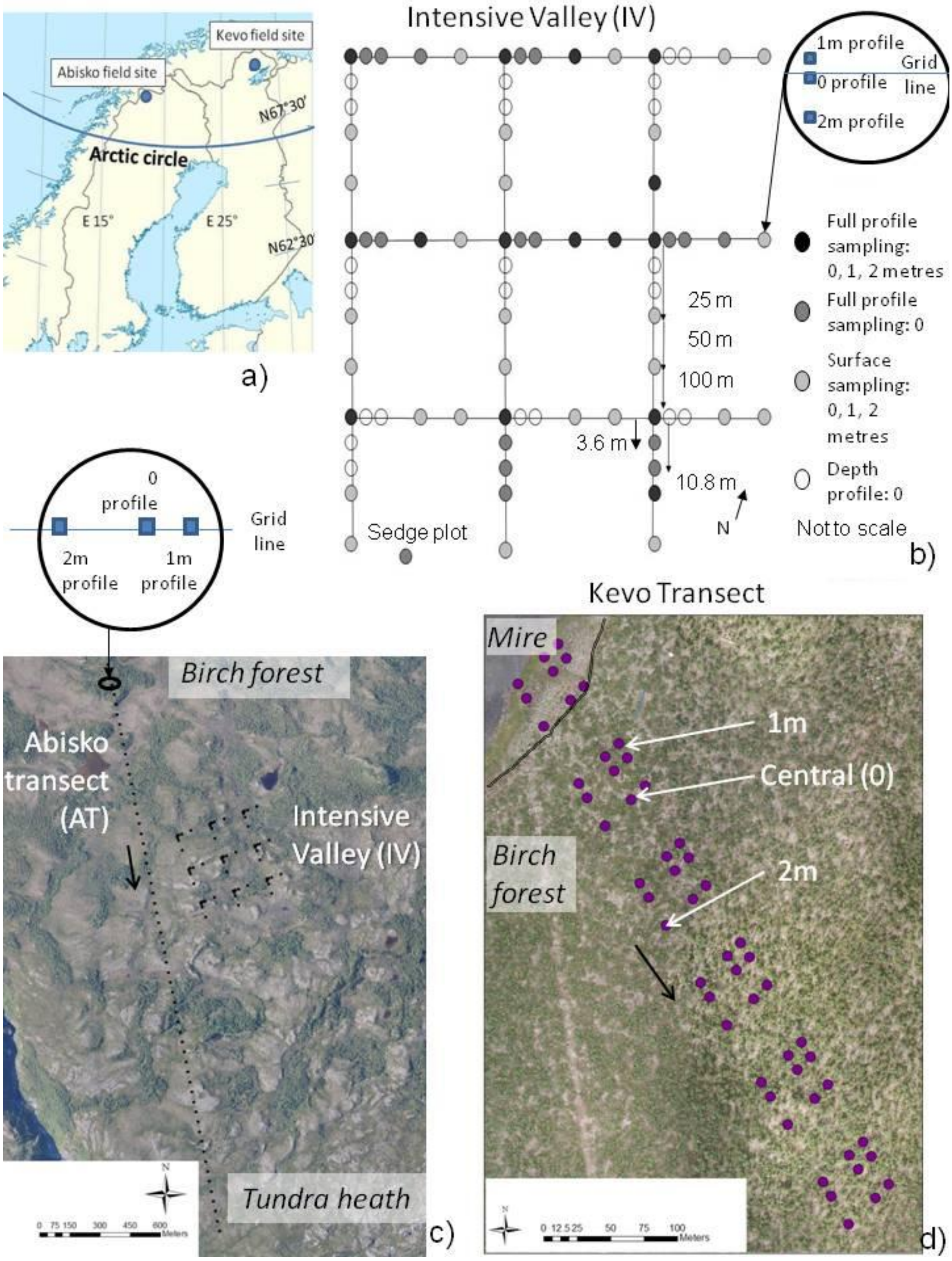


Figure 2.1: Location of the field sites (a), sampling scheme for the Intensive Valley (b), sampling areas and plots for Abisko (c) and Kevo (d). Aerial photographs from the ABACUS group (courtesy of T. Hill)

This site's numerous vegetation and landscape components are amenable to the study of a variety of interactions between vegetation, soil and topography; however, relationships between components can be difficult to characterise simply. A second field site with a simpler gradient between main vegetation types allows for a better estimation of the relations between soil variables and complements the internal study of Abisko with an external comparison.

The second field site chosen was Kevo in Finnish Lapland (69º29'33''N 27º 13'39''E) (Fig. 2.1 a). It is 360 km away from Abisko, and part of the same sub-arctic region of Fennoscandia. At the kilometre scale, the Kevo site presents mainly an alternation between mires on low ground and birch forest bands on gentle ridges, with peaty earth hummocks marking the transition (Van Vliet-Lanoë and Seppälä, 2002). There is no permafrost on the site itself, however we found ice lenses in the hummocks near the mire border and palsa mires are present around the Kevo area (Kujala *et al.*, 2008). Sedge/*Eriophorum* lawns, and *Sphagnum*-based hummocks border the open water of the mires. *(Further characterisation of the vegetation can be found in Chapter 3.)* The bedrock is composed mainly of gneisses covered by glacial till (Hall *et al.*, 2003). The mean minimum temperature is of -36.1°C in January and the mean maximum temperature is of 26.9°C in July; the mean precipitation was 472.5 mm per year for 1962-2008 (Kevo Research Station: Kevo, 2011). The main gradient is hydrological, between the waterlogged mires and the forest soil, as the altitudes of the site span 270 to 300 m over several hundred of metres. This contrasts with the altitudinal gradient found in Abisko (200 m elevation difference over 3 km).

2.3.2 Sampling areas

The sampling area referred to subsequently as the "Intensive Valley" (IV) (Fig. 2.1 b and c) is a 500 by 500 m square area comprising varied topographies and cover types, such as sedge-dominated areas, riparian thickets, snow beds, and tundra heath, amongst others. Thus, many features of a transition zone between birch forest and tundra heath (birch forest - tundra heath ecotone) are concentrated over a small area allowing for fine resolution work. This area has been used for studies of the spatial distribution of Leaf Area Index (Spadavecchia *et al.*, 2008; Williams *et al.*, 2008). The IV is a square area rather than a linear transect as the other sampling areas presented below. The spatial relations between landscape components can be mapped in two dimensions. Thus, the variability of soil properties can be studied across the landscape and not only across the main slope or hydrological gradient.

Even if the IV coverage is thorough, it is limited to the transition area between the main components of the landscape at the kilometre scale, the birch forest and the tundra heath. To cover these vegetation types and complement the fine-grain work of the IV by a larger sampling scheme, a 2.9 km long transect encompasses the altitudinal variation along the main slope between birch forest (563 m) and tundra heath (764 m) (Fig. 2.1 c). It is designated as "Abisko Transect" or AT. AT extends between the locations of two eddy covariance towers used by the ABACUS project; the first tower was situated in the birch forest and the second close to the STEPPS tundra area (Shaver *et al.*, 2007; Abacus, 2010; STEPPS, 2010). As with the IV, the Abisko landscape's complexity is reflected along AT in the variability of its cover. A succession of wet areas, esker ridges, birch thickets and bare areas can be found along the main slope.

In contrast to the topographical heterogeneity of the IV, and the altitudinal gradient of the AT, the main transition in Kevo is a hydrological gradient. A 475 m long transect was established between the waterlogged soils of the mires and the micro-podzols found in the birch forest (Fig. 2.1 d). It is designated as "Kevo Transect" (KT). The distance is shorter than the Abisko Transect, and the intervals used are only half of the Intensive Valley's intervals. However the total distance between the sedge border and the nearest high point in the birch forest is 537 m; the transect therefore covers most of the soil catena.

2.3.3 Sampling design

Table 2.1: Scales of the study and associated sampling locations and objects

Location	Designation	Scale
Abisko, Kevo	Field sites/Sites	Kilometre scale
Abisko Transect, Intensive Valley, Kevo Transect	Sampling area	100 m scale
	Plots	3-100 m scale/ 10 m scale
	Profiles	1-3 m; Metre scale
	Tins	Centimetre scale

The grid and transects used cover the soil variability at the decametre (10 m) to kilometre scale (Table 2.1, Fig. 2.1 b-c). To cover the metre scale, each of the plots has been defined as a short transect of three soil profiles perpendicular to the main direction (Fig. 2.1, Table 2.1). The central profile (named "0") is situated on the intersection between the short transect and the main grid or main transect direction (Fig. 2.1 b-d). The two other profiles are spaced respectively one metre to the left and two metres to the right from the 0 profile, looking toward the end of the transect or grid line. The sampling intervals were thus chosen to cover as many scales as possible, the 1-3 m profiles giving a finer coverage to supplement the 25-100 m intervals of the sampling grid and transects. The 25-100 m intervals were the most adapted to cover larger areas.

The Intensive Valley's (IV) sampling plots have been assigned on a cyclical grid with main orientations of 70.5º (SW/NE) and 160.5º (NW/SE) (Fig. 2.1 b). Cycles of three plots cover distances of 0, 25 and 50 metres, the next cycle beginning at 100 metres. Each line of the grid consists of three cycles. The grid comprises three horizontal and three vertical lines, intersecting at the corner plot of the cycles. Thus the grid has got nine squares with 5 plots each, for a total of 45 plots and 145 profiles. The 1 m and 2 m profiles have been placed perpendicularly to the main slope direction, at 1 m to the NW and 2 m to the SE. The Intensive Valley contains sedge mire/fen and *Sphagnum* hummock areas, however none fell on the grid sampling profiles. Waterlogged soils are potentially important stocks of carbon (Gorham, 1991; Tarnocai, 2006) and to assess the consequences of neglecting these areas, a plot was added to the grid in a sedge mire (Fig. 2.1 b). The waterlogging did not prevent the use of the same techniques as for the other plots. Additional sampling was conducted at nearby unvegetated areas as they occupy a large surface in Abisko, these results are not included with the IV or AT results as they do not belong to these schemes. They are used in Chapter 3.

For the Abisko Transect (AT) sampling plots were located at regular 50 m intervals (Fig. 2.1 c). Fifty-nine plots cover a 2.9 km distance between the forest and the tundra towers. The transect broadly runs perpendicular to the contours of the terrain, with a bearing of 167°. The start of AT has been placed in the forest. The 1 m profiles were situated to the NE of the transect and the 2 m profiles to the SW.

For both the Intensive Valley and the Abisko Transect, some of the profile sampling coordinates included rocks or pools of standing water and thus were not sampled. They were noted accordingly but not replaced by alternative plots outwith the sampling scheme. Indeed the occurrence of these plots enabled the proportion of cover of these land classes to be calculated.

For the Kevo transect, the plots have been defined according to a cyclical pattern along a single transect with bearing 134°. It comprises six cycles of three plots with increasing spacing of 12.5, 25 and 50 m over 475 m. This is different from the cycles used in the IV as longer intervals would yield too few plots. For each plot, the small transect formed by the centre, one and two metres profiles was perpendicular to the main transect with a bearing of 44º.

2.3.4 Soil sampling and analysis

The profiles were cored between 2008 and 2010 and the horizon depth and total profile depth recorded for each of them. Complete soil sampling of all the profiles was not possible due to personnel and time constraints.

Surface sampling consisted of taking only the upper 4 cm of soil. Where “full profile” sampling was undertaken, profiles were dug manually as deep as possible (usually until highly compacted till or large clasts were reached). It was not possible to reach a depth of one metre as soils are formed over fluvial and glacial deposits. They contain important quantities of stones, quickly impeding the sampling (Niessen *et al*., 1992; Hall *et al.*, 2003). Some Abisko soils, in particular, contained a high content of rocks and proved difficult to dig entirely. Rock content was accounted for by weighing the rocks and by measuring the volume of the rocks (size > 2mm) for each sample.

AT was sampled fully in 9 plots (27 profiles), with two plots in the dominant vegetation types - the birch forest and the tundra heath – which define its extremities (Fig. 2.1c). Additional samples were also taken from the transition area in the middle of the transect, while two other sampling plots were chosen in snow beds. Snow beds are characterised by an accumulation of deep snow during winter and as such experience warmer conditions compared to the surrounding areas (Hiller *et al.*, 2005; Björk and Molau, 2007). Plant species form snow bed communities adapted to these conditions (Sonesson and Callaghan, 1991). Snow beds are easily recognisable on the field. The snow cover lasts late in the season (May-June) and after the snow melt the vegetation keeps a browner colour compared to the greener vegetation around. The presence of *Vaccinium myrtillus* in a landscape depression is another clue to a late snow cover.

For the Kevo transect there are 18 plots and 54 profiles. The 0 profile for the first plot of each cycle was excavated and sampled fully (Fig. 2.1 d). For the other plots, only the organic layer was considered with the exception of the first cycle, in which all of the profiles were sampled fully as it covered the mire and the forest border transition. The other cycles were situated entirely in the birch forest.

The procedure followed for sampling was to use Kubiëna tins to retrieve an undisturbed block of soil of fixed volume (4 x 5.5 x 7.5 cm) (Kubiëna, 1938). They have been preferred to coring as they retain more information about the soil structure. After digging a soil pit at each sampling profile's coordinates and exposing the profile, Kubiëna tins were carefully cut into the profile to retain an intact soil structure. Once flush with the surface of the profile a "lid" was pressed to the exposed surface and the back of the Kubiëna tin then excavated, trimmed (excess soil removed and roots carefully cut) prior to lifting the tin out, adding the other lid, and placing in a labelled ziplock bag. This process was repeated down the profile as deep as possible, until clasts and/or coarse roots prevented deeper sampling.

Back in the laboratory the soil within each tin was photographed *in situ*, the dimensions of each horizon recorded and their volume calculated. The soil was then separated by horizon and depth. These samples were weighed in paper bags and were then oven dried at 80°C. Batches were taken out of the oven and kept in a desiccator while each bag was weighed dry. The dry weight of the sample was divided by the volume of the sample to get the bulk density.

The soil was then processed for C and N analysis. Each sample was sieved to remove roots and rocks > 2 mm. Soil aggregates were gently broken up. The soil was then processed in a grinder for 2 minutes at a frequency of 20 strokes/s. The powder obtained was kept in a sealed 1.5 ml reaction tube. Each subsample was then weighed on a precision balance to obtain around 1.5 - 2 mg (±0.5) for organic soil and 20 mg (±1) for mineral soils. The containers used for the organic material were 6 x 4 mm pressed tin capsules and for the mineral samples 8 x 5 mm pressed tin capsules. Carbon and N analysis was conducted on a Carlo Erba CHNS-O Analyser, with a 0.01% detection limit on C and N, and a ±0.01% to ±0.3% precision with increasing C and N content. Organic samples were calibrated with a high organic content rice flour standard (C 40.9% ±0.15, N 1.38% ±0.06; B2278 from Elemental Microanalysis Ltd., Okehampton, Devon, UK). Mineral samples were calibrated with a low organic soil standard (C 1.26 ±0.04, N 0.10% ±0.02; B2152 from Elemental Microanalysis Ltd., Okehampton, Devon, UK).

Due to material and time constraints, most samples collected in 2010 were analysed by loss on ignition (LOI) but this was only undertaken once the relationship between C content (measured by Carlo Erba analysis) and LOI had been established robustly from earlier sampling and analysis. The processing of the Kubiëna tins was the same as for the C analysis samples. Once oven-dried at 80°C, a subsample of a few centimetres cubed was taken from each bag and was transferred to a crucible. The samples were combusted at 550°C for 4 hours. The organic matter content was calculated from the LOI. To get the conversion factor between organic matter and C content, samples from 2009 and 2010 were analysed using both methods. As the quantities required for C analysis are small (2 mg for organics soils, 10 mg for mineral soils), most samples yielded enough material for an analysis by both methods. Results from the study of the 2009 and 2010 samples give the following regression equation, with a high coefficient of determination R^2:

$C_L = 1.724 * C_A \quad R^2 = 0.982$

Where C_L is the organic matter mass percentage obtained by loss-on-ignition (%), C_A is the mass percentage C as measured in carbon analysis (% C), R^2 is the coefficient of determination.

A conversion factor of 1.724 between organic matter and C content is consistent with the factor used traditionally (source unknown; discussed in Pribyl, 2010). It had been recognised as low for some highly organic soils where a value of 1.9-2 has been recommended (Sleutel, 2007; Pribyl, 2010). For this study's samples, when using only the highly organic soils (chosen as >50% C by C analysis), the conversion factor only increases to 1.725. Thus 1.724 is used for all the samples.

Once the carbon and nitrogen content was known, carbon to nitrogen (C/N) ratio was calculated. Soil C stock was derived from the bulk density, C content, rock content and sample depth using the formula (adapted from Post *et al.*, 1982):

$D = B_D * C * d * (1\text{-R}) * s$

Where D is the soil carbon stock (kg C m^{-2}), d is the depth of sampling (cm), B_D is the bulk density (g C cm^{-3}), C is the carbon content (%), R is the rock content (%). s (=10) is the conversion factor from g C cm^{-2} to kg C m^{-2}. Results can be converted in t C ha^{-1} by multiplying by 10.

2.3.5 Generating maps from soil data

The plots of the IV were entered into ArcGIS software (ArcView software, ESRI, Redlands, USA), with their coordinates and associated data (for example C stock, LAI values). A map was generated by indicating the value of each plot for a given variable. Several interpolation methods are available, such as the inverse distance method where the closest samples are given more weight when estimating the value of a non-sampled point (Isaaks and Mohan Srivastava, 1989). Here ordinary Kriging was chosen as the interpolation method between sampled points, as used in similar studies (for example Mishra *et al.*, 2009; Kempen *et al.*, 2011). A mathematical function is fitted to the dataset by using the values of the measured data points to estimate the spatial autocorrelation of the dataset. Using these estimations, values are attributed to the points between the measured ones by weighing both their distance to the measured points and the spatial continuity of the dataset. Another advantage of this technique is its reduction of the error variance (Isaaks and Mohan Srivastava, 1989).

2.3.6 Geostatistics and semi-variograms

To study the patterns of the variability of soil C stocks, semi-variograms of these data were constructed with the ArcGIS software (ArcView software, ESRI, Redlands, USA) and geoR software (Ribeiro and Diggle, 2001; Diggle and Ribeiro, 2007). A semi-variogram plot shows the pattern underlying the distribution of a variable along a distance or across an area. It is built by plotting the average squared difference between pairs of data (semi-variance) separated by a similar lag against the lag distance (h) (Isaaks and Mohan Srivastava, 1989). A semi-variogram cloud presents all of the data pairs' semi-variance values against lag distance, on top of which the semi-variogram can be added. Several functions can be fitted to the semi-variogram to get an estimation of the properties of the spatial continuity of the dataset. The main characteristics of a semi-variogram are the nugget (semi-variance value for a distance of 0 m), the sill (maximum semi-variance value) and the range (distance at which the semi-variogram reaches the sill) (Isaaks and Mohan

Srivastava, 1989). If similar values are grouped together across the landscape, the result should be an increase in variability with increasing distance, as for example in Spadavecchia and others (2008). The semi-variogram surfaces are maps of the estimated semi-variance projected over the landscape, showing the directions of maximum and minimum semi-variance, generated by ArcGIS (ArcView software, ESRI, Redlands, USA).

2.4 Results and Discussion

2.4.1 Rock content

Rock/stone content is used in the calculation of soil C stock and needs to be taken into account together with soil bulk density. Samples contening stones constituted 17% of the IV samples and 23.5% of the AT samples. For the IV, mean rock percentage of the mass was 34.8%, while rock percentage of the volume was of 10.51%. In the AT samples, mean rock percentage of the mass in rocky soils was 33.30%, while mean rock percentage of the volume was of 7.17%. For the Kevo transect, the mean rock percentage of the mass in rocky soils (33% of all samples) was of 15.73%, while the mean rock percentage of the volume was of 5.10%.

2.4.2 H_1: fine scale variability averages over larger areas

2.4.2.1 Intensive Valley

Semi-variograms are plots of the semi-variance against lag distance and show the likeness of the values of pairs of data against increasing distance (see section 2.3.6; Fig. 2.2). In the IV, these pairs were first created between plots of the same cycle (distances from 0 to 75 m; for example 0-25 m, 0-50 m, then 0-75 m) then pairs between coupled plots from different cycles (Fig. 2.1 b). The values of the plots are expected to grow more dissimilar as the distance increases, increasing the semi-variance. Here the maximum distance between plots of the IV is 500 m (Fig. 2.2). The lag is 25 m, the smallest distance used in the cycles. Datasets tested are the soil C stocks associated with surface samples (0 - 4 cm depth) and stocks associated with the whole profiles (Fig. 2.2).

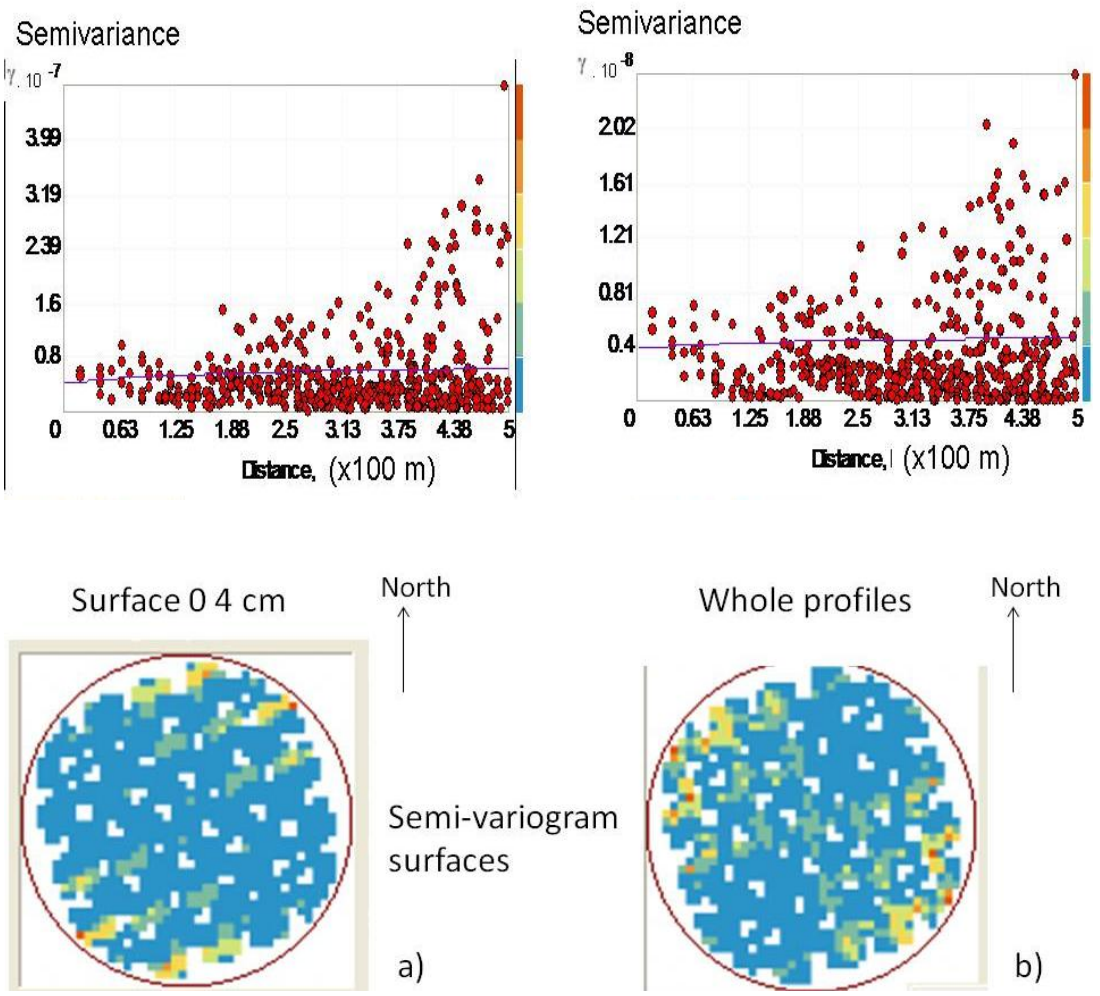


Figure 2.2: Semi-variogram surfaces and semi-variograms fitted on the semi-variogram clouds of the soil C stock (g C m^{-2}) plotted as the semi-variance against lag distance, for the surface 4 cm (a) and whole profiles (b) of the Intensive Valley; done with the ArcGIS software (ArcView software, ESRI, Redlands, USA)

Though some pairs show a growing dissimilarity with distance, numerous pairs show similar values for greater distances. The semi-variogram cloud for the whole profiles shows a larger spread of values, showing a greater heterogeneity of values than for the surface data, though reaching smaller variance values and so less variance (Fig. 2.2). Semi-variograms have been obtained by ordinary Kriging with an exponential model fitted (see 2.3.5) and plotted over the semi-variograms clouds, for both datasets. The semi-variograms have nugget values of $4\ 10^{-6}$ for the surface (Fig. 2.2 a) and $4\ 10^{-7}$ for the whole profiles (Fig. 2.2 b) and partial sill values of $2.2\ 10^{-6}$ for the surface values and $3.8\ 10^{-7}$ for the whole profiles. The presence of a nugget effect (semi-variance > 0 for a lag of 0 m) suggests variability at less than 25 m. However, the shape of the semi-variogram clouds makes the semi-variogram model fitting difficult and these results are given as indications rather than absolute data. Another indicator is the semi-variogram surface, which indicates the directions in which the semi-variance changes. For the 0-4 cm soil depth, close values are more similar along the NW-SE direction (Fig. 2.2 a); however for the whole profiles this direction is NE-SW (Fig. 2.2 b).

This lack of a clear structure in the semi-variogram suggests that the variability at fine scale is too important for a clearer spatial structure to appear in the soil C stocks distributions. To confirm the variability at fine scales, another semi-variogram was estimated for the surface 4 cm C stock, with the R software running the geoR module (Ribeiro and Diggle, 2001; R Development Core Team, 2006; Diggle and Ribeiro, 2007). This supports the hypothesis of a more substantial variability at fine scales. Either the data must lack an underlying spatial distribution pattern, or there are so many patterns that the signal is masked under the noise.

2.4.2.2 Transects

For the Abisko Transect and Kevo Transect, the distribution of soil C stocks was studied between the 1-3 metres profiles groups (formed by the 1 m, central 0 and 2 m plots) and the complete transects formed by the 0 (central) plots (Table 2.1 and 2.2, Fig. 2.1 c and d).

Table 2.2: Surface 4 cm soil C stock statistics for Abisko Transect and Kevo Transect, for the whole datasets and for the 1-3 m groups

Variable		Abisko Transect		Kevo Transect	
		All	1-3	All	1-3
Carbon content (%)	Mean	36.21	33.28	25.23	29.20
	SE Mean	4.85	5.42	3.11	3.99
	Median	40.69	36.07	28.85	30.05
	Q_3-Q_1	16.27	17.20	8.38	12.91
	Std dev	14.54	9.41	13.20	6.91
Soil bulk density (g cm^{-3})	Mean	0.3073	0.31	0.25	0.19
	SE Mean	0.09	0.07	0.05	0.05
	Median	0.25	0.30	0.15	0.16
	Q_3-Q_1	0.23	0.24	0.30	0.17
	Std dev	0.26	0.13	0.22	0.09
C/N ratio	Mean	32.66	31.88	31.61	32
	SE Mean	6.65	4.86	2.39	2.80
	Median	28.34	31.33	30.68	31.58
	Q_3-Q_1	12.67	15.79	8.38	9.18
	Std dev	19.96	8.43	10.16	4.85
Soil C stock (kg C m^{-2})	Mean	3.15	2.63	1.10	1.27
	SE Mean	0.51	0.93	0.114	0.24
	Median	3.73	2.12	1.05	1.24
	Q_3-Q_1	2.58	3.05	0.53	0.78
	Std dev	1.54	1.62	0.48	0.41

The medians for these datasets (Table 2.2) are higher for the 1-3 m than for the whole transects, except for the C content and soil C stocks at AT. The interquartile range (Q_3-Q_1) is always more important for 1-3 m than for the whole transects, pointing to a higher variability of the data at finer scales. The only exception is the bulk density for the Kevo transect.

In Kevo, the standard deviation is higher along the transect than between the 1-3 m plots. The standard error of the mean is higher for the 1-3 m groups too. These results are in line with statistical theory: the smaller number of samples introduces more uncertainty for the mean and the standard deviation is more important for larger groups as more outliers are included (Isaaks and Mohan Srivastava, 1989). However, for the Abisko Transect, the standard deviation for the soil C stocks is greater for the 1-3 m groups and the standard error of the mean is more important for the whole transect for the soil C stock and the soil bulk density. Calculated soil C stocks are more variable at finer scales.

2.4.3 H_2: using a cyclical scheme gives a better representation of the soil C stocks distribution

The sampling scheme used in the Intensive Valley allows the grid to be subsampled according to other sampling criteria. The alternative spatial schemes simulated are a sampling scheme based on 1-3 m profiles groups, a sampling scheme based on 3-11 m profiles groups, a sampling scheme based on cyclical cycles, and a sampling scheme according to the main lines of the grids as transects (Fig. 2.1 b). To simulate a stratified sampling, alternative subsampling comprises only the main vegetation components (birch forest and tundra heath) or only the main components and their transition. The less represented vegetation categories are voluntarily neglected. These schemes have been applied as filters for the soil variables (Table 2.3).

The means of the 1-3 m scheme make it the closest of the spatial schemes to the full dataset for most variables except the soil C stock, while the 3 - 11 m scheme is always the furthest. Using cycles gives more dissimilar results to the whole dataset than the transects for the soil C stocks, but this is not mirrored in all of the results for the other variables' means and medians.

Most results for the vegetation schemes show smaller differences from the mean of the full dataset than the spatial schemes, while the SE of the means is higher for the spatial schemes than the vegetation schemes (Table 2.3). The medians are closer to the full dataset results for the vegetation schemes than for the spatial schemes. Choosing an alternative vegetation scheme introduces less bias than choosing an alternative spatial scheme.

The SE of the mean is always lower for the full dataset than with any subsample.When the SE is lower, the estimate of the mean is better. So using all of the vegetation components within a sampling grid leads to a better estimation of the mean soil C stock compared to using only the main categories or a linear transect. This is important if the mean value of C stocks is used for upscaling.

Table 2.3: Soil variables mean of means, mean SE of means and mean of medians for the Intensive Valley according to different sampling schemes, with comparison to the full dataset between brackets

Variable	Sampling scheme	Mean of means	Mean SE of the mean	Mean of medians
Carbon content (%)	1-3 m	39.5 (+0.2%)	2.1	43.9 (-1.8%)
	3-11 m	37.2 (-5.5%)	4.0	39.1 (-12.5%)
	Cycles (3-175 m)	47.0 (+19.5%)	7.8	44.5 (-0.5%)
	Lines (3-500 m)	38.7 (-1.6%)	2.7	44.4 (-0.7%)
	All plots	39.4	1.2	44.7
	Forest/tundra/trans.	39.1 (-0.7%)	1.4	44.7 (+0.1%)
	Forest heath	41.3 (+4.9%)	1.6	45.3 (+1.4%)
Surface soil bulk density (g cm^{-3})	1-3 m	0.2 (-8%)	0.1	0.1 (-7.1%)
	3-11 m	0.5 (+84%)	0.2	0.3 (+92.9%)
	Cycles (3-175 m)	0.4 (+64%)	0.2	0.2 (+21.4%)
	Lines (3-500 m)	0.3 (+12%)	0.1	0.3 (+121.4%)
	All plots	0.2	0.0	0.1
	Forest/tundra/trans.	0.3 (+4%)	0.0	0.1
	Forest heath	0.3 (+16%)	0.1	0.1
C/N ratio	1-3 m	39.0	3.7	34.2 (+0.9%)
	3-11 m	32.4 (-16.8%)	2.8	32.5 (-4.1%)
	Cycles (3-175 m)	39.1 (+0.4%)	5.3	35.1 (+3.7%)
	Lines (3-500 m)	37.7 (-3.4%)	4.0	33.7 (-0.4%)
	All plots	39.0	2.2	33.8
	Forest/tundra/trans.	39.3 (+0.9%)	2.7	33.6 (-0.6%)
	Forest heath	38.7 (-0.8%)	3.4	33.8
Soil carbon stock (kg C m^{-2})	1-3 m	2.3 (-11.5%)	0.3	1.9(-2.8%)
	3-11 m	3.8(+42.2%)	1.1	3.0 (+54.8%)
	Cycles (3-175 m)	2.7 (+2.2%)	0.5	2.2 (+13.4%)
	Lines (3-500 m)	2.6 (-0.7%)	0.4	2.0 (+4.8%)
	All plots	2.6	0.2	1.9
	Forest/tundra/trans.	2.6 (-2.3%)	0.2	2.0 (+0.6%)
	Forest heath	2.9 (+9.5%)	0.3	2.0 (+2.3%)

2.4.4 *H_3:* variability of soil C stocks with depth

2.4.4.1 Transects

Horizon depths have been obtained for all the profiles, as far as it was possible to dig. Along AT, the soil profiles' depths and organic horizon depths are variable, with some profiles less than a centimetre deep and others as deep as 41 cm (Fig. 2.3 a). The deepest sampled profiles for the Abisko Transect profiles are found under the snow beds (Fig. 2.3 c and e) while birch forest profiles are the shallowest (Fig. 2.3 b), being formed over rocky mineral horizons. In the Kevo Transect, profile depth decreases sharply from the mire border to the birch forest with on average 41 cm deep profiles for the mire border (average of 28 cm organic) against 8 cm (2 cm organic) for the birch forest (Fig. 2.4 a).

Soil C stocks per unit area have been calculated for 2 cm slices. Stocks are plotted along the profile depths. For AT, the sampling was as deep as practically possible into the mineral horizons. For KT, some profiles were only sampled at the surface 4 cm due to the necessity of limiting the number of samples. For both transects, the curves of average stocks (Fig. 2.3 b - f and 2.4 b - c) show the importance of the chosen sampling depth. Overall, the cumulated soil C stock (kg C m^{-2}) encompassed in the surface 4 cm is up to 15 times (in size) smaller than the stock accounted for by sampling the whole profile. Mineral horizons are up to 16 times deeper than organic horizons. Their lower carbon content (percentage of the mass) is offset to some extent by greater depth (in some instances) compared to the shallow organic horizons, as well as greater bulk density.

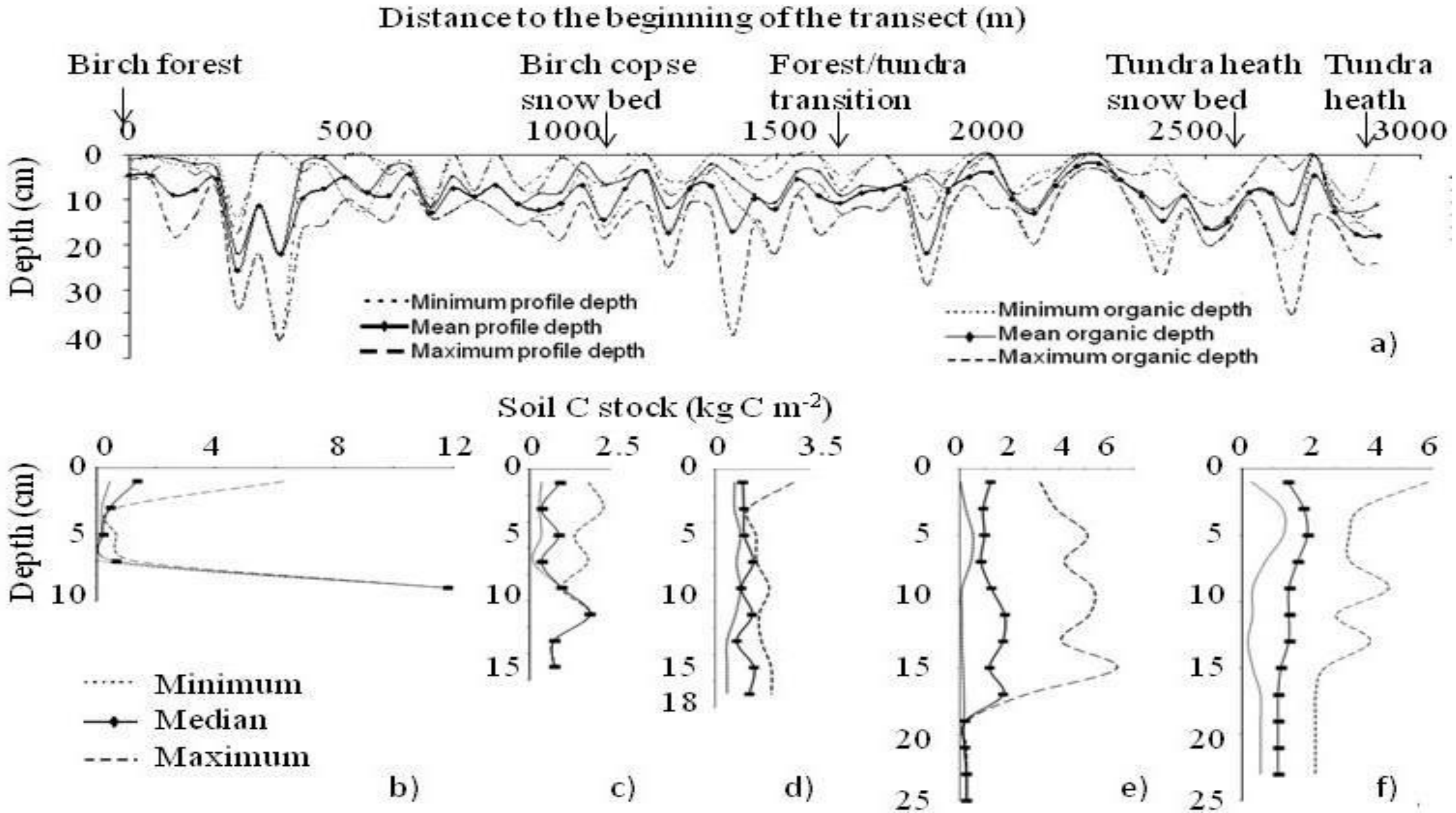


Figure 2.3: Depths of the soil profiles along the Abisko Transect (a) and average soil C stocks curves (kg C m^{-2}) for the birch forest (b), birch copse snow bed (c), forest/tundra transition (d), tundra heath snow bed (e) and tundra heath (f)

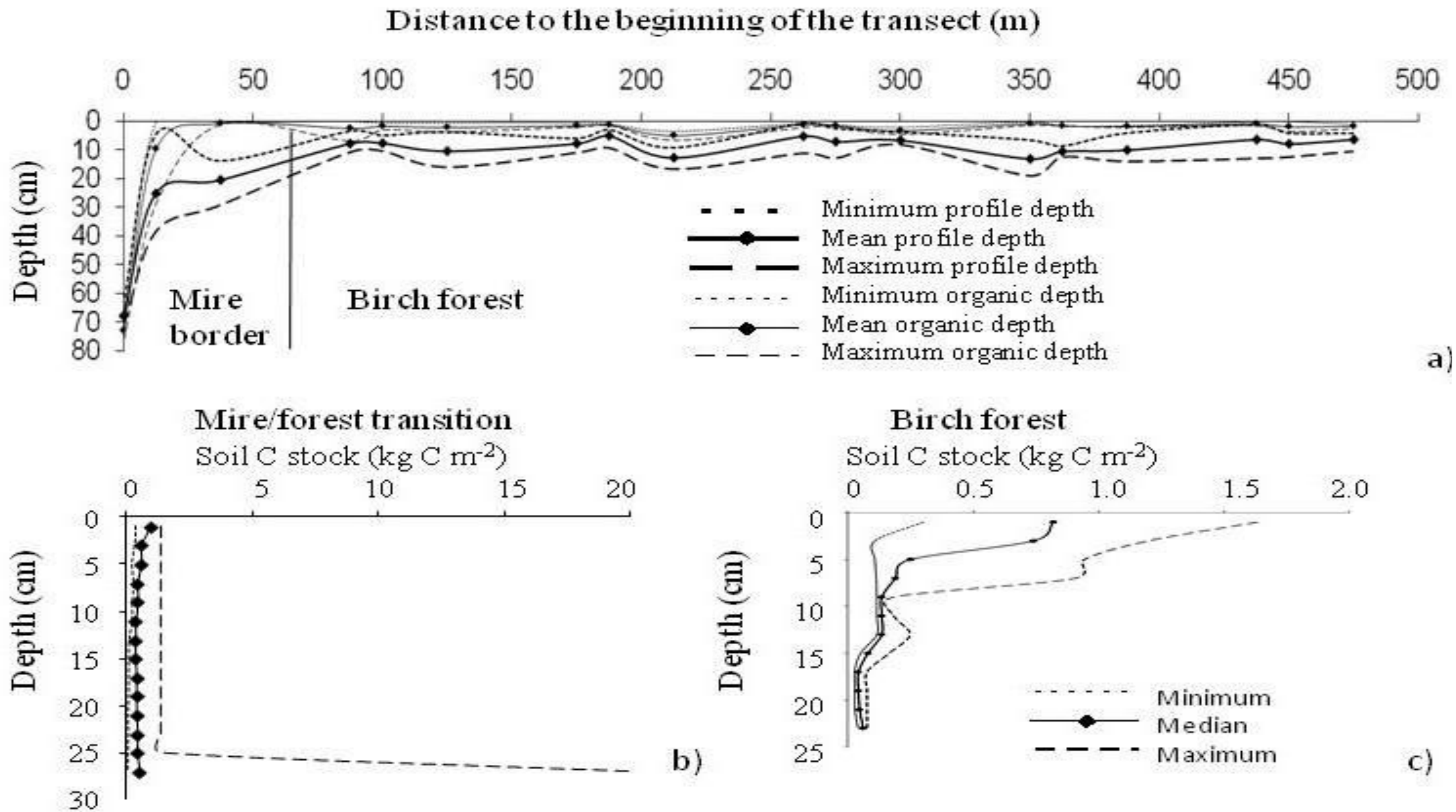


Figure 2.4: Depths of profiles (a) and average soil C stocks (kg C m^{-2}) profiles for the mire/forest transition (b) and the birch forest plots (c) along the Kevo Transect

However, these general results cover different soil types with different soil C stock distributions. In both sampling areas, the birch forest profiles show an increase in soil C stock with the transition to the mineral horizons due to higher bulk densities (Fig. 2.3 b and 2.4 c). In Kevo, the numerous plots in the birch forest show a high variability in soil C stock for the whole profiles, with a minimum of 1.27 kg C m^{-2} and a maximum of 2.52 kg C m^{-2}, a mean of 2.00 kg C m^{-2} (SE mean 0.2 kg C m^{-2}) (Fig. 2.4 c). The Abisko tundra heath profiles and the mire border profiles in Kevo are mainly organic and contain C stocks up to 8 times higher than the forest stocks in Kevo (Fig. 2.3 f and 2.4 b-c). The snow beds profiles, whether situated in a birch copse or in the tundra heath, contain even more C and are deeper than the other profiles (Fig. 2.3 c and e).

2.4.4.2 Intensive Valley

The extended coverage of the IV grid yields enough data to produce maps by ordinary exponential Kriging in ArcGIS. The evolution of soil C stock (kg C m^{-2}) at depth is mapped for different simulated depths of sampling: 0-4 cm (Fig. 2.5 a), 0-10 cm (Fig. 2.5 b), 0-15 cm (Fig. 2.5 c), 0-20 cm (Fig. 2.5 d) and whole profiles (Fig. 2.5 e). Whole profile data have to be used together with profile depths data for comparison with other sites (Fig. 2.5 f).

The surface 4 cm sampling is enough to cover most of the IV organic horizons. The higher C stock values (kg C m^{-2}) are situated in the middle of the Valley and on its south-west corner, and slightly lower values on the north-west corner and the south-east corner. By adding 6 cm in simulated depth of sampling, based on the field data, the distribution is smoothed, and extreme values are fewer. The 0-15 cm, 0-20 cm and whole profile maps changes are in the ranges of the data, which increase as the stocks are cumulated with depth (Fig. 2.5 c-e). The distribution of high and low values across the landscape stays the same, with a slight smoothing of the values. The sedge plot, with its high water content and low bulk density, does not create an anomaly on the maps as the surrounding plots exhibit relatively high values of soil C stock too.

The C stocks for the whole profiles have different distributions across the IV. Low C stock values in the north-east and south correspond to mid-range to high depths, while high values in the north-west are found for both C stocks and soil depths (Fig. 2.5 e-f).

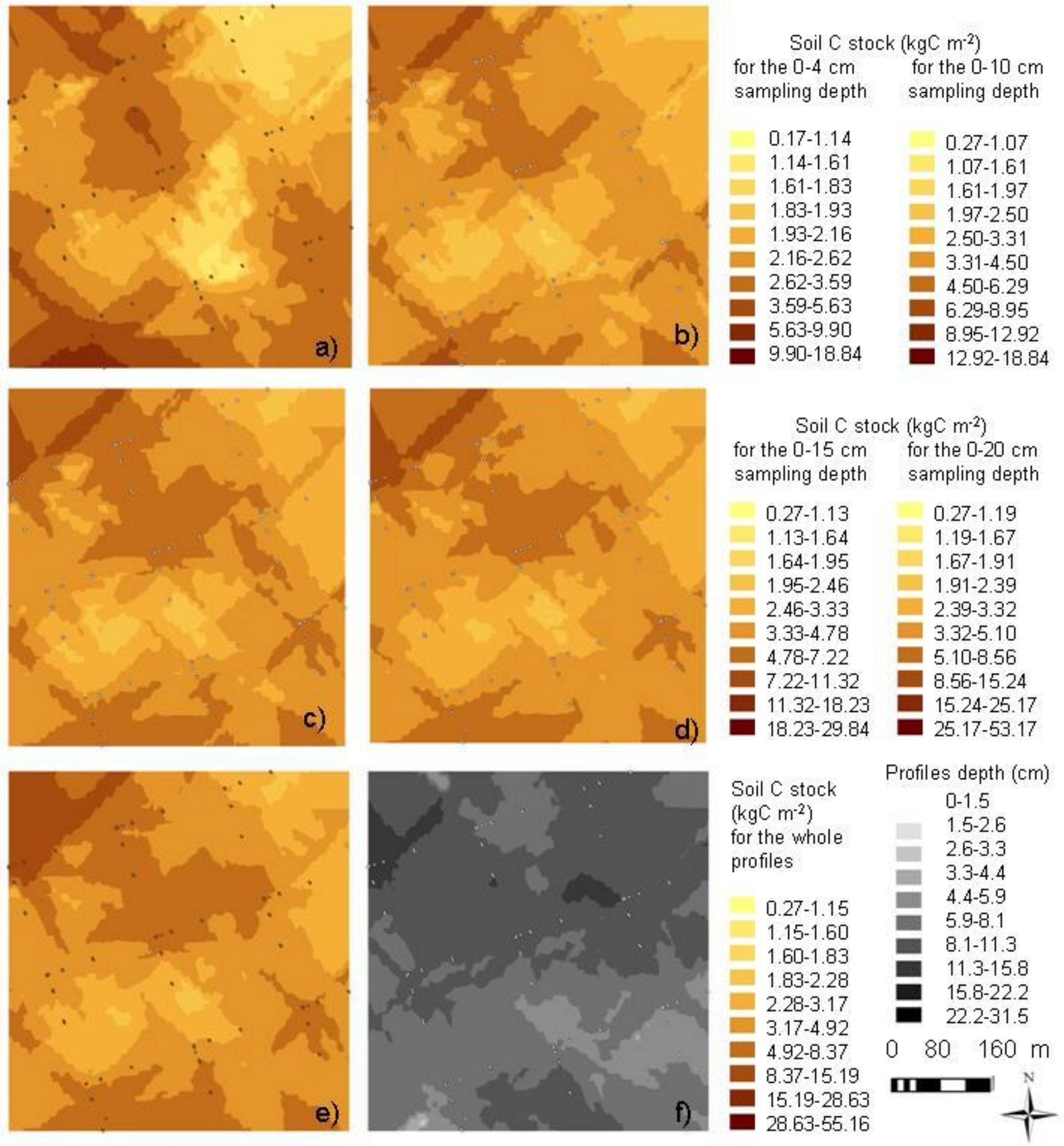


Figure 2.5: Intensive Valley maps of the soil C stocks (kg C m^{-2}), obtained by ordinary exponential Kriging in ArcGIS, for soil depths of 0-4 cm (a), 0-10 cm (b), 0-15 cm (c), 0-20 cm (d) and whole profiles (e); profile depths are indicated in (f).

2.4.5 H_4: relationships between soil variables will differ for Abisko and Kevo

The boxplots of C content and C stocks (kg C m^{-2}) for all samples show closer results for the IV and AT compared to KT (Fig. 2.6 b and d). The bulk density and C/N ratio distributions (Fig. 2.6 a and c) do not show an obvious difference between Abisko and Kevo. The bulk density, C/N ratio and C stock distribution show numerous outliers. Some of the higher outliers have been taken out of the graphs for more visual clarity, without affecting the statistics presented for each boxplot.

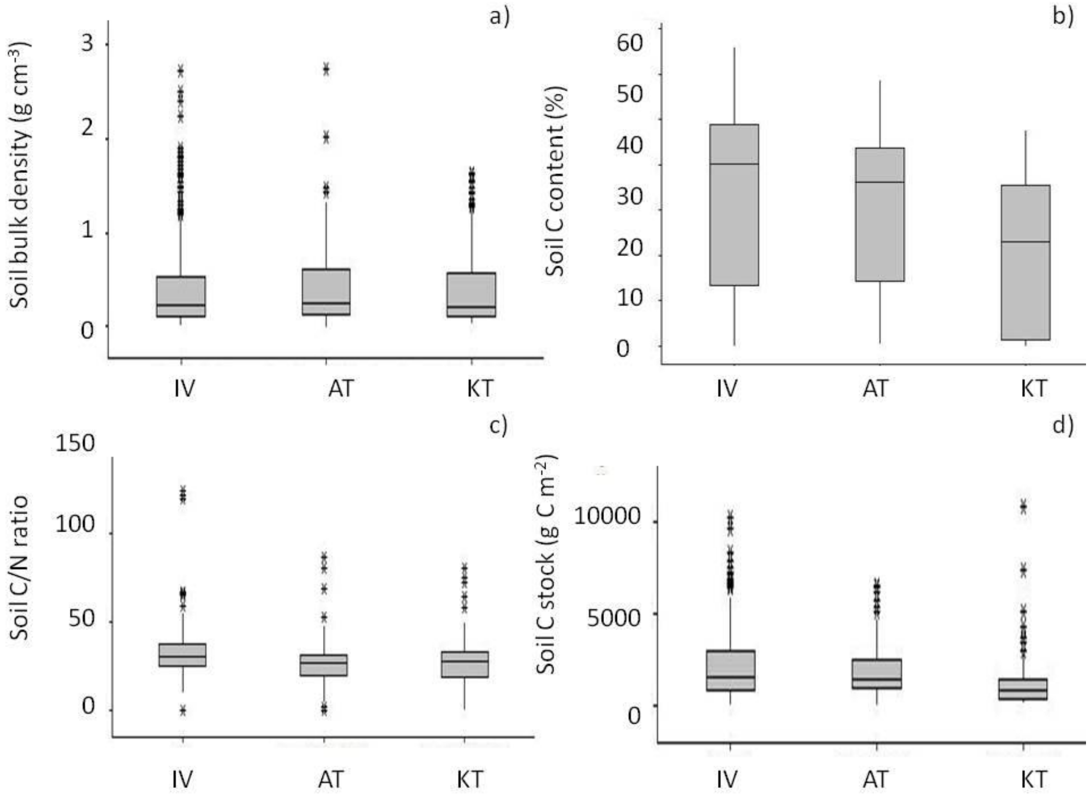


Figure 2.6: Box and whisker plots for the AT, IV and KT sampling areas of the surface 4 cm bulk density (a), surface 4 cm soil C content (b), carbon to nitrogen ratio (c) and surface soil C stock/density (d) for the profiles of both sites with bars for the first quartile (lower), median and third quartile (upper). The lower whisker is the minimum and the upper whisker is the maximum.

However the dendrograms for the Abisko and Kevo soil variables for all samples (Fig. 2.7 a and b) show relationships differing between soil variables. They represent the variable clusters obtained by correlation analysis, the greatest correlation being 100%. They provide an easy way to visualise the correlation between variables, and to compare these degrees of correlation between datasets. For Abisko, the soil C stock is closer to the bulk density, while the soil C stocks data in Kevo are closer to C content.

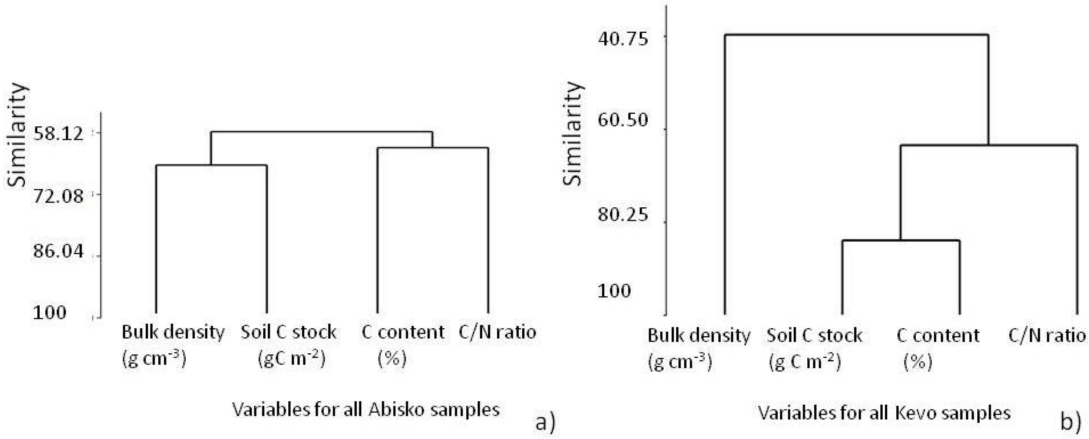


Figure 2.7: Dendrograms for soil variables for the Abisko (a) and Kevo (b) samples

2.5 Synthesis

2.5.1 Soil C stocks range

The soil C stocks range mainly from 0.04 to 10.0 kg C m^{-2} (median 1.49 kg C m^{-2}) in the IV, 0.004 to 6.49 kg C m^{-2} for the AT (median 1.36 kg C m^{-2}) and 0.044 to 7.31 kg C m^{-2} for the KT (median 0.82 kg C m^{-2}) (Fig. 2.6). These values are lower than the estimated arctic average C stocks of 9.20 kg C m^{-2} for the arctic and alpine tundra, of 11.75 kg C m^{-2} for the forest tundra, of 34.80 kg C m^{-2} as an average for North American and of 38.3 kg C m^{-2} as an average for European Russian arctic soils (Callaghan *et al.*, 2005; Ping *et al.*, 2008; Hugelius and Kuhry, 2009). However, more detailed regional studies suggest lower values for the North American uplands of 7.50 kg C m^{-2}, for mountains of 0.70 kg C m^{-2} (Ping *et al.*, 2008), and values for the Swedish sub-arctic 'tundra' of 1.14 ± 0.2 kg C m^{-2} for *Empetrium* heath; 1.32 ± 0.155 kg C m^{-2} for *Myrtillum* heath, and 4.61 ± 0.96 kg C m^{-2} for mixed shrub heath (Jonasson, 1982). These are closer to the results presented here. Further sampling in these sites should be accompanied by an assessment of the uncertainties associated to the methods and scales used, which could not be implemented in this project due to time constraints (Goids *et al.*, 2009). This could explain some of the variation in these stocks estimates and allow for a better comparison of C stocks across the Arctic.

2.5.2 Soil C distribution across the scales

In the IV, values for the whole depth profiles show more heterogeneity over large distances than surface 4 cm values. This stresses the importance of considering depth in the soil C distribution (Fig. 2.3 and 2.4). This is accentuated by the inversion of the semi-variogram surface anisotropy between the surface data and the whole profiles (Fig. 2.2), hinting at the different spatial distribution along the profiles' depth observed in the IV maps (Fig. 2.5). The soil C stock variability is higher at fine scales for the transects and seems to justify averaging over larger areas, ($\boldsymbol{H_1}$) (Table 2.2). However, this is not verified for all soil variables in both sampling areas. This is a *caveat* on sampling only over large areas and neglecting minor components. Not all scales have to be covered as intensively, which eases the work involved in sampling and analysis.

2.5.3 Cyclical sampling coverage of the soil C stocks distribution

Cyclical sampling is tested as an alternative to regular sampling or stratified sampling, covering the variability of soil C stocks at different scales ($\boldsymbol{H_2}$). It is meant to avoid bias introduced by the selection of the main vegetation categories as sampling locations. Using different sampling schemes by sampling less vegetation categories, not covering as many scales or using transects rather than a grid, brings more uncertainty in the mean used for upscaling (Table 2.3). This is a factor to take into account if the final stocks results are used for upscaling.

Selecting data only for the dominant categories or for the main categories and their transition introduces less deviation from the whole dataset than using an alternative spatial scheme (grid, transect, cycle). The means of means are less variable when choosing alternative vegetations schemes (Table 2.3). The scale of the sampling design chosen and its spatial coverage are more important to consider than the vegetation categories sampled. Wherever possible, all the vegetation categories and their transition areas should be represented in the scheme.

2.5.4 Soil C distribution changes at depth

The soil C distribution was tested for heterogeneity at depth (***H_3***). The sampling depth chosen is an important factor for the calculation of soil C stocks. The horizons can be quite shallow in Kevo and quite rocky in Abisko, preventing sampling to depths recommended to cover all the potential C pools (at least 1 m to 2 m; Callaghan *et al.* (2005); Ping *et al.* (2008)). It was not possible to reach a depth of one metre when sampling these sub-arctic alpine soils. In Abisko, the soils form over fluvial and glacial deposits (Niessen *et al*., 1992) and Kevo soils form over glacial till (Hall *et al.*, 2003). These materials contain important quantities of stones that impeded sampling at depth. Comparisons with other sites and soil types are difficult when these soils can be sampled for several metres, from peatlands around 2.5 m deep (Gorham, 1991) to 25 m deep yedoma permafrost (Zimov *et al.*, 2006).

IV maps are similar in their spatial distribution of cumulative soil C stocks from a 10 cm sampling depth to whole profile sampling depth (Fig. 2.5). This could be due to the lower number of deep profiles, with most profiles not being sampled at these depths. As there are less and less sample data with depth, however, the maps contours decline in resolution. This sparsity of data for the bottom of the profiles leads to the cumulative results for the 0-20 cm depth and for the whole profiles being very similar (Fig. 2.5 d and e). However the difference between results from surface sampling and whole profiles show that some profiles contain only a minor fraction of their soil C stock at the surface (Fig. 2.5; similar to the transects, Fig. 2.3 and 2.4). These differences in soil C stocks and profiles depth distributions in the IV would benefit from being related to other soil variables and vegetation variables (see Chapters 3 and 4 for analyses of the relations between soil profiles, vegetation variables and C stocks and fluxes).

The transect results for Abisko and Kevo show substantial heterogeneity of soil C distribution at depth between vegetation categories. AT soil profiles reflect the heterogeneity of landscape and vegetation components that is seen on the Abisko aerial photograph and indicate that the soil properties are not independent of the various surface components of the landscape (Fig. 2.1c, 2.3 and 2.5). Kevo's profiles contain higher C stocks in components that could be under-represented if considering only the main vegetation components (Fig. 2.4).

The heterogeneity of soil C stocks at depth has consequences for modelling. It requires data on soil composition in three dimensions instead of two. The dynamics of C exchange in differing physico-chemical conditions will be complicated by the behaviours and properties of the different soil layers (Kirschbaum, 1995). Here the distribution of soil C stocks has been mapped as quantities, however these numbers say nothing regarding different soil qualities, for example types of organic matter and degrees of decomposition (more details in Chapter 3). Understanding the relations between soil C distribution and the components of the soil column is crucial in upscaling these results to other sites. Average C stocks may be quantitatively similar at contrasting sites, but dissimilar soil organic matter quality may mean that soil C dynamics react differently to climate change (Mikan *et al.*, 2002). Thus, information on soil C stocks and their spatial and depth distributions needs to be accompanied by information on the lability of soil C at depth.

2.5.5 Relations between soil variables

The relations between soil variables are similar between the sampling areas of the same site. However, they differ between Abisko and Kevo as was hypothesised (***H_4***). The soil C stocks averages over these landscapes cover different interactions between soil properties. Sites that may appear similar when comparing their C stocks or vegetation components could cover different soil systems and react differently to a similar change in soil conditions.

2.5.6 Comparison between sampling areas

The Intensive Valley scheme can not be easily replicated as it involves substantial work and covers large areas. However it covers the diversity of vegetation components present and gives a more complete representation of the soil C distribution across the landscape than a linear transect (allowing mapping: Fig. 2.5, Table 2.3). The complementary AT covers a longer altitudinal range, but its sparse sampling only permitted thorough mapping of soil C stocks at depths and not as well across the landscape. It revealed the contrasts between the main vegetation components that are only covered marginally in the IV (Fig. 2.1). For example, the tundra heath snow beds are far from the IV area and contain large C stocks that could be neglected.

The KT covers a hydro-topographical gradient between the border of waterlogged mires and birch forest shallow soils. Most of its profiles are situated in the dominant vegetation component, the birch forest. Although it covers less vegetation components than the AT, the contrast between soils is as important. Its simpler composition could be a base for modelling landscapes that are more complex. However, the differences in relationships between soil variables in Abisko and Kevo show the importance of conducting thorough field surveys before upscaling models from one site to another (Fig. 2.7).

2.5.7 Importance of the transition area

Transition areas are more heterogeneous than the main vegetation and landscape components. The IV illustrates the heterogeneity of the soil C distribution in such an area while KT illustrates the importance of soil C stocks that can be held by minor landscape components. This variability over small areas can be a serious challenge for modelling (Williams and Rastetter, 1999). If the main vegetation components show less variability, a more intensive sampling could be directed at the transition zones. The grid must cover all the components present in a landscape proportionally to their presence. The importance of transition areas has to be assessed before designing the sampling scheme for a new site.

2.5.8 Sampling strategy recommendations

The calculation of soil C stocks requires robust data on bulk density, soil depth and C content (Eq. 1). Sampling of the soil variables has to be accompanied by sampling of other variables, such as vegetation composition, as the links between soil profiles and vegetation communities are important in KT and AT. Furthermore, in terms of upscaling, it is important to have information on site properties which can be mapped and quantified by remote sensing (i.e. vegetation and surface/near surface properties), even if it is acknowledged that the relationship between these and soil properties is not always straightforward (as indicated in Chapter 3 and 4). Nitrogen analysis on soil samples, and the study of the organic matter "quality" may be used to assess the lability of soil C stocks, and this information can complement data on soil C stocks (Sjögersten *et al.*, 2003; Hugelius and Kuhry, 2009; Hugelius *et al.*, 2010), and should be considered in the sampling plans.

An extended grid can cover extended transition areas. Extra points can be added in the centre of each grid square to avoid under-sampling. Smaller grids can be used in the main vegetation components, to help assessing the differences in variability between the heterogeneous transition areas and the dominant vegetation components. If several grids are used, they should be placed along a regular or cyclical transect to sample across landscape gradients and encompass as many landscape and vegetation components as possible. Once designed the sampling scheme has to be adhered to, not overlooking plots located on stones/boulders or open area.

In designing the sampling scheme, time and possible material and laboratory constraints should be planned for. A first reconnaissance of the site should include an estimation of the soil depths and rock content for the different landscapes units, as these are important factors in choosing the sampling depth and the number of samples expected along a profile.

If the sampling is designed for use in modelling, it should be remembered that model complexity would have to increase to take into account all the components and their interactions. Considering which landscape components are the most important for the variability of soil C stocks should be assessed from the beginning of the study.

2.6 Conclusion

Soil C distribution is highly variable between field sites, sampling areas and depending on the vegetation and landscape cover. The cyclical sampling scheme apparently sampled most of this heterogeneity but required very substantial work in the field and the laboratory. This approach can be supplemented, however, with transects, to cover more of the landscape diversity and/or environmental gradients with fewer profiles.

The results of this study show that sampling as many vegetation categories as possible is a better choice than targeting the main vegetation categories present on the field. A detailed coverage of the heterogeneous areas of the site should be sufficient to sample most of the vegetation diversity, simpler grid or transects could give more information about the variability of soil properties in the areas under the main vegetation categories. The choice of the sampling scheme configuration has, therefore, to be considered carefully, as it has an influence on the results for the different vegetation categories.

Sampling soil variables gives an estimate of the state of soil C stock distribution across the sites. Considering the difficulties brought by the choice in sampling scheme and field work conditions, a shortcut brought by remote sensing surveys could be an easier solution. For this, a link between an easily measurable vegetation properties, quantified from above, and the hidden below-ground soil C stocks would be ideal. Links between vegetation and soil properties are further explored in Chapter 3.

Chapter 3 - Linking vegetation distribution to soil carbon distribution in two sub-arctic landscapes

3.1 Abstract

1 Soil carbon (C) storage is a key variable in the C cycle and earth system models. Regional datasets on soil C stocks are sparse due to limited sampling and lack of remote sensing capability for investigating soil properties. By contrast, large datasets for variables linked to the above-ground vegetation cover can be relatively readily obtained. If an above-ground proxy for vertical soil C distribution is found, that would provide a means to use remote sensing as a tool for soil C distribution studies. For instance, Leaf Area Index (LAI) and vegetation type are two variables already quantified by remote sensing, and these are likely to be related to total soil C stocks, although potentially in complex ways.

2 From the field survey of two sub-arctic landscapes, no direct relation between soil C stocks and LAI or vegetation categories was found. Using larger categories when classifying vegetation masks the variability of soil C stocks (between 1.1 and 6.3 kg C m^{-2}) and gives an average soil C stock value (here around 2.3 kg C m^{-2}) which could be used for upscaling.

3 In this analysis, correlations between soil, vegetation and topography variables are weak. No relationship has been shown which permits the use of a single variable as an above-ground proxy for soil C distribution.

4 The soil profiles at the transition between forest and tundra heath indicate that vegetation composition, rather than topographic controls, exerts the stronger

influence on soil development and organic matter composition (although it must be borne in mind that vegetation composition is itself related to topography). Though the average soil C stocks of forest and treeless areas in the immediate ecotone area are similar, the profile characteristics and physico-chemical environments differ, and these soils could therefore respond differently to climate change.

5 *Synthesis:* A study of soil, vegetation and topographical variables has, perhaps unsurprisingly, failed to identify an above-ground proxy for soil C distribution in vegetated areas. There is substantial variability of soil C distribution over the landscape but an average value over forests and treeless areas can be found, and this value could be used for upscaling. The possible evolution of the present soil C distribution following climate change, and also potentially the advance of trees, has to be monitored by further field surveys, as no solid proxy or method permits the estimation of soil C stocks at depth from above-ground.

3.2 Introduction

Soil carbon (C) is one of the major components of the C cycle, and thus an important part of the models simulating the feedbacks between terrestrial, atmospheric and oceanic processes (Denman *et al.*, 2007; Randall *et al.*, 2007; Qian *et al.*, 2010; Gärdenäs *et al.*, 2011). These models are one of the main tools used to forecast the consequences of climate change on the Earth's ecosystems (Sitch *et al.*, 2003; Qian *et al.*, 2010). They require the input of large and comprehensive datasets. A way to obtain such large quantities of data is to use remote sensing measurements for a standardised and comprehensive cover of large areas (Mulder *et al.*, 2011). Surface soil C stocks and spatial distribution can be directly measured by several remote sensing techniques on unvegetated lands (Mulder *et al.*, 2011), but measurements on partially vegetated agricultural soils are still accompanied by important uncertainties (Bartholomeus *et al.*, 2011). Soil maps can be obtained by using spectral information from remote sensing images when sufficient pedological information is available on the ground to differentiate soil categories (for example field survey information, topographic and geological maps; Hugelius *et al.*, 2011a).

The Arctic is one of the regions hypothesised to be particularly sensitive to any change in climatic and physico-chemical conditions and it therefore warrants careful monitoring (Callaghan *et al.*, 2004c; Christensen *et al.*, 2007). Reviews of the available datasets attempt to estimate soil organic C stock values for Arctic regions (Ping *et al.*, 2008) and for the whole Arctic (Tarnocai *et al.*, 2009). They are based on a limited number of soil profiles as wide areas of the Arctic are difficult to access and are relatively poorly known (Walker *et al.*, 2005). The short arctic field season adds time constraints on field surveys. Soil studies are also impeded by the frozen state of soils during most of the year (Tarnocai *et al.*, 2009).

Remote sensing already provides a way to assess the status and distribution of arctic vegetation and phytomass comprehensively, and vegetation cover can be mapped over the whole arctic region (1: 4,000,000 or 1: 7,500,000) (Gould *et al.*, 2002; CAVM team, 2003; Walker *et al.*, 2005). The vegetation of arctic landscapes shows a complex distribution over small areas (m^2 to km^2) (Van Wijk and Williams, 2005; Shaver *et al.*, 2007). The mismatch between these fine scale detailed categories and satellite-based maps has been recognised, and a map based on remote sensing and local field information has been generated for the Arctic (CAVM team, 2003; Walker *et al.*, 2005).

Finding a significant and direct relationship between soil C distribution and one or several vegetation properties is a step towards surveying soil C distribution more frequently and more easily than by using intensive field surveys. The Leaf Area Index (LAI) is a vegetation variable measured indirectly by remote sensing, although still needing calibration against field measurements (Williams *et al.*, 2008). It represents the leaf area implicated in light interception, and is closely linked to the Normalised Difference Vegetation Index (NDVI), an index of the greenness of vegetation (Van Wijk and Williams, 2005). Extensive LAI studies can be made over large areas (Garrigues *et al.*, 2008), but LAI has a high variability (up to one order of magnitude) over short scales, which make it a fine-resolution indicator of the plant production (Williams and Rastetter, 1999; Williams *et al.*, 2008). LAI can be used as a proxy for vegetation categories (for example shrub tundras and tussock tundras) as well as vegetation variables, such as foliar nitrogen, and C cycle components, including the Gross Primary Production (GPP) and Net Ecosystem Exchange (NEE) (Myneni *et al.*, 1997; Williams and Rastetter, 1999; Williams *et al.*, 2001; Denman *et al.*, 2007; Shaver *et al.*, 2007). Similarly, NDVI correlates with above-ground biomass, Gross Ecosystem Production (GEP) and ecosystem respiration (Boelman *et al.*, 2003).

In the present study, two sub-arctic field sites have been selected to assess the possibility of using vegetation variables as a proxy for soil C stock distribution; Abisko (Swedish Lapland) and Kevo (Finnish Lapland). In Abisko, the Intensive

Valley (IV) is a 500 m by 500 m area for which LAI has already been mapped (Spadavecchia *et al.*, 2008). In parallel, the IV shows a complex distribution of soil C (see Chapter 2). Another sampling area on this field site is the 2.9 km long Abisko Transect (AT), linking the birch forest and tundra heath, two major vegetation types in Abisko. In Kevo, a transect has been used to link mire border and birch forest, two major vegetation types in the region (Heikkinen, 1998; Christiansen *et al.*, 2010).

Several hypotheses linking vegetation properties and soil properties are tested with the aim of finding a method to measure soil C stocks using above-ground variables.

H_1: LAI can be used as a replacement of the vegetation categories. This requires the existence of a unique distribution of LAI for each vegetation category. If this relationship is verified on these sites, obtaining the LAI distribution over these landscapes facilitates attributing the vegetation category without the necessity for detailed vegetation mapping in the field.

H_2: There is a direct relationship between soil C stock and LAI values: thus obtaining LAI from remote sensing permits calculation of the stock size of soil C. Both variables are continuous and thus not constrained by the definition of categories, which could make them easier to link than the C stocks and discrete vegetation categories. Leaf area index is linked to the species and plant functional types present in the vegetation cover, which interact in heterogeneous ways with the soil. Thus, it is possible that a link between vegetation properties as the LAI and the soil C stocks can be found.

***H*$_3$**: The third hypothesis is the direct relationship between soil C stock and vegetation categories. Vegetation categories are an assemblage of different species, and the species they share can have contrasting distributions in different categories. Thus, each category can have a "signature" C stock.

If these first three hypotheses are verified, then NDVI and LAI, as well as vegetation categories, may have potential to be used to forecast C stocks sizes in these landscapes. Otherwise deriving robust information on soil C stock from above-ground vegetation variables can be compromised or not possible.

***H*$_4$**: As other soil properties are linked to soil C stock (for example soil C content by percentage, C/N ratio, soil profile depth, and soil bulk density), a clear link between LAI and one or several of these soil properties could identify and establish a proxy for soil C stocks, if the latter do not present a direct relationship with one of the vegetation properties studied here.

***H*$_5$**: The transition area profiles between birch forest and tundra heath present a mixture/hybrid of these soil profiles' characteristics, as part of a catena. Birch forest profiles are shallow micro-podzols, while tundra heath profiles contain substantially deeper organic layers. If the transition between these two soil types is smooth, then upscaling the distribution of soil C stocks is easier than if boundaries have to be defined. This would ease upscaling; if a proxy is found between LAI/NDVI and soil C stocks, the use of remote sensing to measure soil C stocks can be impeded by a great variability over fine scales especially in transition areas between the two main vegetation types. More field information would then be needed.

To address these questions, a survey of Normalised Difference Vegetation Index (NDVI), understorey and canopy Leaf Area Index (LAI) has been combined with a study of soil properties in the two sub-arctic landscapes. The soil sampling is accompanied by micromorphology sampling in selected locations in Abisko, to estimate the soil organic matter distribution and composition from the micrometre to centimetre scales, in relation to the vegetation cover. This complements the quantitative results at the metre to kilometre scale obtained with soil sampling and the LAI and vegetation survey, by showing the direct links between soil profiles composition, microtopography and vegetation cover. If a relation is found (or not) between the soil C stock and vegetation cover at the kilometre scale, the micromorphology data will show if it is mirrored in the underlying soil structure at the centimetre scale.

While Abisko has a heterogeneous mosaic of contrasting vegetation covers, Kevo is mainly marked by a transition between birch forest and mire. Consequently fifteen land cover types have been defined for Abisko but only two for Kevo, as the transition covers too small an area to be split into more categories. The surfaces covered by each vegetation category in one of the Abisko sampling areas, called Intensive Valley (IV), have been delimited by using aerial photographs and satellite remote sensing of the site as a basis. This complements the LAI plot-based survey by giving estimates of the areas covered by each vegetation type. This is combined with data obtained in the field during the Abisko and Kevo sampling campaigns (see Chapter 2) to calculate surface and total C stocks, even in unsampled parts of the IV. The relations between these soil variables and the LAI and NDVI data are evaluated via correlation matrices.

3.3 Methods

3.3.1 Field sites

The two chosen sites contain transition zones (ecotones) between dominant vegetation types, from birch forest to sub-arctic tundra heath in Abisko, and from mires to birch forest in Kevo. Abisko village (68°21'N, 18°49'E) is situated 200 km north of the Arctic Circle, and 385 m above sea level. The climate is under maritime influence (Abisko Research Station, ANS[5]). The mean annual temperature (MAT) at ANS (365 m asl), between 1961-1990 was of -1.0°C, with monthly means for the warmest and coldest months (July and January) of 11.0°C and -11.9°C respectively (Alexandersson *et al.*, 1991). Mean annual ground temperatures, for the 1943-1983 period at the ANS, was of 1.7°C at -0.5 m and 1.6°C at – 1 m (Niessen *et al.*, 1992). Mean annual precipitation over this period was around 304 mm. Birch forest extends to the shores of Lake Torneträsk (341 m asl) to the north. To the south/south east, forest grades in a mosaic, interspersed with sub-arctic/alpine heaths and mires upslope to low/mid-alpine heaths, fens and mires on the flanks of Nissuntjårro mountain (summit, 1738 m asl), part of the Scandes mountains. Two sampling areas have been defined within this catena in the Abisko region: the Intensive Valley (IV) is a 500 x 500 m area covering the transition between birch forest and tundra heath (Spadavecchia *et al.*, 2008) at altitudes ranging from 601 to 635 m asl. The Abisko Transect (AT) follows the main slope from the upper birch forest (575 m asl) to the tundra heath (764 m asl) over 2.9 km. The areas are predominantly well-drained (Van Wijk and Williams, 2005), although there are some sedge fens and *Sphagnum*

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[5] website, http://www.linnea.com/~ans/, last accessed August 2011

mires in depressions, and seasonally-inundated (snow melt period) hummocky boulder fields in some riparian areas. At Abisko there is no permafrost. In view of the contrast in altitude between these field sites and the meteorological station at ANS (Abisko, 2010), there is likely between them a reduction in temperature during the thaw period, reflecting an adiabatic lapse rate of around 0.6°C.

Kevo, in Finnish Lapland (69°45'N, 27°01'E), is 60 km north of the continuous pine forest line, and 80 m above sea level (Kevo Research Station, 2010[6]). The air MAT is -2.8°C and the soil MAT is 1.9°C (range 0.9°C - 2.4°C) with a mean monthly temperature of the warmest month (July) of 13°C, and a mean monthly temperature of the coldest month (in January) of -16.0°C; these are cold temperatures for Finland, Kevo being one of the northernmost sites. This difference between soil and air MAT is one of the most important in Finland, due to the importance of the snow cover (Yli-Halla and Mokma, 1998). The snow cover lasts around 200 days, from the end of October until mid-May, one of the longest durations in Finland (Yli-Halla and Mokma, 1998). The annual precipitation is of 415 mm (Kevo, 2008). There is discontinuous permafrost in the palsa mire areas but little elsewhere (Christiansen *et al.*, 2010; Kevo Research Station[7], 2010). Soil sampling was conducted at a site 31.2 km south of Kevo Research Station, and there at an elevation of 271 m to 292 m along a 475 m transect between mire border and birch forest.

[6] http://www.kevo.utu.fi/en/ last accessed in 2010

[7] http://www.kevo.utu.fi/en/

3.3.2 Selection of sampling plots, soil sampling and analysis

These are described in the Chapter 2 Material and Methods section 2.3.

3.3.3 Micromorphology sampling and processing

In Abisko, samples for micromorphological analysis were taken alongside the AT's soil sampling for C/N analysis samples (Fig. 2.1 c). The resulting slides are three dimensions photographs of the soil profiles, allowing a comparison of the soil profiles under different vegetation types at very fine scales (Fig. 3.1 and 3.2), while maintening intact the structure of the soil and the structure of its components as well as their quantity and quality. These characteristics are by necessity lost in the C/N analysis, which could end up as a purely quantitative exercise without the information brought by a detailed study of the soils profiles.

Five plots, with three profiles each, were chosen; a birch forest plot close to plot 1 (three thin section slides), a tundra heath plot (STEPPS area close to the end of the transect (STEPPS, 2010); six slides) and a transition plot between birch forest and tundra heath (plot 35 in the middle of the transect; four slides). The remaining two plots were snow bed plots, a copse snow bed in the forest near plot 22 of the transect (six slides) and an exposed snow bed in the heath near plot 54 of the transect (two slides). They have been included because snow beds experience substantially different thermal regimes compared with the surrounding vegetation (Björk and Molau, 2007), and the thin section slides can reveal what these particularities bring to the soil composition. Thin section production being an expensive and long process, it has been necessary to reduce the numbers of samples taken for micromorphology analysis.

At each plot, additional Kubiëna tins have been taken in the same pits as the carbon analysis samples (This is illustrated by Fig. 3.1. for the birch forest to tundra heath transition area, and Fig. 3.2). Thus, the carbon content of the different horizons and their organic matter composition can be linked. As was done for the carbon content samples, the central plot, 1 and 2 metres plots have been used to get replicates of each horizon (Fig. 3.1). The basic stratigraphic profile information was collected while doing the parallel sampling for C stocks analysis in the same profiles (Chapter 2). Due to the priority given to C/N analysis over micromorphology (higher number of samples necessary) and the short time available in field season, no stratigraphic profile was drawn. All soil pits were photographed for further reference.

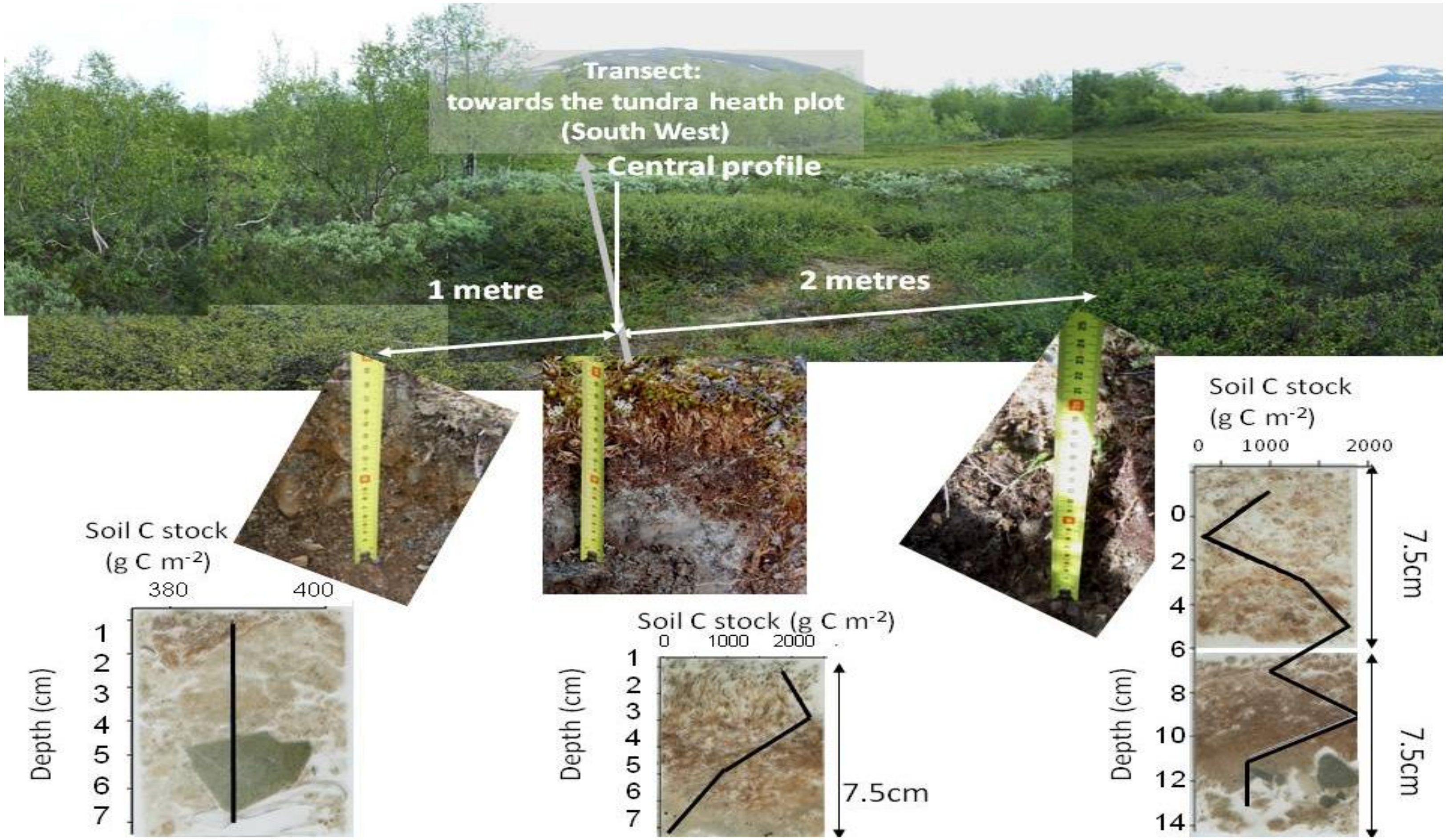


Figure 3.1: Soil profiles of the transition area between birch forest and tundra heath in the middle of the Abisko Transect, presenting the plot and the location of the sampling plots, soil C stocks profiles calculated from soil samples analysis (g C m^{-2}), the associated soil profiles and the micromorphology thin sections produced from soil samples taken in these profiles

While awaiting processing, the samples were kept in a cold container (-5°C) to stop decomposition processes. The decomposition state of the soil organic matter is one of the parameters studied in the soils. If decomposition continues after the sample has been taken out of the field, the soil component will appear to have a higher degree of decomposition than in its natural state. The soil's physical structure was also retained by keeping the samples whole during the process, to get a picture of the soil in its natural state.

In the thin section production laboratory, the tins were processed to obtain thin sections (35-40 micrometres thick) presenting 7.5 cm by 5.5 cm soil samples (Kubiëna, 1938). Once dried through vapour-phase acetone exchange, the sample is impregnated with polyester resin. Once the resin has set, the sample is cut, ground and polished to a 30 μm slide for petrographic microscope analysis. A glass cover slip is applied unless SEM (Scanning Electron Microscope) analysis is required later. Taking replicates of the samples allows compensating for any incomplete or broken slide, as getting samples in a later season was not possible. It also provides more information about soil profiles under a similar vegetation type, to ensure the samples are not taken from an atypical profile.

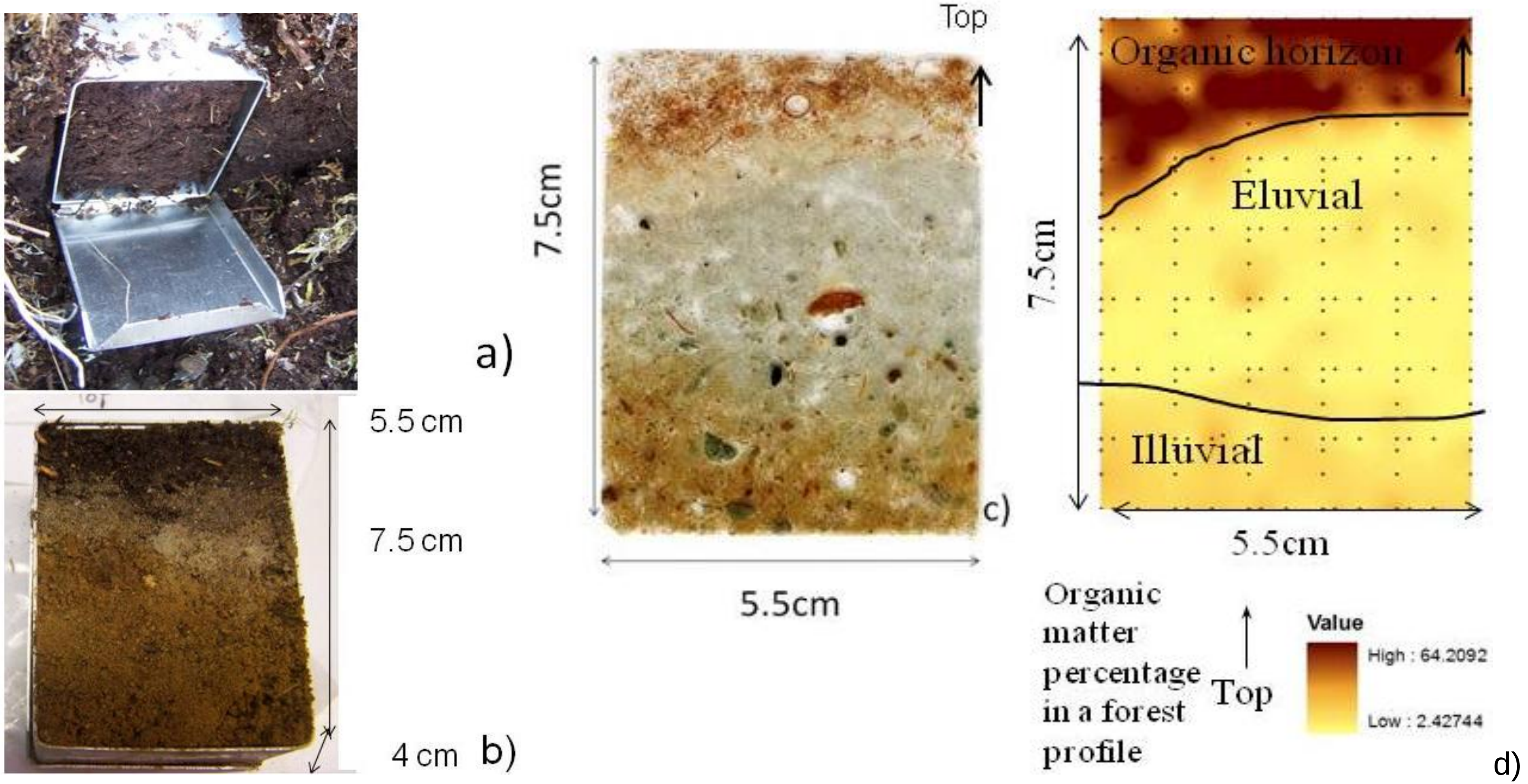


Figure 3.2: From the field sampling to the image analysis, the continuity is kept; the soil is sampled from the field in a Kubiëna tin (a), and so is protected during the transport to the laboratory (b), the thin section shows the soil structure (c) the final output is a map of soil properties at the microscale (d)

A general analysis of the slides was conducted with the aim of identifying the categories of components present in these soils. The usual methods for analysing the slides are qualitative descriptions of the components of the slides and quantification by point counting or studying the slide area by area (Stoops, 2003). However, these processes are time-consuming and a selective micromorphology analysis procedure was adopted to gain more general information on the categories and distribution of the soil components. To get standardised results for all the slides and keep the number of areas to be described at a workable level, a cyclical scheme similar to the one used in the IV has been applied to the slides (Fig. 2.1 and 3.2 d). A randomised pattern would not have ensured that the slides could be compared and that all the soil depths would be treated similarly. The regular pattern used permits to treat all the slides along the same template. The quality and quantity of data will be similar on all the slides and the comparison between soils is standardised for this study.

For the cyclical scheme application, each slide was divided in 1.5 mm by 1.5 mm areas (visible over the map on Fig. 3.2 d). A margin was left on the four sides of the central area, as the soil can be damaged during the transport in the tin or the thin sections processing. The grid obtained is 33 columns by 43 ranks, totalising 1419 frames, of these 220 fall in the cyclical scheme. These areas were automatically photographed using a mechanical stage controlled by AnalySIS software[8]. The image analysis was conducted by counting percentage areas for different soil components (roots, fungi, excremental features, decomposed organic matter, amorphous organic

[8] I am grateful to Dr Paul Adderley for helping me design the image analysis protocol in AnalySIS.

matter; table 3.2). The micromorphological description tables and the categories used have been designed specifically for this project (Table 3.1 and 3.2) and so differ from the standardarized tables presented in Bullock and colleagues (1985) and Stoops (2003).The resulting dataset contains enough data per horizon whatever the horizon's depth, especially when using the analyses of the replicates available for each soil.

Table 3.1: Extract from a micromorphological table used for statistical analysis

Picture number	X	Y	Void percentage	Roots type	Percentage covered
4	1	1	65	0	0
5	2	1	50	0	0
7	4	1	45	0	0
10	7	1	40	0	0
11	8	1	40	0	0
13	10	1	48	4	2
16	13	1	65	0	0
17	14	1	43	0	0
19	16	1	45	0	0
22	19	1	70	0	0
23	20	1	70	0	0

The main data categories are the voids (pore space), the roots, excremental features, fungi, amorphous organic matter, tissues and organs, and the mineral content (see table 3.2). The aim of this study is to characterise organic matter so the minerals are not described in details. However, it is important to know the area they cover and the horizons they define. The multiple categories of organic matter cover the main components present in this batch of slides. Most of the quantification is made on the area covered by these components in the field of view rather than by counting the number of objects of this category present. For example, counting the number of droppings would not indicate the area they occupy, as they can be found in a range of sizes even for the same species (Babel, 1975). The different degrees of decomposition can be due to different environments or organisms, finding which are dominant will be impossible so the category will be general rather than specific. One criterion determined from the fieldwork is the presence of trees or not near the plot, as it should influence the size and quantity of the roots in the profiles.

Table 3.2: Categories of the slide analysis created for this study

Category	Variables			
Void	Percentage area covered (%)			
Roots	Type*	Percentage area covered (%)		
Droppings	Enchitraeids (%)	Mites (%)	Other species (%)	Dropping fabric (%)
Fungi	Hyphae strands number	Spores number	Sclerotiae number	Fungal deposit (%)
Amorphous organic matter	Percentage area covered (%)			
Tissues	Type *	Percentage area covered (%)		
Minerals	Total percentage area covered (%)	Amphibole	Quartz	Mica

*Type is divided between “not present”; “living/fresh”; “slightly decomposed”; “moderately decomposed”; “strongly decomposed” and “very strongly decomposed”.

The next step in this analysis is the mapping of soil C at very fine scales (micrometre to centimetre). For now, only organic matter rather than C can be comptabilised. The SEM can map the elemental C distribution within the slide and produces maps, but on small targeted areas. This approach was not implemented in this project due to time constraints, but is thought as another step in the analysis of this work’s data. The resin in the slides will have to be accounted for. The maps produced will be used in conjunction with the maps estimated by Kriging (see

Chapter 2) to map soil C in three dimensions. This will help modelling soil C distribution and be an important tool for an upscaling of this distribution.

3.3.4 Vegetation categories

Vegetation was surveyed at each plot. The list of the plant species recorded is presented in Appendix 3.1. Categories were defined according to the range of plant communities encountered at the sampling areas once the surveys were completed (Table 3.3 and Appendix 3.1). In Abisko, birch cover (represented by the “Continuous” and “Upper birch” forest categories) is denser in the north, at the lowest point (and ‘start’) of the transect. It is sparser at the northern edge of the IV and only birch copses are present further south (category “Birch copse”). They are mainly located in sheltered depressions and riparian areas (Fig. 3.3).

Treeless areas show a great variety in vegetation types and statures (Table 3.3, Appendix 3.1). *Empetrum hermaphroditum* and *Betula nana* are the most common species in the tundra heath. Heath dominated by *E. hermaphroditum* has been classed as “*Empetrum* heath”, while the heath dominated by *Betula nana* and some *Salix* (mainly *S. lanata*, *S. lapponum* and *S. glauca*) in shrub form (~1 m high) associated with *E. hermaphroditum* has been classed as “Shrub heath” (Table 3.3). Exposed ridges (Fig. 3.3) are sparsely vegetated with crustrose/fruticose lichens, *E. hermaphroditum*, and prostrate *Vaccinium uliginosum* and *B. nana* (category “Exposed Heath”). Solifluction lobes and boulders are more completely vegetated by lichens, *E. hermaphroditum* and *Pinguicula* spp. (*P. vulgaris* and some *P. alpina*), *Loiseleuria procumbens*, *Andromeda polifolia* (category “Species-rich heath”) (Table 3.3). The small depressions separating them shelter some deciduous shrubs, such as

B. nana. *Salix* shrubs are present in deeper snow beds, associated with *V. myrtillus*, *B. nana* sub-shrubs and *E. hermaphroditum* (category "Snow bed margin") (Table 3.3 and Fig. 3.3). Transitions between the forest and tundra heath and between the tundra heath and wetlands have been categorised as "Heath-forest transition" and "Heath-sedge transition". Heath-forest transition is more easily defined in the field and less obvious on the aerial maps (Fig. 3.3). These ecotone areas are often dominated by *B. nana* in shrub form, and sometimes hybrid *Betula pubescens* × *nana*.

Though the soil is predominantly well-drained at the Abisko areas (Van Wijk and Williams, 2005), wetland areas are found in the forest clearings and in the depressions between the forested ridges to the north and between bare ridges to the south. In the IV, graminoids such as *Eriophorum* and *Carex* spp. are present, as well as forbs such as *Rubus chaemaemorus* (category "Sedge and wetlands areas").

Wetlands constitute a greater part of the Kevo field site, where the main ecological transition is between the mires and the birch forest. From the survey of the plots' vegetation, it is clear that the birch forest is similar to the one in Abisko: the main tree species is *B. pubescens*, with an understorey of *B. nana*, *E. hermaphroditum*, *V. vitis-idaea*, *V. uliginosum*, *V. myrtillus*, some *Phyllodoce caerulea* and mosses, lichens (for example *Cladonia* spp., *Cetraria* spp.) and graminoids (Table 3.3). Scots pine (*Pinus sylvestris*) is found sporadically within the birch forest. The slope is gentler than in Abisko (21 m over 475 m). The transition between birch forest and mires is marked by the numerous hummocks, some of which we noted to be ice-centred in late summer. This phenomenon is amplified in the nearby palsa mire expanses over till and at Skalluvaara, an elevated mire with hummocks comparable to those of Kevo around *Sphagnum* pools, and with similar vegetation (36 km above field site), (Lloyd *et al.*, 2001; Seppälä, 2003; Kujala *et al.*, 2008; Christiansen *et al.*, 2010). The mire borders are occupied by a diversity of plants from the *Eriophorum*, *Carex*, *Tricophorum* and *Sphagnum* genera as well as *Rubus chamaemorus* and *Ledum palustre* (Table 3.3; Laurila *et al.*, 2001).

The transition between the mire border and the birch forest could have been another vegetation category by itself. However the bands of mire border and transition vegetation covered by the transect are too thin to provide enough profiles to get statistical data. Therefore, these two categories (mire border and transition area) are treated together. This is another contrast with Abisko and its numerous vegetation categories.

Table 3.3: Vegetation categories and associated species in Abisko (upper rows) and Kevo (lower rows)

Continuous birch forest	*Betula pubescens* (dense cover); *Empetrum hermaphroditum* ssp. *nigrum; Vaccinium vitis-idaea*
Upper birch forest	*Betula pubescens* (important cover); *Betula nana; Salix* spp.*; Empetrum hermaphroditum* ssp. *nigrum*
Birch copse	*Betula pubescens* (groups); *Betula nana; Vaccinium vitis-idaea; V. myrtillus*; bryophytes
Shrub heath	*Betula nana* sub-shrubs; *Salix* bushes
Species-rich heath	*Betula nana; Empetrum hermaphroditum* ssp. *nigrum; Salix* bushes; *Andromeda polifolia*; *Cassiope tetragona*; *Dryas octopetala* lichens
Exposed heath	*Betula nana; Empetrum hermaphroditum* ssp. *nigrum*; lichens; *Vaccinium uliginosum; Loisleuria procumbens*
Empetrum heath	*Empetrum hermaphroditum* ssp. *nigrum; Betula nana; Salix;* lichens; graminoids (principally grasses e.g. *Calamagrostis lapponica*); bryophytes
Sedge and wetlands	*Eriophorum; Sphagnum*; graminoids (principally sedges e.g. *Carex rostrata*)
Heath-forest transition	*Betula nana* sub-shrubs and dwarf form*; Betula pubescens × nana; Salix* bushes*; Empetrum hermaphroditum* ssp. *nigrum*; bryophytes; *Vaccinium vitis-idaea; Betula pubescens*
Heath-sedge transition	*Empetrum hermaphroditum* ssp. *nigrum; Andromeda polifolia*; lichens; *Carex bigelowii*; graminoids (sedges and grasses); bryophytes
Snow bed margin	*Salix; Empetrum hermaphroditum* ssp. *nigrum; Betula nana*; graminoids (principally grasses); *Vaccinium myrtillus*
Kevo mire border	*Eriophorum* spp.*; Sphagnum* spp.*; Tricophorum caespitosum; Betula nana* bushes and dwarf form; *Empetrum hermaphroditum* ssp. *nigrum*; *Vaccinium vitis-idaea; V. uliginosum; V. myrtillus; Rubus chamaemorus;* bryophytes; lichens
Kevo birch forest	*Betula pubescens; Betula nana* bushes sub-shrubs and dwarf form; *Empetrum hermaphroditum* ssp. *nigrum*; *Vaccinium vitis-idaea; V. uliginosum; V. myrtillus;* bryophytes; lichens

Abisko and Kevo are both sub-arctic landscapes, and as such are not present on the Circumpolar Arctic Vegetation Map (CAVM; by the CAVM team, 2003). However, vegetation at these sites (excluding forest and copses) can be classed broadly according to the same categories. Kevo's mire border and Abisko's tundra heath as a whole belong to the S2 low-shrub tundra class; however, the exposed heath and *Empetrum* heath categories are similar to the S1 erect dwarf-shrub tundra. Abisko's and Kevo's wetlands fit in the W3 sedge, moss, low-shrub wetlands class (CAVM team, 2003).

3.3.5 Leaf area index survey

Understorey and tree canopy Leaf Area Index (LAI) were estimated using measurements of Normalised Difference Vegetation Index (NDVI) with two channels sensor SKR1800 (Skye Instruments, Powys, UK, channel 1 = 0.56–0.68 nm, channel 2 = 0.725–1.1 nm). One sensor was upward facing with diffuser on and the other downward facing. The sensors were placed on a 1.80 m high pole, covering an area of ~0.50 m^2 for each measurement. Understorey LAI was obtained using the formula (Van Wijk and Williams, 2005):

$$L_{AI} = 0.003e^{7,845 * N}$$

Where L_{AI} is the understorey LAI (m^2/m^2) and N is the NDVI value

Tree canopy LAI was calculated from photographs taken with a fish-eye lens and digital camera (Nikon E4500). Images were processed with the Gap Light Analyzer software (GLA, by Simon Fraser University, Burnaby, Canada).

3.3.6 Aerial data and derived properties

The aerial data (including aerial photographs) for Abisko and Kevo have been obtained during fly-overs of the site by the Edinburgh School of Geosciences ABACUS aircraft (Diamond HK36 TTC-ECO ABACUS, 2010). Photographs were taken using an under-wing mounted Canon EOS 5D digital camera and a Canon EF 50mm f/1.4 lens. Photographs were stitched together using the Graphical User Interface for Panorama Tools (PTGui) software package. The flight over Abisko was performed on the 2nd of August 2008 and the flight over Kevo was performed on the 7th of August 2008[9].

Another fly-over in July 2005 by the Natural Environment Research Council's (NERC) Airborne Research and Survey Facility (ARSF) aircraft with a Daedalus 1268 Airborne Thematic Mapper (ATM) multispectral scanner provided base data for the Digital Elevation Model's (DEM) (Stoy *et al.*, 2009b). The DEM was generated from the base data in ArcGIS (ArcView software, ESRI, Redlands, USA). Topographic characteristics of the site, such as the aspect and slopes, were derived from the DEM. To include the topography into the statistical analysis with the soil and the vegetation properties, the Compound Topographic Index (CTI) has been chosen as a variable. It takes into account the relative elevation via the slope and the flow direction, and was conceived to analyse soil moisture (Spadavecchia *et al.*, 2008).

[9] I am grateful to Timothy Hill (ABACUS) for the technical details concerning the production of the DEM and aerial pictures, and Ana Prieto-Blanco and Mat Disney for providing me with the DEM data; the NERC data were provided by B Huntley and R. Baxter

The CTI is defined as:

$C_{TI} = \ln (As / \tan \beta)$

Where C_{TI} is the Compound Topographic Index, β is the slope (radians) and A_s is the upslope area; A_s = (flow accumulation + 1) * (pixel area in m^2)

3.3.7 Generating maps from field data

Measurements in the field of properties such as NDVI, or derived datasets like soil C stocks, can be mapped in ArcGIS (ArcView software, ESRI, Redlands, USA) and laid over the DEM (provided by ABACUS, 2010). The technique used to estimate missing data between the plots is ordinary Kriging fitted with an exponential model. It is easier to use with a grid and has been applied to the IV data for variables such as the LAI and soil C stocks (these geostatistical methods have been described in Chapter 2 and used for C stocks map in Fig. 2.5). Using the same mapping techniques and plots enables comparison of the distribution of these properties over the sampling area (Fig. 3.10).

The land cover map (Fig. 3.3) was generated in ArcGIS from the aerial photograph of the IV (provided by ABACUS, 2010). The aerial photograph has been used as a background, over which the polygons corresponding to the vegetation patches have been delimited and the vegetation categories coded by creating feature classes. The vegetation classes were those defined from the field work. The attribution of a patch to a class is made by recognising the vegetation class according to its characteristics, determined during the field work. The areas occupied by the different categories are calculated by an automatic addition of the areas of all the polygons belonging to the same class.

3.3.8 Distribution of the land cover types in the Intensive Valley

The IV was chosen as a sampling area partly because of the substantial heterogeneity in land cover on a relatively small area (500 m by 500 m) (Fig. 3.3). The plots have been defined according to the cyclical sampling grid to assess if this sampling design adequately covers these vegetation types' diversity.

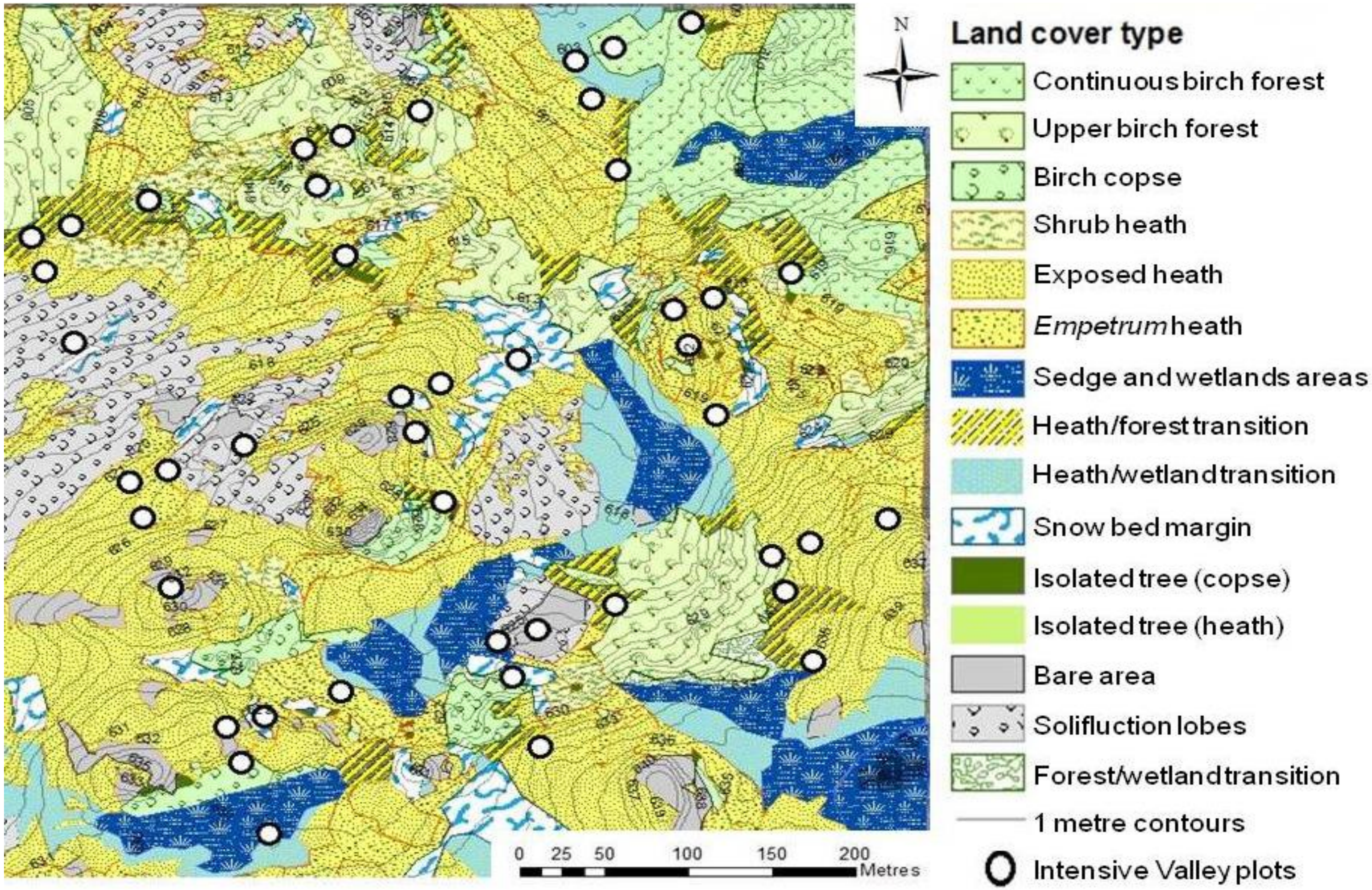


Figure 3.3: Map of the Intensive Valley cover types

The tree cover is most important to the north of the area, at the lowest altitudes. Isolated trees are found across the whole IV; in depressions of the landscape, sometimes forming a small copse, and even as isolated trees on freely-drained ridges (some likely esker features). Ridges are generally the most exposed, however, and are often largely devoid of the exposed heath and *Empetrum* heath communities, which are usually found nearby. Large areas contain solifluction lobes, covered with low vegetation but sheltering low (<30 cm) *Betula nana* sub-shrubs in the inter-lobe depressions. In the lower parts of the landscape, snow accumulates in winter in deep beds. After the snow-melt, water stagnates as wetlands, or forms ephemeral streams that can disappear in summer. Such areas are mainly situated to the east of the IV. Smaller snow beds can be found on breaks of slope beneath exposed ridges. Shrub heath borders the forests, close to snow bed margins.

3.3.9 Dataset analysis and correlation tables

LAI was surveyed at the same plots as the C stocks. The lack of clear information provided by the semi-variograms of soils C stocks prevents a comparison between these semi-variograms and those which could have been derived from the LAI dataset. This limitation in the information acquired on the spatial pattern of LAI distribution compared to that of soil C stocks is partly compensated by the use of vegetation maps of the IV. They allow an estimation of the areas covered by the different vegetation types and of the associated C stocks (see 3.3.7, Fig. 3.3 and 3.10, and Table 3.4). Spadavecchia and co-authors (2008) made a detailed study of the geostatistical properties of LAI and NDVI in the Intensive Valley.

These geostatistical techniques are not used here, other methods of comparison being preferred which do not need to include the spatial position of the plots. These are, for example, scatterplots of soil and vegetation variables for the sampled plots (Fig. 3.7), comparison of C stocks and LAI maps (Fig. 3.10) and correlation analysis between vegetation and soil properties in Tables 3.5 and 3.6.

Most of the datasets in this study are not normally - distributed. Correlation analyses have therefore been conducted in R (R Development Core Team, 2006) by generating matrices of the Spearman rank correlation coefficients method. Categorical properties (for example vegetation classes) can not be included as the test would consider the categories' codes as numerical values. The function calculating the Spearman rank correlation coefficients indicates the p-value for each correlation in the same matrix.

3.4 Results

3.4.1 H_1 Leaf Area Index and vegetation categories

If each vegetation category defined corresponds to a distinct LAI range, then case studies can use either the LAI or the vegetation categories as substitute for each other, depending on which one is easier to measure. Some expected differences in the distribution of LAI emerge (Fig. 3.4 a); Exposed heath, with a substantial component of exposed rocks, presents low LAI values (median 0.28 m^2/m^2). Other low values are found in the sedge and wetlands with a high proportion of graminoids (median

0.23 m^2/m^2). The heath-sedge transition has higher values as the higher proportion of *B. nana* and *E. hermaphroditum* balances the wetland vegetation (median 0.50 m^2/m^2). The Shrub heath, with its extensive cover of *B. nana*, has the highest median (1.05 m^2/m^2). The *Empetrum* heath and Species rich heath categories are close to the Continuous birch forest and Birch copse categories (0.56, 0.55, 0.50, 0.48 m^2/m^2 respectively). Snow bed margins are found in the forest and the heath, usually sheltered by trees and compare with the Upper forest and Heath forest transition categories (medians 0.61 m^2/m^2, 0.68 m^2/m^2 and 0.66 m^2/m^2).

In Kevo (Fig. 3.4 b), the forest LAI range is narrower than for the mire border, which amalgamates several vegetation covers. Mire border LAI is closer to 0.25 m^2/m^2, indicating a smaller leaf area than the forest understorey (median close to 0.5 m^2/m^2). Canopy LAI (Fig. 3.4 a and b) is only measured for plots over-topped by trees and is not defined for some of Abisko’s categories (for example Shrub heath and Exposed heath) and the Mire border in Kevo. Some low values are found in Abisko where lone trees are above a plot of *Empetrum* heath or Heath-sedge transition (0.01 m^2/m^2). Values for Continuous forest canopy LAI are quite low (0.24 m^2/m^2 and 0.28 m^2/m^2).

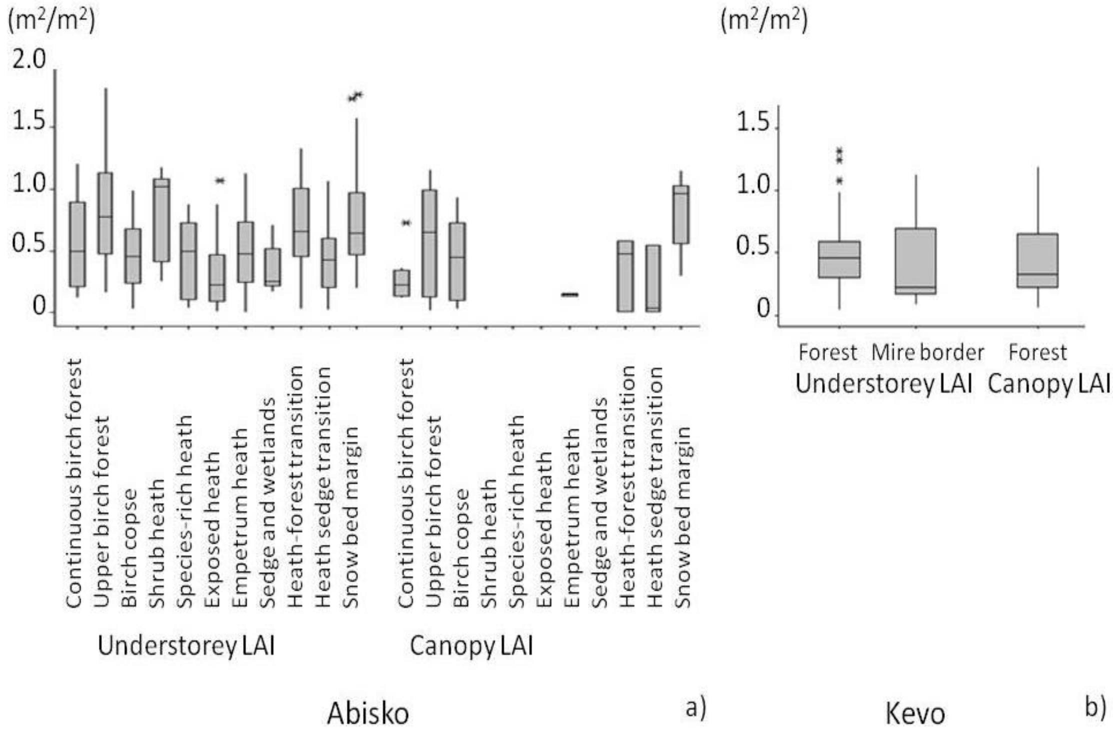


Figure 3.4: Box and whisker plots of the understorey and canopy LAI for Abisko (a) and Kevo (b); with bars for the first quartile (lower), median and third quartile (upper), lower whisker for the minimum and upper whisker for the maximum

The overall distribution for the NDVI in Abisko is skewed towards higher values (Fig. 3.5 a). Kevo's NDVI distribution is less skewed but appears bimodal (Fig. 3.5 d). Understorey LAI distributions for Abisko and Kevo are skewed towards lower values (Fig. 3.5 b and e). Abisko's canopy LAI values have a more uniform distribution than Kevo's (Fig. 3.5 c and f).

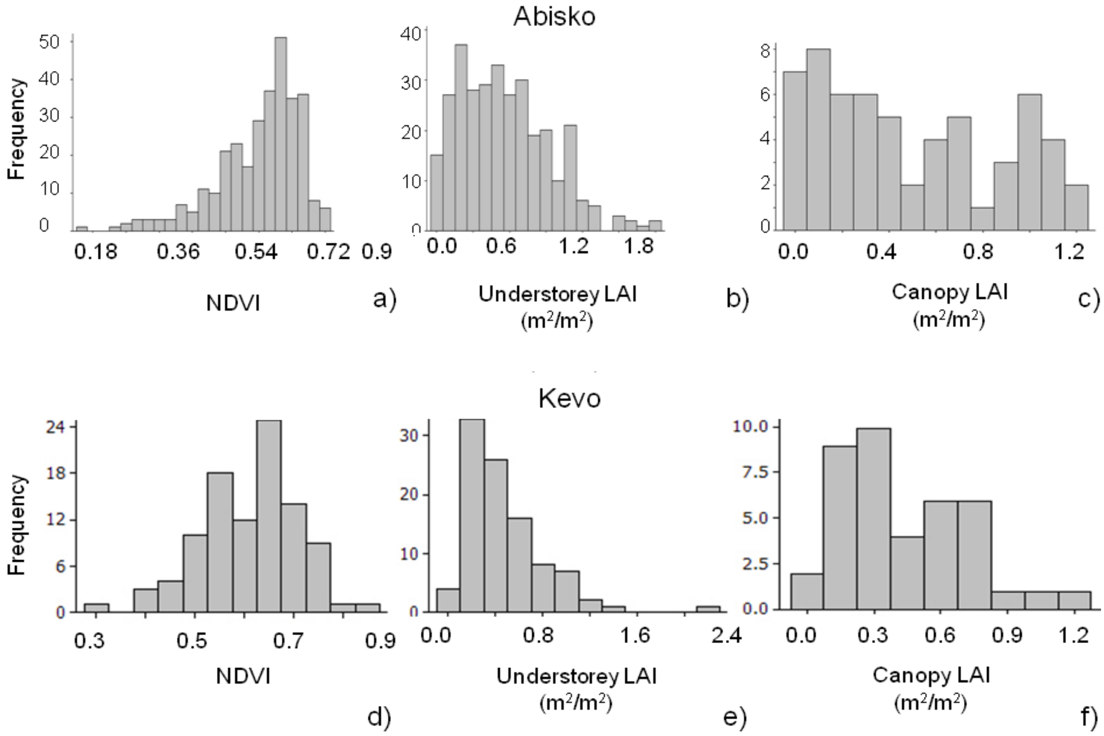


Figure 3.5: Histograms of the NDVI, understorey LAI (m^2/m^2) and canopy LAI (m^2/m^2) for Abisko (a, b, c) and Kevo (d, e, f)

The Kruskall-Wallis tests on the understorey LAI and NDVI values show the existence of several populations (p value < 0.001). However, Mann-Whitney tests on the medians of the vegetation groups made with the NDVI and LAI can not distinguish between all the vegetation categories used, for instance Birch copse and Continuous forests are not separated, whilst the tundra categories show significant differences, and tundra groups and forest groups can be distinguished. The transition areas and snow beds are too close to forest values to be separated. Overall, the categories defined do not allow the separation of vegetation cover into different classes of LAI values: this goes against results in Spadavecchia and colleagues (2008), who found tighter relationships between LAI and vegetation types. However, Spadavecchia and co-authors (2008) do mention more heterogeneity under 10 m, with different plant functional types on the same plot. The test for areas with trees and areas with no trees shows that they are different and poses the distinction tree/no tree as an alternative to the categories used.

3.4.2 H_2 Relation between the Leaf Area Index and the soil C stocks

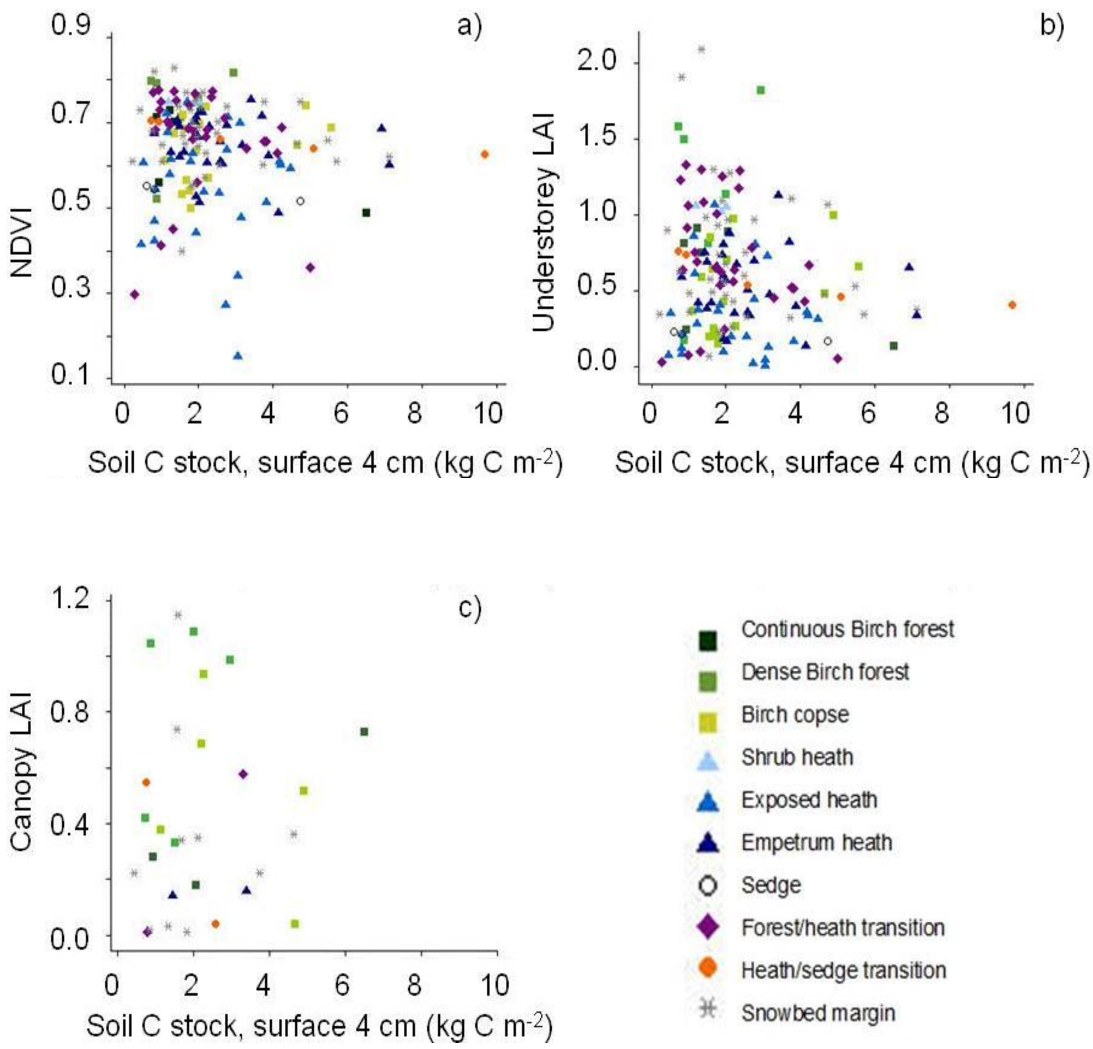


Figure 3.6: Scatterplots of the surface 4 cm soil C stocks of all Abisko plots versus NDVI (a), understorey LAI (b) and canopy LAI (c) per vegetation category

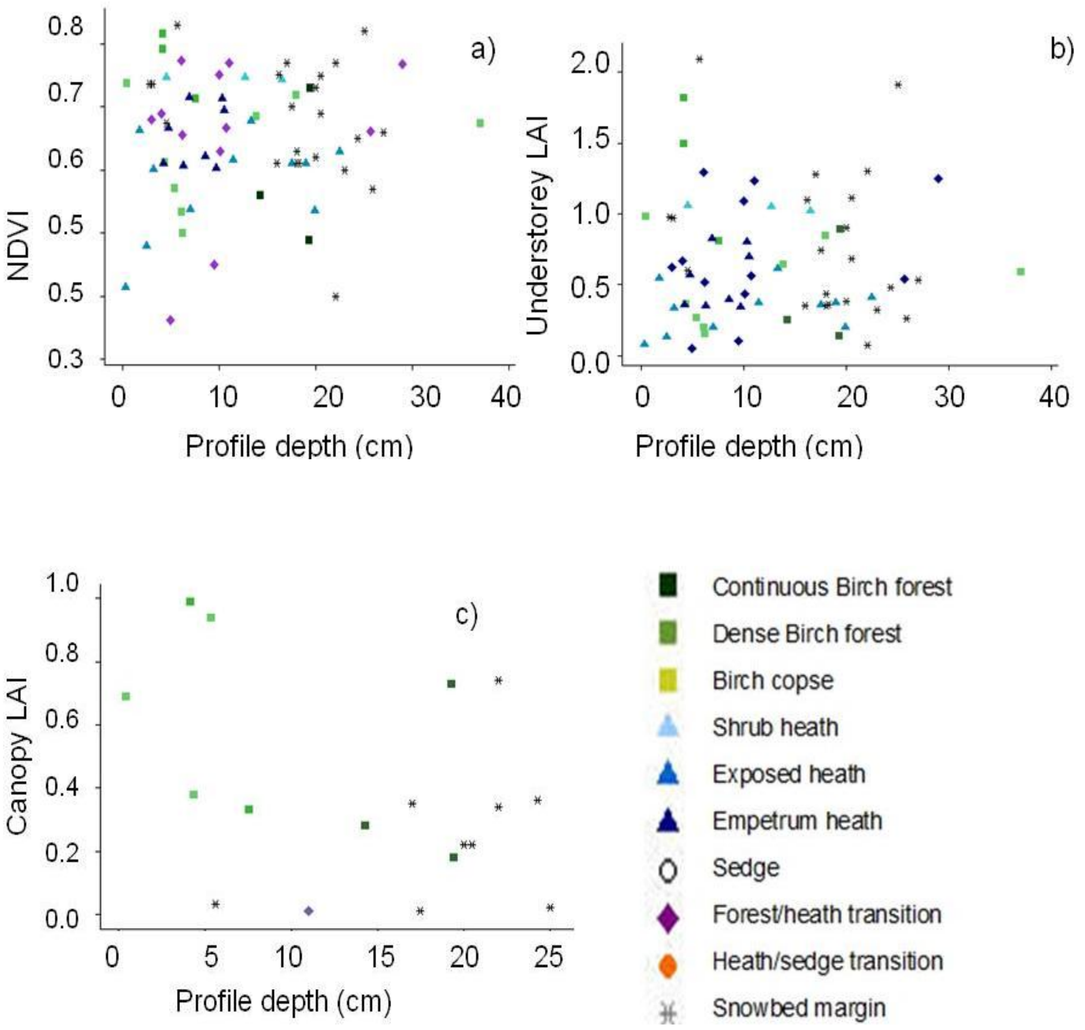


Figure 3.7: Scatterplots of the profile depths (cm) of all Abisko plots versus NDVI (a), understorey LAI (b) and canopy LAI (c) per vegetation category

LAI is not a categorical variable and therefore the problem of defining boundaries between categories is avoided. The surface 4 cm C stocks values and profile depths for all Abisko plots have been plotted against NDVI, understorey and canopy LAI (Fig. 3.6 and 3.7). Plots of total C stocks are not presented here, as surface 4 cm data are available for more plots; the NDVI and LAI plots against total C stocks are similar to those against surface 4 cm C stocks.

The overall clouds of NDVI/surface C stock values and profile depth/NDVI do not highlight any linear relationship or any exponential one (Fig. 3.6 a, 3.7 a). The results seem contained in an envelope, as are the understorey LAI results; however, the spread of data is too large to be useful. The LAI values for understorey (Fig.3.6 b, 3.7 b) and canopy LAI (Fig. 3.6 c, 3.7 c) do not give any clearer indication of a defined relation between these variables. Vegetation categories do not correspond clearly to tight groups of LAI values as was shown in Fig. 3.4. In Kevo, the understorey LAI against surface 4 cm C stock and NDVI against surface 4 cm C stock fit envelope shapes as well (Kevo data not shown, as there were not enough data per category). The forest plots are the most represented and are spread from low LAI and low soil C stock values to low stock/average LAI to high stocks/ low LAI. The mire border values also show high variability, overlapping with the forest's values. Canopy LAI vs C stocks is even more variable in Kevo than Abisko.

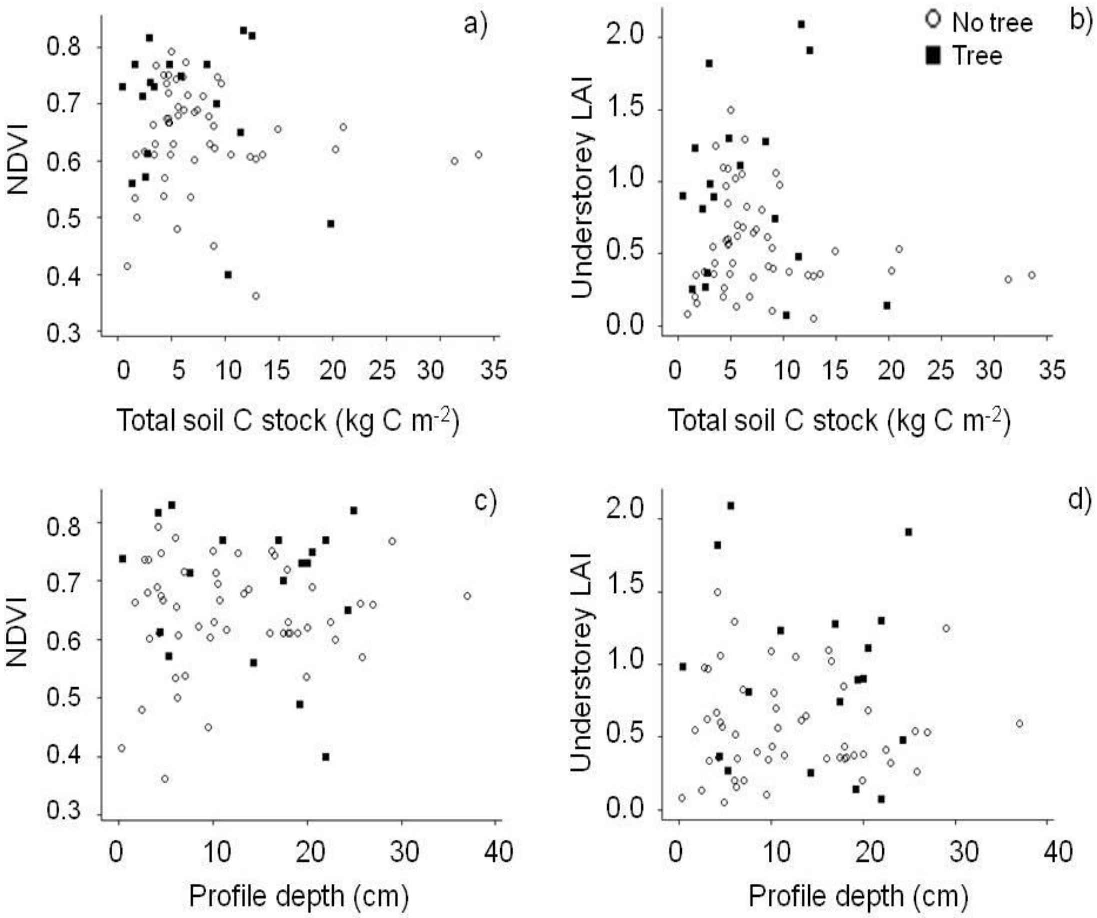


Figure 3.8: Abisko scatterplots of total soil C stocks (g C m^{-2}) and the profile depths (cm) versus NDVI (a, c), understorey LAI (b, d) for plots with trees or no trees

The total C stocks and soil depths dataset contains more data coming from the Intensive Valley than from the Abisko Transect. These data are plotted with a distinction between plots with trees or treeless, against NDVI and against understorey LAI. There is a difference between the results for total soil C stocks and those against profile depths (Fig. 3.8). The presence of trees is linked to lower C stocks in a large range of NDVI values, but no clear relation can be found with the profile depth.

In Kevo, both the C stocks and the profile depths are smaller when trees are present, i.e. in the Kevo birch forest category compared with the Kevo mire border

(Fig. 3.9). The number of sampled plots is smaller than in Abisko and the distinction between the two vegetation covers is sharper, which could explain the greater contrast between them.

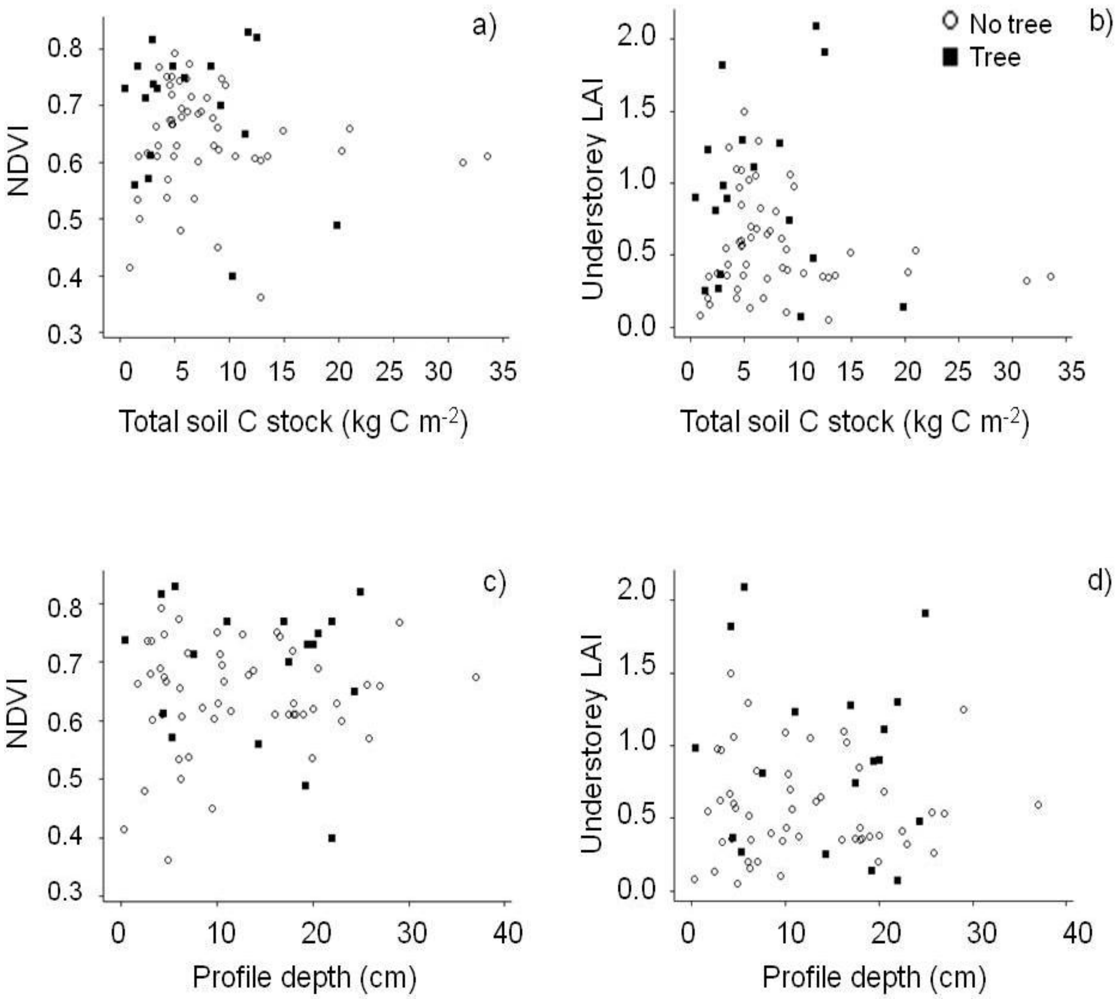
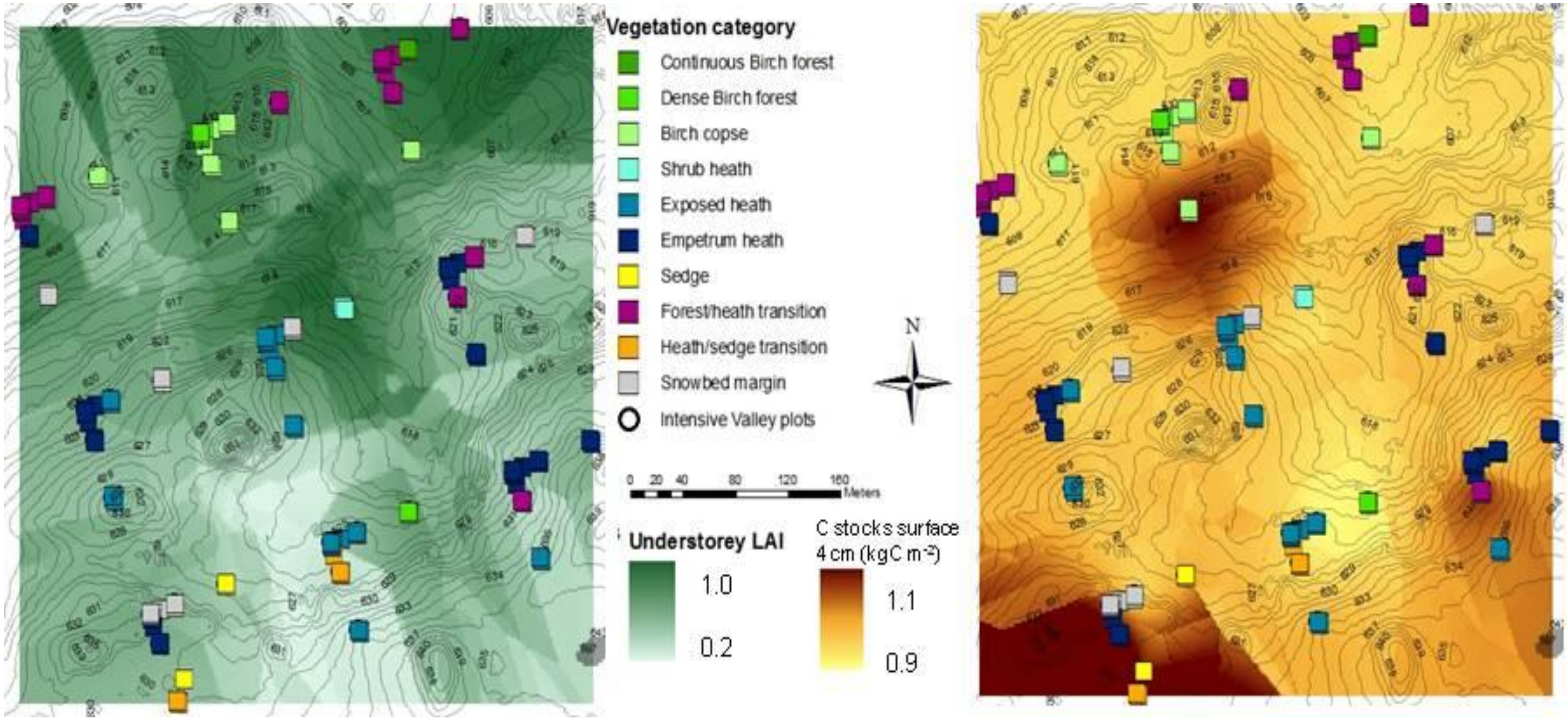


Figure 3.9: Kevo scatterplots of the total soil C stock (g C m^{-2}) and profile depth (cm) versus NDVI (a, c), understorey LAI (b, d) for plots with trees or no trees

At the Abisko IV, the kriged maps for understorey LAI and surface 4 cm C stocks show that the spatial distributions of these properties are dissimilar too (Fig. 3.10 a and b). Low values for understorey LAI correspond to the wetland areas in the south, which contain moderate C stock values (Fig. 3.3 and Table 3.4). High values of C stocks correspond to medium values of LAI in the south-western corner but to higher values just north of the map centre. High values of LAI correspond to medium values of C stocks everywhere else (Fig. 3.10 a and b). The only similarities are due to mapping artefacts as the same grid is used and the data coverage of the map is uneven.

The Abisko Transect follows the main slope between the birch forest (around 560 m high) and the tundra heath (around 760 m of elevation at the end of the transect) and covers a larger distance than the IV. Relations between LAI and soil properties that were not highlighted in the IV could appear if considered along a larger topographical gradient. Due to the length of the transect, obtaining C stocks data for all the plots was not possible. However, the soil profiles and horizon depths are available.

Profile depths and horizon depths are irregular along the transect (Fig. 3.11). Some plots are situated on rocks or in pools of water and there are no soil profiles on these. The changes in profile depths do not mirror the changes in LAI (Fig. 3.11). Neither variations of profile depths nor those of LAI values show a clear trend from forest to tundra (Fig. 3.11). Trees are found quite far into the transect (2400 m into a 2900 m distance), with high canopy LAI values similar to those found in the first part at the transect (upper forest) but not in the continuous forest. Understorey LAI follows a multimodal pattern. Low values are found almost every 600-800 m. Peaks reach different values with a maximum at 1700 m into the transect, close to its centre.



a) b)

Figure 3.10: Kriged maps of the understorey LAI (a) and surface 4 cm C stocks (kg C m^{-2}) (b)

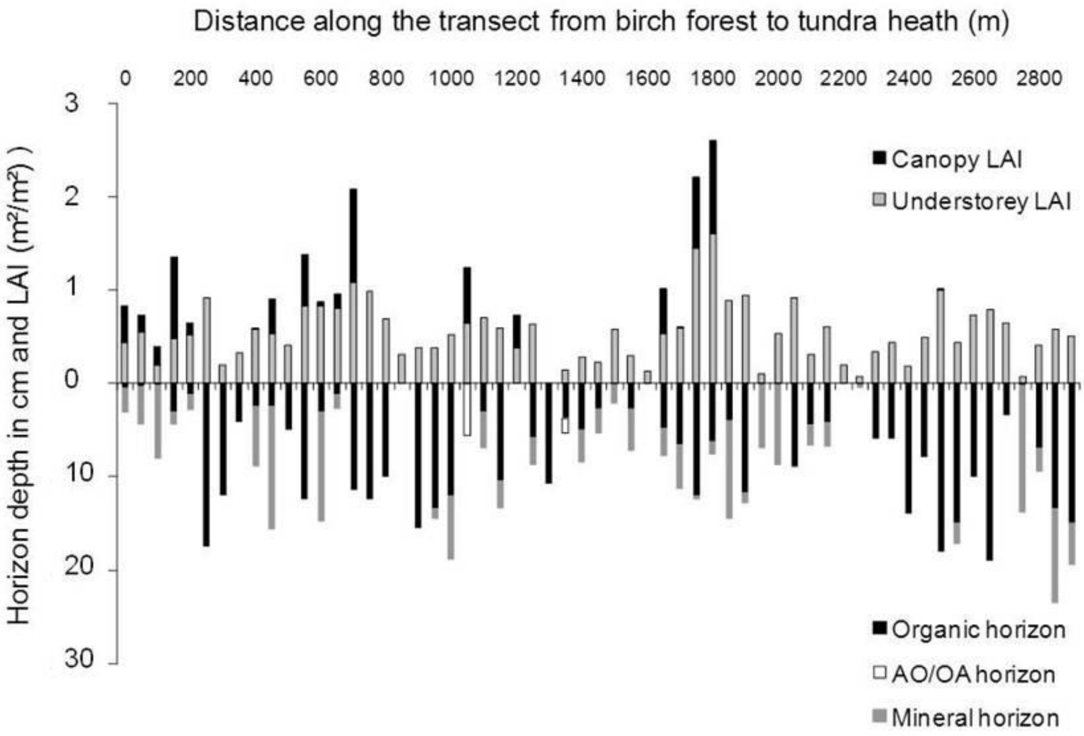


Figure 3.11: Histogram of the soil profile depths (cm) and LAI (m^2/m^2) along the Abisko Transect

3.4.3 H_3 Estimates of soil C stocks and vegetation categories

The vegetation categories used for Abisko have been defined from the field survey and represent the land cover of the area. However using so many categories (eleven) can be a hindrance for modelling the relationships between soil properties and vegetation categories, as comparison with other areas or field sites is made more complicated. Two alternative ways of grouping these categories have been tested (Table 3.4). The first was to aggregate the heath categories together and to do the same for the forest and copse categories, as well as the wetlands and their margins.

The heath/forest transition and the snow bed margins have been left separate, as they cannot be linked to either the tundra or the forest exclusively. Bare areas also stand apart as no soil develops there. The second way to group vegetation category is using a simple distinction between areas with trees or no trees (Table 3.4).

The vegetation categories used for the land cover map contrast in terms of area covered (from less than 1% for isolated trees to 15% for *Empetrum* heath), and the average area covered is 6.6% of the IV (Table 3.4). This echoes the fragmented nature of the IV landscape cover (Fig. 3.3). Soil profile characteristics differ as well, as seen here with the soil profile depths and C stocks. Variability in these soil properties within each of the vegetation categories can be quite high; hence, the range has to be considered together with the mean. There are only a small number of samples in some categories. These factors explain high standard deviations for the means (Table 3.4).

The calculated C stocks, both as mass (t C) and C stock per area (g C m^{-2}), depend on the categories defined. The categories used determine which plots/ field data will be grouped together or left out, and this choice influences the value of the average stock per category. When using the maximum number of vegetation categories to represent the Abisko IV vegetation diversity, surface 4 cm C stocks span a large range (Table 3.4). Surface 4 cm C stocks are used, as they are available for all plots and so permit a comparison of all the vegetation categories. The mean C stock in the Continuous birch forest category of 1.1 kg C m^{-2} contrasts with the Heath-sedge transition C stock of 6.3 kg C m^{-2}. The heath/forest and heath/sedge transition areas' soil C stocks per area are not intermediate between the main vegetation categories' values (heath, forest, sedge). Some forest values are higher than heath ones (for example the Upper forest; 3.1 kg C m^{-2}, compared to the Exposed heath; 1.7 kg C m^{-2}) (Table 3.4). Grouping several categories leads to similar surface 4 cm C stock values, between 2.0 kg C m^{-2} and 2.5 kg C m^{-2}. The only exception is the Sedge and wetlands category with a mean of 4.0 kg C m^{-2}. The largest aggregated groups (tree or no tree) have similar mean C densities, 2.3 kg C m^{-2} for the treeless areas and 2.4 kg C m^{-2} for the areas with trees. In the IV, treeless areas occupy about 75% of the surface and yield higher stocks of soil C.

Table 3.4: Vegetation categories derived from the land cover map with the number of profiles (n) and percentage of profiles fully sampled (% full) indicated for each category, as well as the area covered in the IV (and % of the total area), the profiles depths and C stocks in kg C m^{-2} for the whole profiles. For the surface 4 cm C stocks, values are given for different vegetation category groupings (all categories on the left, main vegetation types in the middle and with trees or without trees on the right).

Vegetation category	N^{o} of profiles/ % fully sampled	Area covered/ % of total area (m^2)	Mean ± std. dev. min.- max. profile depth (cm)		Mean± std. dev min.-max. whole depth C stocks (kg C m^{-2})		Mean surface 4cm C stocks, min.- max. in sampled area (t C) (kg C m^{-2}): All categories				Main vegetation types		Presence of trees or not	
Continuous forest	3 / 0	22 742/ 6.5	10.1±2.1	8.7-12.5	1.1±0.2	0.9-1.3	25.8	19.9-30.1	1.1±0.2	0.9-1.3	179.2 47.3-860.3	2.3 0.7-12.7	197.0 22.0-1053	2.4 0.3-12.8
Upper forest	7 / 50	31 360/ 9.0	4.8±2.1	2.0-8.0	4.4±5.8	0.7-17.1	96.8	22.0-401.0	3.1±4.3	0.7-12.8				
Copse	16 / 40	11 600/ 3.3	11.7±10.1	0.4-37.0	4.3±4.0	1.5-18.1	32.1	14.4-24.0	2.8±2.0	1.1-8.4				
Isolated trees	0	1 582 / 0.4	--		--		--		--					
Heath/forest	32 / 33	15 148/ 4.35	9.4±8.0	0.0-29.0	8.5±15.0	0.3-65.6	38.6	4.0-118.2	2.5±1.9	0.3-7.8	38.6 4.04-118.2	2.5±1.9 0.3-7.8		
Snowbed margin	18 / 50	17 023/ 5.0	5.7±4.4	0.0-16.2	2.9±2.2	0.7-9.6	34.8	12.5-80.7	2.0±0.9	0.7-4.7	34.8 12.5-80.7	2.0±0.9 0.7-4.7	615.5 3.6-4 954.3	2.3 0.01-18.8
Shrub heath	3 / 100	11 990/ 3.4	11.2±6.1	4.5-16.5	6.9±2.0	5.4-9.2	20.2	14.3-24.0	1.7±0.4	1.2-2.0	540.7 87.1-1428.4	2.5 0.1-7.2		
Exposed heath	29 / 33	86 363/ 25	7.0±6.7	0.0-21.5	3.3±2.6	0.5-11.2	203.5	38.0-603.0	2.3±1.5	0.4-7.0				
Empetrum heath	32 / 33	51 649/ 15	9.9±7.8	0.8-31.5	5.7±5.0	0.8-19.5	164.0	41.9-373.2	3.2±2.0	0.8-7.2				
Sedge and wetlands	6 / 50	25 614/ 7.4	15.6±9.5	5.0-28.0	5.9±5.9	0.6-12.2	52.5	15.6-121.2	2.0±2.3	0.6-4.7	215.7 8.3-908.5	4.0 0.2-18.8		
Heath/sedge	8 / 0	21 319/ 6.1	8.6±6.0	0.0-16.7	11.1±13.3	0.7-40.2	134.1	3.7-401.7	6.3±6.7	0.2-18.8				
Forest/sedge	0	1 282/ 0.4	--		--		--		--					
Bare areas	3/0	47700/ 13.7	10		0.06	0.03-0.1	1.1	0.6-2.2	0.02	0.01-0.05	1.1 0.6-2.2	0.02 0.01-0.05		
Total for all the categories	154	0.35 km^2	--		--		803.6 185.6-2 252.5		--		812.5 138.9-3 053.6	--	812.5 25.6-6008.3	--
Average for all the categories	15.4 (39)	23 024/ 6.6	8.6±3.0	1.9-23.1	4.2	0.8-15.2	104.3	22.5-294.8	2.3 0.5-6.6		229.6 39.9-774.6	2.3 0.6-12.0	515.6 8.0-4023.4	2.3 0.07-17.4

The AT has been only sampled for C data at five locations and the resulting soil profiles are presented in Chapter 2 (Fig. 2.3). The surface 4 cm soil C stocks are 2.0 kg C m^{-2} for the birch forest, 1.3 kg C m^{-2} in the transition area and 1.8 kg C m^{-2} in the tundra heath. The snow beds yield stocks of 2.2 kg C m^{-2} in the tundra and 1.7 kg C m^{-2} in the forest. The high values for the forest, compared to the other plots' values, are in the range found in the IV. However, the result is skewed by the presence of an outlier in the surface 4 cm C content distribution. The tundra heath value is consistent with the IV's shrub heath value. The transition area result is lower than the IV's result. The snow bed values are either side of the IV's mean value, as they are encompassing both forest and tundra snow bed margins.

Kevo's soil C distribution has been considered in Chapter 2 (Fig. 2.4). The two vegetation categories are the mire border and the birch forest. Mire border plots, especially the plots closer to the mire, present deep organic profiles (60 – 80 cm) and the cumulative soil C stock per profile can reach just less than 40 kg C m^{-2}. Forest profiles are shallower (20 cm maximum) and present only a thin organic layer over differentiated mineral horizons. The cumulative stock per profile does not exceed 7.5 kg C m^{-2}. The average 4 cm surface stocks are, respectively, 1.7 kg C m^{-2} for the mire border and 1.2 kg C m^{-2} for the birch forest. This value is lower than Abisko's birch forest data.

3.4.4 H_4 Controls on the C stock distribution

The soil and vegetation variables have been paired and each relation has been tested with a Spearman correlation test in R (R development team, 2006). In Tables 3.5 and 3.6, only the significant relationships between the different soil and vegetation variables ($p < 0.05$) are presented. The other results did not show any relationship between the variables paired for the tests. For Abisko (Table 3.5), the Spearman correlation coefficients for most relations are less than 0.5 (ignoring sign), showing weak correlations. The only coefficients greater than 0.5 (again, ignoring sign) are mostly self-evident: the profile depth and organic horizon depth, the surface 4 cm soil bulk density against the surface 4 cm C content, and the surface 4 cm C stock against the surface 4 cm bulk density (used in its calculation). Some relationships between soil variables, such as the surface C content against organic horizon depth, are weaker than expected, possibly due to too many environmental factors influencing the soil development.

The coefficients indicate higher correlations for the plots with trees (in the left part of the parenthesis for each variable pair, only presented if there is a significant relationship). Plots with no trees only have a significant correlation coefficient for the organic horizon depth against profile depths, which is a logical relation as most samples come from organic horizons (as seen for AT, Fig. 3.11). This absence of significant correlations between variables for the plots with no trees can bring the correlation significance for the overall population down, compared to the relatively higher correlation coefficients observed in the plots with trees. Overall, the surface soil properties have only weak or indirect relations with the vegetation and topographic parameters.

Table 3.5: Spearman correlation coefficients for pairs of variables (lower left half of the table) for p-values < 0.05 (p-values presented in the upper right half of the table) for the Abisko IV plots, for all profiles (profiles with trees/ profiles with no trees); italicised numbers indicate a p-value between 0.01 and 0.05

	NDVI/ Understorey LAI (m^2/m^2)	Organic horizon depth (cm)	Mineral horizon (cm)	Profile depth (cm)	Compound Topographic Index	Surface C content (%)	Surface bulk density (g cm^{-3})	Surface C/N ratio	Surface 4 cm C stock (kg C m^{-2})
NDVI/Understorey LAI (m^2/m^2)		0.008 (0.005/)		*0.010* (0.008/)	(*0.016*/)	0.002 (0.000/)	0.000 (0.000/)		
Organic horizon depth (cm)	0.229 (0.262/)			0.000 (0.000/0.001)	0.001 (0.001/)	0.000 (0.000/)	0.000 (0.000/)		
Mineral horizon (cm)				0.000 (0.000/)	0.002 (0.007/)				
Profile depth (cm)	*0.225* (0.247/)	0.848 (0.860/0.726)	0.455 (0.463/)			0.000 (0.000/)	0.002 (0.002/)		
Compound Topographic Index	(*0.224*/)	0.296 (0.305/)	-0.272 (-0.250/)						
Surface C content (%)	0.268 (0.324/)	0.459 (0.476/)		0.385 (0.420/)			0.000 (0.000/)	0.000 (0.000/)	
Surface bulk density (g cm^{-3})	-0.322 (-0.386/)	-0.340 (-0.334/)		-0.274 (-0.283/)		-0.653 (-0.688/)		*0.015* (0.004/)	0.000 (0.000/)
Surface C/N ratio						0.427 (0.439/)	-0.212 (-0.265/)		
Surface 4 cm C stock (kg C m^{-2})							0.653 (0.669/)		

Table 3.6: Spearman correlation coefficients for pairs of variables (lower left half of the table) for p-values < 0.05 (p-values presented in the upper right half of the table) for Kevo, for all profiles (profiles with trees/ profiles with no trees); italicised numbers indicate a p-value between 0.01 and 0.05

	NDVI	Understorey LAI (m^2/m^2)	Organic horizon depth (cm)	Mineral horizon (cm)	Profile depth (cm)	Surface C content (%)	Surface bulk density (g cm^{-3})	Surface C/N ratio
NDVI		0.000 (0.000/0.000)			(/0.001)			
Understorey LAI (m^2/m^2)	0.999 (0.998/0.999)				(/0.001)			
Organic horizon depth (cm)						0.004(*0.045/*)	0.002(*0.037/*)	
Mineral horizon (cm)					0.035 *(/)*			
Profile depth (cm)	(/0.783)	(/0.793)		*0.287(/)*				
Surface C content (%)			0.386 (*0.319/*)				0.000 (0.000/0.000)	*0.034* (/0.026)
Surface bulk density (g cm^{-3})			-0.421 (-*0.331/*)			-0.795 (-0.800/-0.846)		(/0.034)
Surface C/N ratio						*0.289(/0.591)*	(/-0.569)	

In Table 3.6, only the significant relationships ($p < 0.05$) for the Kevo parameters are presented. Surface 4 cm soil C stock did not show significant relation with another variable and so is not included in the table. The higher correlations are between understorey LAI and NDVI, and between the surface 4 cm bulk density and surface 4 cm C content. Overall, the surface soil properties have only weak relations with the vegetation parameters.

Some high coefficients are only significant for the mire border plots (NDVI and profile depth, understorey LAI and profile depth, surface bulk density and surface C/N ratio). Relations between surface C content and surface C/N ratio are also higher for the mire border plot compared to the overall dataset. As in Abisko, vegetation variables and soil variables do not show strong relations.

These results are for the surface 4 cm, and stronger correlations appear for the soil variables considered for all the samples (see Chapter 2). In both sites, the vegetation variables show only weak correlations with the soil surface properties and surface soil C stocks.

3.4.5 Heterogeneity of the soil profiles

A detailed micromorphological description is out of the scope of this thesis. Nevertheless, a short description of the slides already brings out interesting facts, and highlights the contrasts between soil profiles under different vegetation types. These profiles have been taken along the Abisko Transect, from Birch forest to tundra heath. They all represent soils taken under differing vegetation types: birch forest, tundra heath, an area of transition between these two extended vegetation covers. Two types of snow beds, respectively in birch forest and tundra heath areas, have been sampled to provide an insight into the composition of the soils in these sheltered depressions in the landscape. For each vegetation type, three profiles have been taken where possible, at 1 m and 2 m around a central profile. The slides for the birch forest (Fig. 3.12), transition area between birch forest and tundra heath (Fig. 3.13), tundra heath (Fig. 3.14), tundra snow bed (Fig. 3.15) and forest snow bed (Fig. 3.16) have revealed a great heterogeneity in soil composition over a few metres. The transition area between birch forest and tundra heath soils shows an interesting succession between a mini-podzol close to the birch copse (similar to the birch forest profiles (Fig. 3.12)), a profile slightly deeper and richer in organic matter at the central plot, and a deep organic profile under the shrub tundra at plot 2 metres (more similar to the tundra heath profiles (Fig. 3.14)). Therefore, the soils characteristics are closer to the ones of soils situated hundred of metres away under similar vegetation types than to the ones a few metres away. The snow beds plots are situated close to the main vegetation types of the area (forest snow bed (Fig. 3.16) close to the Birch forest (Fig. 3.12); tundra snow bed close (Fig. 3.15) to the tundra heath (Fig. 3.14)). However they do not present the same horizons as neighbouring soils; they contain mixed organo-mineral horizons instead of well-defined organic and mineral horizons. Their particular thermal conditions, with greater vegetation cover in winter, seem to favour a higher activity than neighbouring soils. Transition area and snow beds profiles highlight the heterogeneity of the soil profiles and the difficulties in designing a representative profile for each of these soil types.

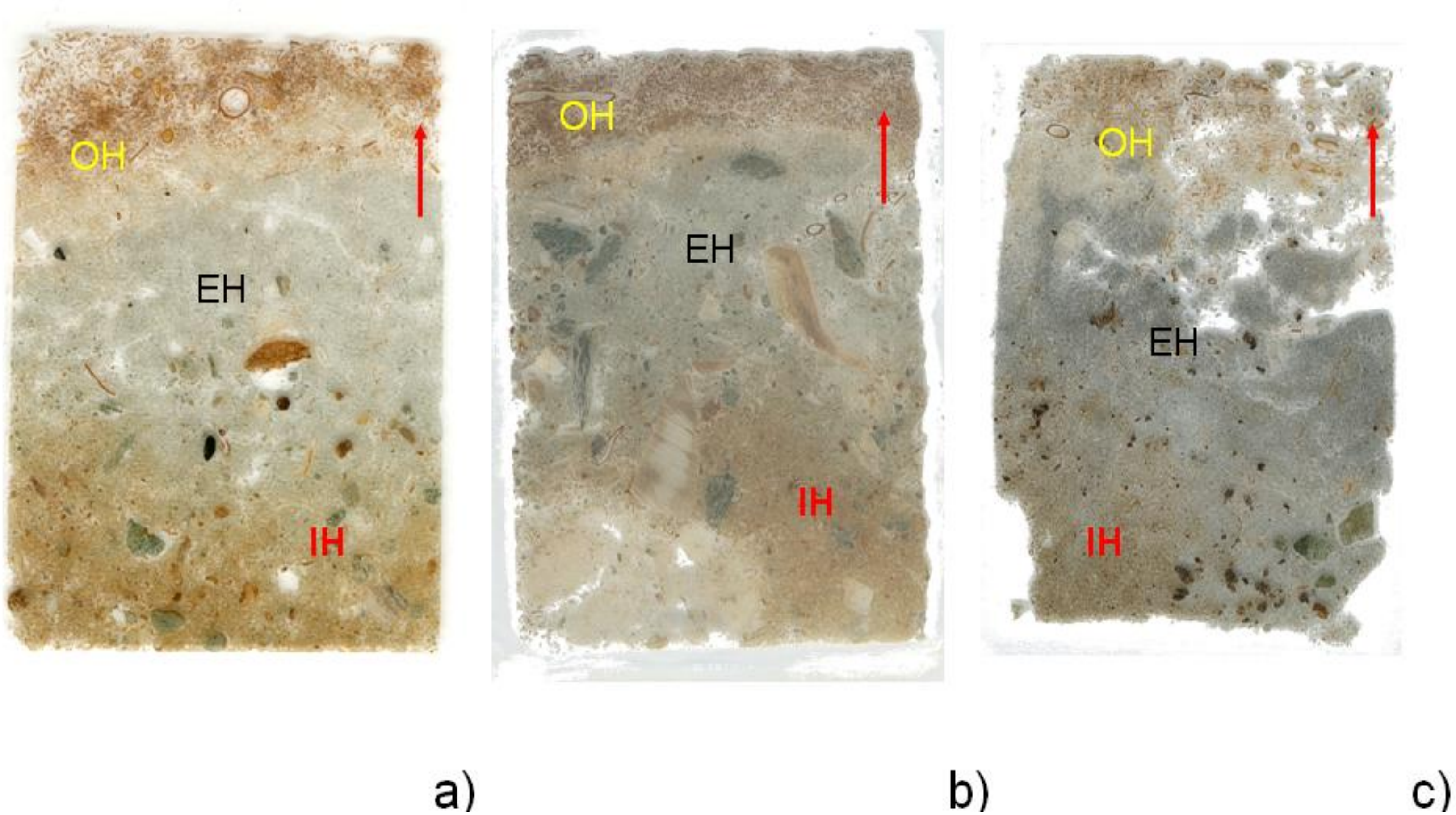


Figure 3.12: Micromorphology slides of the birch forest in the Abisko transect (plot 1): 1 m (a), central (0) (b) and 2 m profiles (c); OH is an organic horizon, EH is an eluvial horizon, IH is an illuvial horizon.

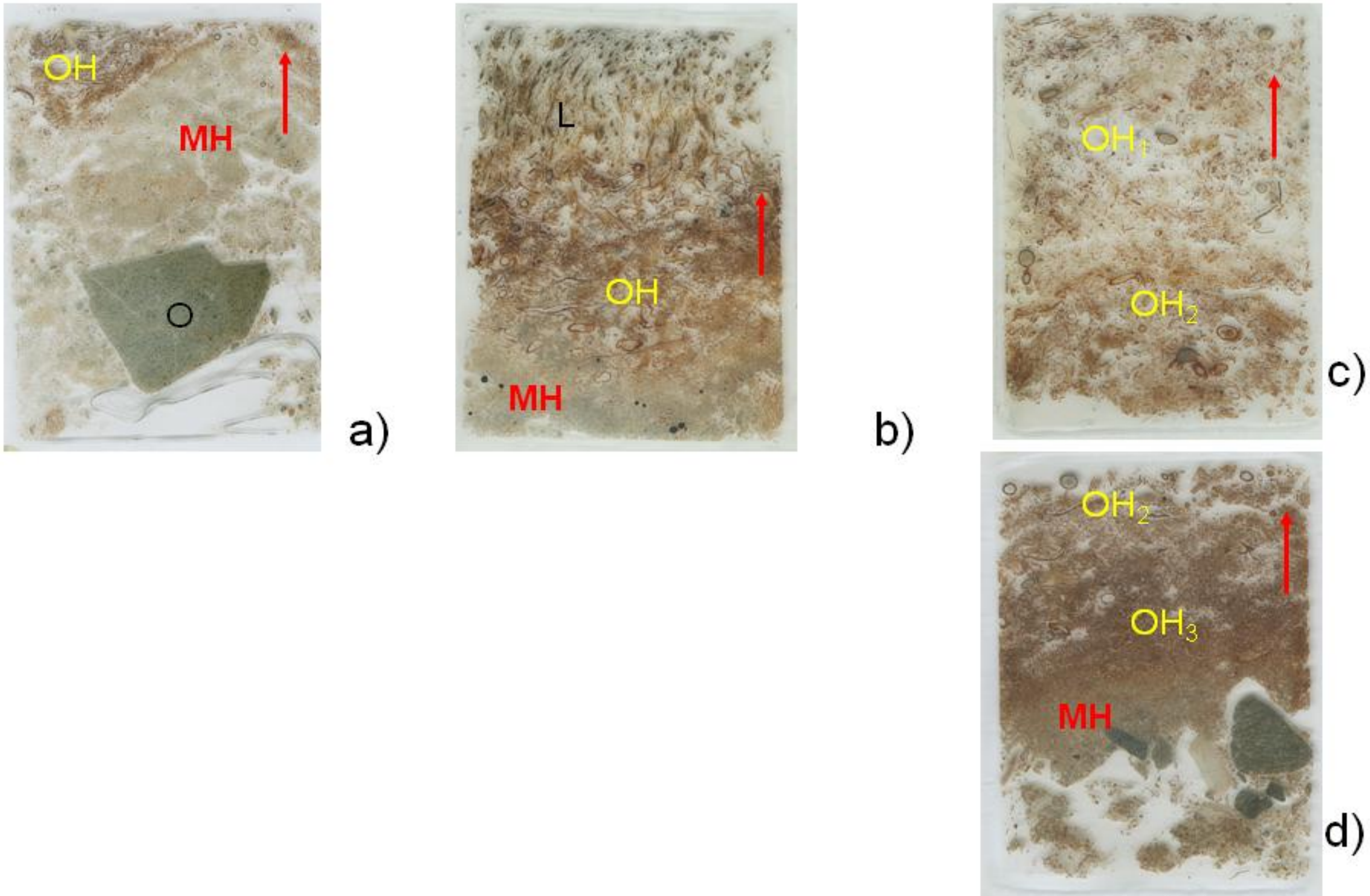


Figure 3.13: Micromorphology slides of the transition area between tundra heath and birch forest in the middle of the Abisko transect (plot 35): 1m (a), central (0) (b) and 2 m (upper 7.5 cm (c) and lower 7.5 cm (d) profiles); L is litter, OH, OH_1, OH_2 and OH_3 are organic horizons, MH is a mineral horizon, o is an olivine mineral.

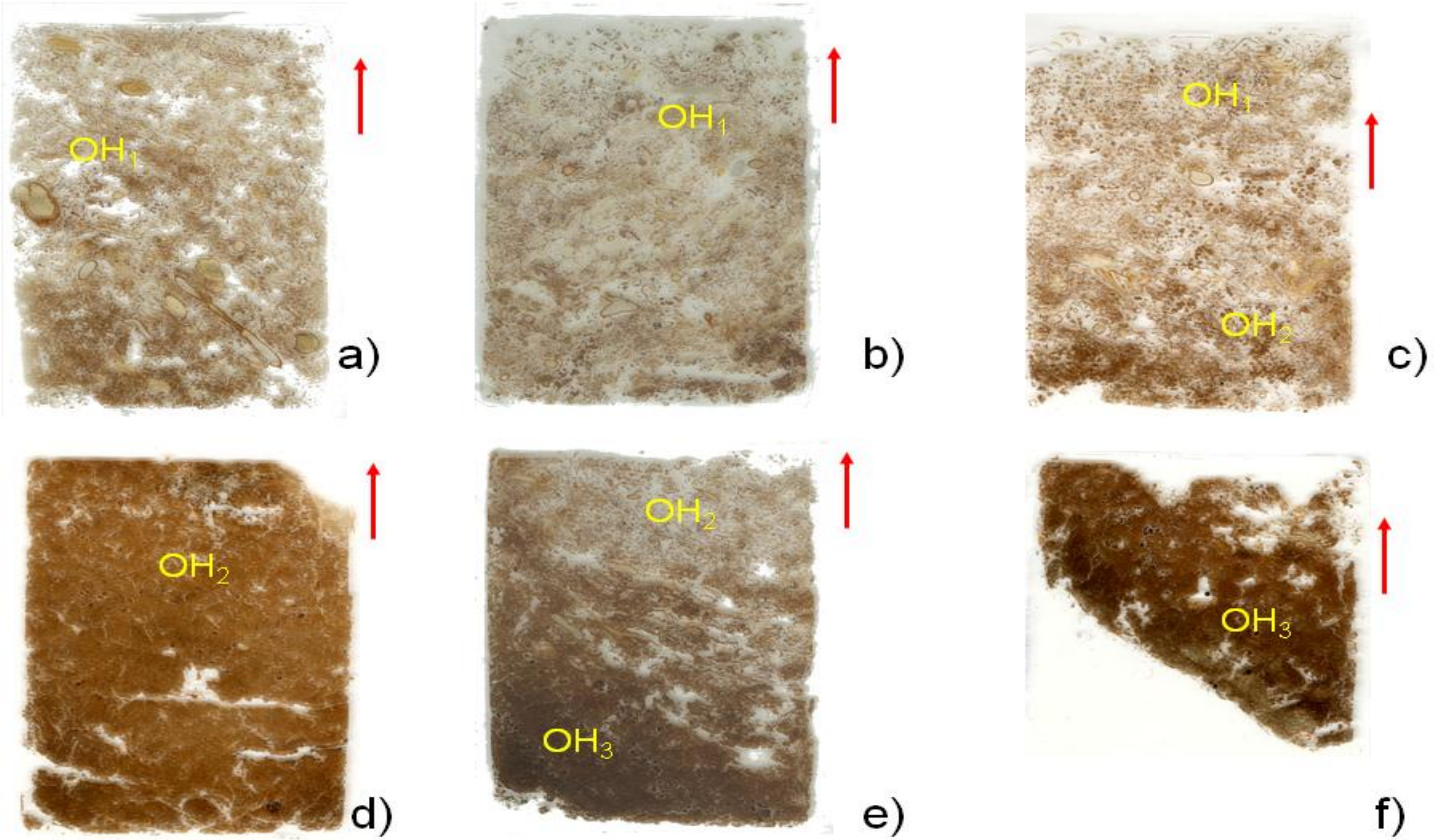


Figure 3.14: Micromorphology slides of the tundra heath in the Abisko transect at the STEPPS area: 1m (upper 7.5cm (a), lower 7.5cm (d)) , central (0) (upper 7.5cm (b), lower 7.5cm (e)) and 2 m profiles (upper 7.5cm (c), lower 7.5cm (f)); OH, OH_1, OH_2 and OH_3 are organic horizons.

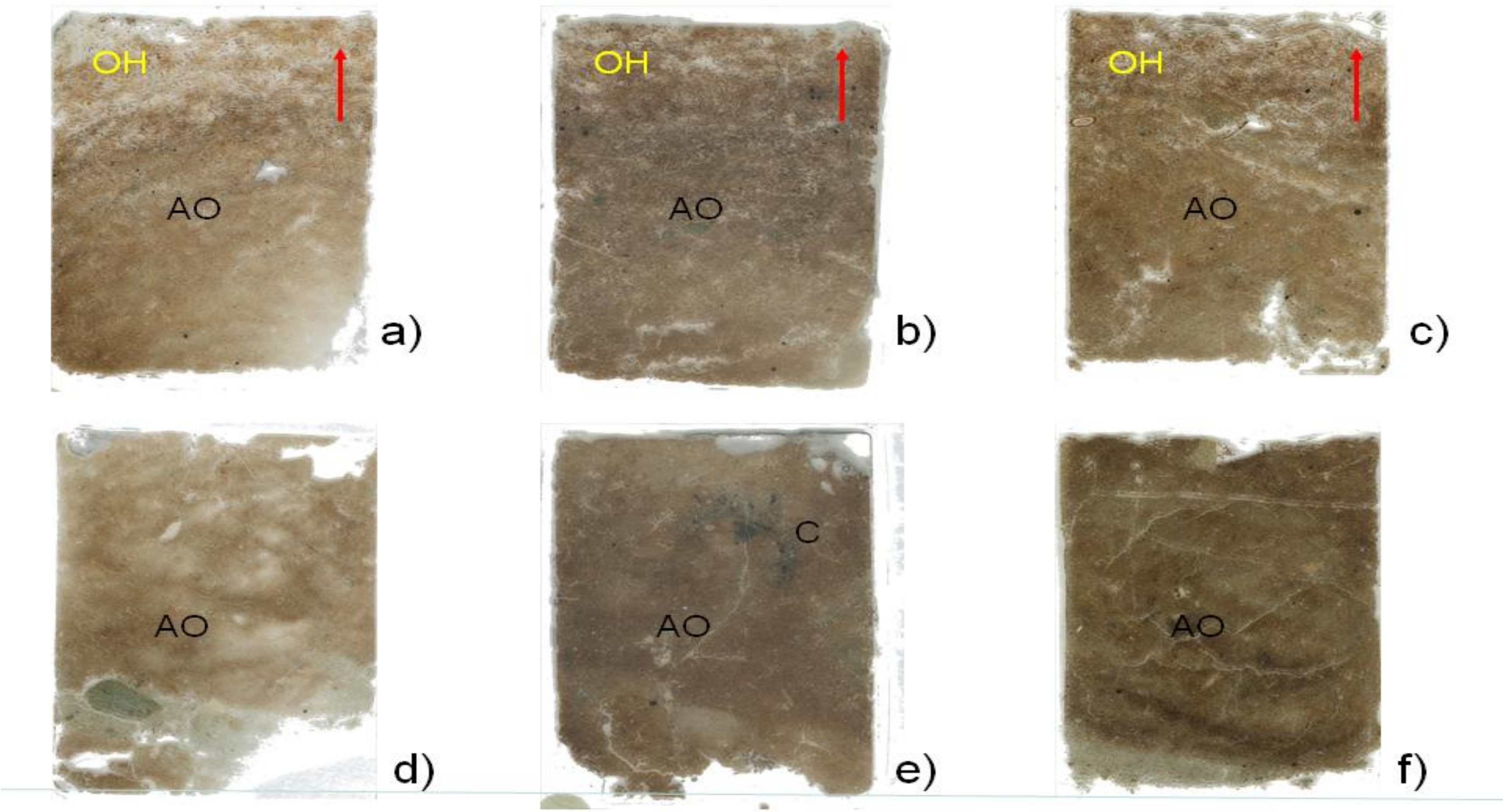


Figure 3.15: Micromorphology slides of the tundra snow bed in the Abisko transect (plot 54): 1m (upper 7.5cm (a), lower 7.5cm (d)) , central (0) (upper 7.5cm (b), lower 7.5cm (e)) and 2 m profiles (upper 7.5cm (c), lower 7.5cm (f)); OH is an organic horizon, AO is a mixed organo-mineral horizon, C is a piece of charcoal.

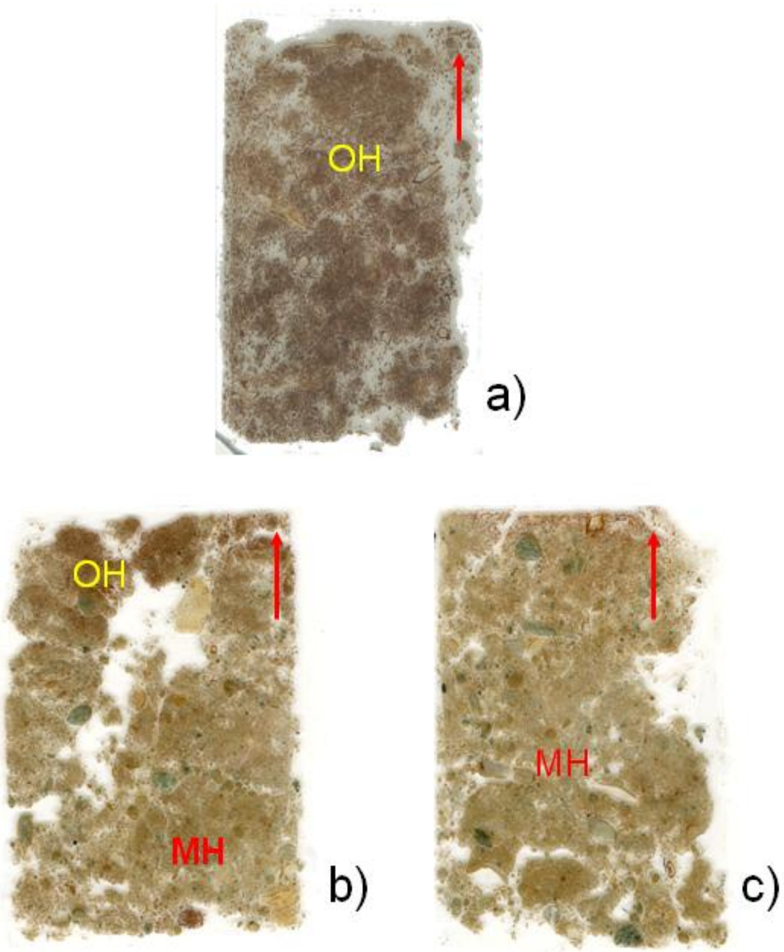


Figure 3.16: Micromorphology slides of the forest snow bed in the Abisko transect (plot 22): central (0) (upper 7.5 cm (a) and lower 7.5cm (b and c)); OH is an organic horizon, MH is a mineral horizon.

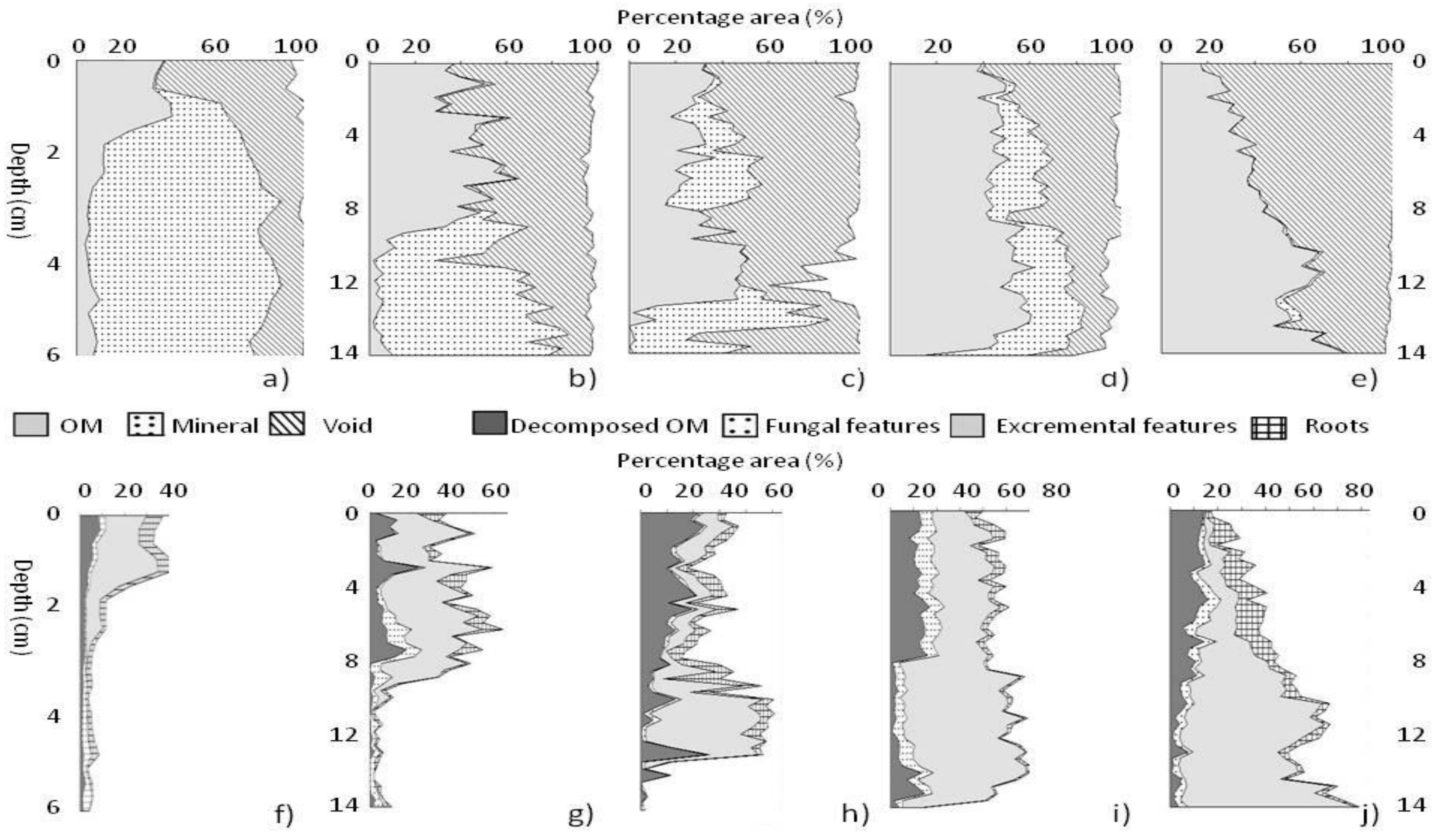


Figure 3.17: Area graphs of the void, mineral and organic matter percentages with depth for the birch forest (a), forest snow bed (b), transition (c), tundra snow bed (d) and tundra heath (e) and for the organic matter components for the birch forest (f), forest snow bed (g), transition (h), tundra snow bed (i) and tundra heath (j). Note: the forest profiles a and f have been re-scaled for clarity.

3.4.6 H_5 Importance of the transition zone

The micromorphology slides show the distribution of organic matter, mineral and void percentages with depth for the sampled AT plots (Fig. 3.17 a-e). They also allow semi-quantification of different organic matter components present in these slides and an assessment of their decomposition state (Fig. 3.17 f-j).

The total area does not always add up to 100%, as there are artefacts from the manufacturing process in some slides (Fig. 3.17 a-e). The profiles show an increase in the organic matter proportion and void area from forest to tundra, whilst the mineral percentages decrease accordingly. The forest snow bed profile is similar to the forest profile, but with a thicker organic matter horizon and less mineral (Fig. 3.17 a and b). The transition area profile and the tundra snow bed profile seemingly have predominantly organic layers in the middle of their mineral horizons (Fig. 3.17 c and d). These are due to the method used to build the profiles. For the transition area the upper 7.5 cm (depth of the sampling tin) of the synthesis profile are an averaging of data for 3 profiles, and two of them are mineral from only a few centimetres depth; thus the bottom part of these 7.5 cm is classed as mineral. The lower 7.5 cm (other sampling tin) are only sampled for one profile which goes from organic to mineral at a depth of 11 cm (see Fig. 3.13 and 3.15). So an organic matter layer appears between the end of the two shallow profiles and the rest of the deeper profile: this artefact shows once more the difficulty of finding an “average” or “typical” profile in areas of high soil properties variability.

If some general characteristics of the transition area are expected (lower organic matter percentage and shallower than the tundra heath, lower mineral percentage and deeper than the forest), closer inspection at the metre scale shows a strong influence of the vegetation. Soil characteristics vary on a fine scale. The results confirm those visible on the soil profiles themselves (Fig. 3.13). Here only the central ('0') profile is presented alongside the other vegetation types in Fig. 3.17. At the profile just one metre away ('1'), however, close to a birch copse, there is a micro-podzol similar to the one taken at the beginning of the transect. A profile three metres away on the other side of the central profile borders a heath; it is, itself, similar to the tundra heath profile at the southern end of the transect (Fig. 3.1 and compare 3.13 to 3.12 and 3.14).

The snow bed profiles are very mixed (Fig. 3.17 b and d). The tundra snow bed profile has a mineral layer unlike the tundra profile; while at these depths in the tundra profile there is an increase in organic matter (Fig. 3.17 d and e). The proportion of organic matter increases steadily with depth in the tundra profile, which is likely due to the compaction of organic matter reducing the pore area and so increasing the proportion of organic matter per surface area.

As well as the overall organic matter proportion, the proportions of organic components change with depth and along the transect (Fig. 3.17 f-j). Despite the shift to a mineral horizon, the shallow forest profile is similar in composition to the others for the first two centimetres (Fig. 3.17 f). The proportion of excremental features is particularly high and increases with depth for the tundra heath and tundra snow bed (Fig. 3.17 i and j), and there are layers containing high proportions of excremental features in the other profiles too. Fungal features are a minor component but are present in all profiles. Decomposed organic matter is calculated here as the sum of the amorphous tissues/structures and unidentified organic matter. It decreases with depth for all profiles. Root proportion comprises roots of different sizes. It decreases with depth but is present for all profiles with their different vegetation covers.

3.5 Discussion

3.5.1 Variability of the vegetation cover

Abisko and Kevo, being sub-arctic sites, do not appear in the Circumpolar Arctic Vegetation Map (CAVM). The closest area represented, in the north of Norway, is classed as S2 low-shrub tundra (CAVM team, 2003). Williams and Rastetter (1999), based on the results of Chapin and co-authors (1988), characterise the shrub tundra as having particular conditions and responses in the Arctic compared to the other tundra heaths (for example denser canopies, deeper thaw depth, more rapid N mineralisation), amongst which are warmer soil temperatures. Spadavecchia and others (2008) link the vegetation distribution in the Intensive Valley (IV) particularly to topography (exposure and elevation). This variety of interactions of vegetation with the soil and topography is masked if a dominant vegetation type, such as tundra heath, is defined without taking into account the different structural types of heath present in the landscape (Williams and Rastetter, 1999).

The Intensive Valley and Abisko Transect (AT) are situated in a transition area between tundra heath and birch forest. When mapping the IV, a relatively large number of land cover types (15) had to be defined due to the vegetation heterogeneity (Table 3.3 and Fig. 3.3, Appendix 3.1). The AT shows a similar diversity along the main slope between birch forest and tundra heath (from the same aerial photograph used as a base for the IV cover map; presented in Chapter 2, Fig

2.1 c). When linking these categories to the CAVM, most vegetation types from Abisko and Kevo are grouped under the same S2 category as the whole sites (CAVM team, 2003). The complex landscape (across relatively small areas; metre to kilometre) and associated mosaic of vegetation communities and soils present at the Abisko sampling areas (Fig. 3.3), are masked when viewing the site inside a larger region (10 km to pan-Arctic maps with a resolution of 1: 7,500,000, such as the CAVM (CAVM team, 2003)). Indeed, the final CAVM map had to be simplified, as the 400 communities defined from base data could not be presented effectively at this scale (CAVM team, 2003).

Some of the categories for Abisko mirror the five topographic situations distinguished by Walker *et al.* (2005) for referencing plant communities in the Arctic: dry exposed sites (tundra heath), mesic zonal sites (*Empetrum* heath), wet sites (sedge and wetland areas), snow beds, stream sides (riparian plots were placed in the wetland/heath transition or wetland/forest transition). Categories such as the bare areas and exposed heath have little to no soil profile development but occupy large areas (Table 3.4). Others, such as the transition areas, are hard to define, because the boundary between vegetation types is gradual rather than sharp. Hugelius and co-authors (2011a) found similar difficulties in ground-proofing their land cover classification. In the CAVM, polygons are attributed to the zonal vegetation present under non-extreme conditions in that area (Walker *et al.*, 2005). But the authors recognise that defining categories and attributing areas still presents intractable issues, for example too many vegetation categories means a necessary simplification for the map; only the dominant plant functional types can be used when information is lacking on plant community composition, so plant communities adapted to the extremes of climatic and physico-chemical soil conditions are neglected (Walker *et al.*, 2005).

Uncertainty about attributing some areas to particular vegetation categories is an argument for using more vegetation categories. More categories mean a smaller coverage for each category. In the IV, the mean area cover per category is only of 6.6% (Table 3.4), a practical consequence of which is to have too few plots or samples per category for a robust statistical coverage of the area. Hugelius and colleagues (2011a) recommend having at least 30 samples per category. Their criteria for differentiating classes are populations with significant statistical differences and unimodal distributions. In the present study, however, the distribution of vegetation variables for each category is unimodal, with the exception of some of the mixed categories (transition areas and snow bed; data not shown).

3.5.2 H_1 Relationship between vegetation categories and LAI

Leaf Area Index (LAI) values have been used to define shrub cover and tree cover in other studies (Walker *et al.*, 2005). In the IV, Van Wijk and colleagues (2005) established that plants with low LAI value cover most of the landscape. However, in this study the vegetation categories defined from the field survey can not be direct substitutes for the LAI/ Normalised Difference Vegetation Index (NDVI) measurements or *vice versa* (Fig. 3.4). The spatial distribution is not as variable for the understorey LAI (Fig. 3.5 d) as for the vegetation categories (Fig. 3.3). The relationship between LAI and NDVI can change slightly if using different methods of estimation and for different vegetation types (Shaver *et al.*, 2007; Williams *et al.*, 2008). There is a choice of methods to generate LAI maps, and the resulting maps can show widely contrasting LAI distributions over the same site

(Williams *et al.*, 2008). Scaling-up LAI results still requires field knowledge regarding the structure of vegetation communities and topography to reduce errors (Williams and Rastetter, 1999).

The mismatch in this study could be due to the greater spatial resolution of the aerial photographs on which the vegetation categories have been mapped (resolution of 0.5 m^2, allowing the delimitation of vegetation patches of a few m^2), compared to the LAI and C stocks maps generated from fewer values (sampling plots) and with a minimum resolution of 25 m. The LAI range is greater at finer scales due to the patchiness of the vegetation (Williams *et al.*, 2008) and therefore local measurements have small spatial influence (Williams *et al.*, 2008). Three measurements over three metres have been averaged at each plot to compensate this.

Williams and Rastetter (1999) averaged LAI values for sites separated into different vascular types (shrubs, wetlands, tussocks and heath). Plant functional types (PFTs) show a closer relation to LAI than the vegetation categories (Spadavecchia *et al.*, 2008). In Williams and Rastetter's (1999) study, LAI was significantly different for each vascular type; however, an individual site's LAI distribution could be similar to other sites attributed with different vascular types. The importance of species such as *B. nana* and *E. hermaphroditum* in several categories can blur the differences between classes further. The patchiness of vegetation in the IV makes it more likely that polygons attributed to different vegetation types would be closer in their actual vegetation cover. Spadavecchia and co-authors (2008) recognise that at scales under 10 m, using dominant PFT does not represent well the variability of vegetation cover on this site and advise the use of continuous variables such as LAI.

3.5.3 H_2 *and* H_3 Relationship between soil C stock and vegetation variables

The present study was aimed at representing the land cover components. Plots were chosen according to a regular cyclical grid rather than targeting vegetation types (see Chapter 2). Even with this method, soil C stocks per area differ for each vegetation category (Table 3.4). However, the high number of vegetation categories leads to using a small number of samples and plots per category, hence these results are marked by high standard error of the mean (Table 3.4) and the data variability is of the same magnitude as the results.

Amalgamating several categories leads to an averaging of the C stock per area (Table 3.4); for instance, by using only a distinction between areas with trees and areas without. This seems to contradict the fact that soil C stocks are lower for plots with trees in Kevo, so this averaging has to be carefully targeted. This could help to simplify studies of the soil C distribution by using fewer vegetation types. Similarly, when studying Russian forest-tundra sites, Hugelius (2011) found that when changing map resolution, C estimates do not vary substantially; however, the contribution of different vegetation classes changes. The natural variability is then masked and this simplification could lead to neglecting different soil conditions and properties present in the landscape, as was seen in the first discussion topic (3.5.1). In Kevo, the border of the mires covers only a few metres, while the birch forest is the dominating vegetation type. However, soil profiles in the mire border contain larger soil C stocks as the profiles are far deeper than beneath birch forest (see 3.4.3 *Estimates of soil C stocks and vegetation categories* and Chapter 2). In Abisko, the wetlands category presents deeper and more C-rich profiles than the tundra heath and birch forest profiles, but would be neglected if considering only heath and forest.

Even averaging values by vegetation type could be an over-simplification. Chapin and colleagues (1988) noted that sedge increases its productivity and nutrient cycling if there is a water channel, even underground. This type of change in C cycle is another factor that could lead to a heterogeneous distribution of C stocks for the same vegetation type. For example, the snow bed soils profiles are different from the two dominant vegetation types, despite being situated in the birch forest or tundra heath (Fig. 3.17).

Forested sub-arctic soils have lower C stocks than arctic tundra sites (Post *et al.*, 1982; Ping *et al.*, 1997); previous studies on C stocks for arctic tundra yield higher values than those found for the IV. Hugelius and Kuhry (2009) sampled Russian forest-tundra sites to a depth of 30 cm and more, and Ping and colleagues (2008) summarised data for the whole North American Arctic. Ping and coauthors (2008) found, for uplands sites containing CAVM S2 vegetation sites, values of 7.5 kg C m^{-2}; greater than all of the IV categories' average data. For Hugelius and Kuhry (2009), results are higher for the birch forest (4.2 kg C m^{-2} compared with 3.1 kg C m^{-2} maximum in the IV) and for the tundra heath (between 7.5-10.9 kg C m^{-2} for shrub tundra; 1.7 kg C m^{-2} in the IV), but lower for exposed heath (1.3 kg C m^{-2}; 2.3 kg C m^{-2} in the IV). The same labels can define slightly different vegetation communities; bare areas also get higher values in Hugelius and Kuhry (2009) than in this study (0.4 kg C m^{-2} rather than 0.02 kg C m^{-2}). Overall, these values are lower than the values for peatland and bogs (80-120 kg C m^{-2}) which occupy 72% of the sites studied by Hugelius and Kuhry (2009). It is also worth noting that the soils described by Hugelius and Kuhry (2009) are all underlain by permafrost, which does not appear in our field sites. This illustrates the difficulties in comparing sites across the Arctic when values are given for vegetation types that are similar in composition/physiognomy but play different roles in the landscapes.

Soil C stock is a continuous variable, as is the LAI. A direct relation between the two would facilitate the forecasting of soil C stocks from remote sensing measurements. However, no such relation has been shown by mapping these variables to estimate their spatial distribution (Fig. 3.10 a and b) or analysing datasets with geostatistical methods (Table 3.5 and 3.6). Hugelius and colleagues (2011a) found that pedogenetic information could be necessary to complete a Land Classification Cover map describing only surface vegetation. The key to representing soil C distribution from remote sensing data could be the combination of topographic data (Digital Elevation Model) and remote sensing of other variables, soil C data from the field for calibration, and geostatistical analysis to fill the gaps (Mulder *et al.*, 2011).

3.5.4 H_4 Controls on the C stock distribution

The study of the correlations between soil and vegetation variables highlights a lack of direct relationships between vegetation characteristics and soil properties. However, the detailed study by Spadavecchia and colleagues (2008) of IV LAI distribution did find that LAI variability over a small area (1.5 km^2) was better explained by vegetation controls, but that over a larger area (2.5 km^2) topography had more influence. Using models based on topographical variables to map the distribution of LAI explained 16% to 32% of the variance in LAI distribution

(Spadavecchia *et al.*, 2008). These results should be reflected in the correlation coefficients table (Table 3.5), but relationships are weak (coefficients <|0.5|).

The only control on surface 4 cm soil C stocks is the bulk density, which is used as a factor in the soil C stock calculation (see Chapter 2), and so has logically to be correlated to it. However, some relations are surprisingly weak, such as the correlation between C content and C/N ratio. This should be highly correlated as the C content is used as a factor in the C/N ratio calculation. Separating the samples into broad categories (wooded or treeless; mire and forest) does not increase the correlations' strength. Correlation coefficients obtained for the samples dataset for all depths show stronger correlations between soil variables (See Chapter 2). As surface soil layers are more in contact with the vegetation and climate, there are more potential controls on their C stock and thus the influence of each separate parameter is weakened.

3.5.5 H_5 Transition area between birch forest and tundra heath

Although the transition area presents a mixture of soil profile characteristics between the birch forest and the tundra heath ones (Fig. 3.17), the profiles are mainly related to the vegetation cover at the metre scale rather than by the position of each plot along the 3 km transect across an altitudinal gradient. The presence of snow beds both in the birch forest and tundra heath further emphasises the fragmented distribution of soil profiles along the soil transect (Fig. 2.3, 3.11 and 3.17). On a fine scale, vegetation types seem to be a more important control than the position in the larger landscape, as seen with the transition area (Fig. 3.17), which ties in with the results by Spadavecchia and colleagues (2008) for LAI.

One of the predicted (and, in some cases, documented; Callaghan *et al.*, 2005; Van Bogaert *et al.*, 2011) changes due to increasing temperatures in the Arctic is the advance of the treeline onto heath areas (Wilmking *et al.*, 2006), which is very variable in Abisko (Van Bogaert *et al.*, 2011). As tundra profiles (excluding the exposed heath) contain more organic matter than under the birch copses (Table 3.4), a transition from tundra heath to birch copse could be accompanied by a remobilisation of existing soil organic matter. The present intermediate - the central profile of the transition area - contains the same maximum percentage of organic matter (73%) as the forest profile, with a larger spread in the profile. This soil profile is, however, still shallower than the tundra profile. As well as the organic matter content, monitoring transition areas has to include measurements of soil depth and porosity. If the transition area represents a mixture of the properties of birch forest and tundra heath on a distance of a few metres, there is no clear catena between birch forest and tundra heath soil properties at the kilometre scale. For instance, birch forest soils with similar properties to the ones at the beginning of the transect can be found in the middle of the transect; if there was a catena from birch forest to tundra heath these profiles would present soil properties between those of “typical” birch forest and tundra heath. This variability at finer scales (metres) can complicate the modelling of the advance of the treeline.

The constraints associated with the micromorphological techniques limited the number of samples that could be processed; for further studies, a more complete scheme representing more vegetation types and topographical positions would facilitate the study of the spatial distribution of soil components.

3.6 Conclusion

An integrated examination of soil, vegetation and topographical variables has not identified a robust above-ground proxy for soil C distribution and stocks. There is high variability of soil C distribution over a landscape mosaic of 2.5 km^2 but average values for areas with trees and treeless areas can be found, and these values could be used for upscaling. Using the presence or absence of tree, however, as an indicator of the size of C stocks could be feasible in the structurally/topographically simpler landscapes (Kevo) but is not sufficient in more complex and heterogeneous landscapes (Abisko). The possible responses of the present soil C stocks to climate change, and the advance of trees have to be monitored by further field surveys (or process studies) until a good proxy permits a study by remote sensing. However, present advances in technology (see Chapter 2) are still limited and this chapter shows that single isolated variables are not sufficient as predictor of C stock sizes.

Despite these limitations in linking vegetation and soil variables, Chapter 2 and 3 have permitted to get a picture of the present state of the C stocks distribution in these soils and of the variability in vegetation cover on these sub-arctic landscapes. This survey needs to be completed by a study of the soil C fluxes that could be released from these stocks in the near future, in the context of the forecasted Arctic warming. Such a study, based on the data acquired in the field and presented in Chapters 2 and 3, estimates respiration rates from these soils by using a tailored soil respiration model. It is presented in Chapter 4 along an estimation of possible soil C stocks evolution.

Appendix 3.1: plant species present on the plots in Abisko and Kevo

Scientific name	Common name	Field site	Abundance
Andromeda polifolia L.	Bog rosemary	A K	Medium
Arctostaphylos uva-ursi (L.) Spreng.	Common bearberry	A	Low
Astragalus L.	Milk-vetch	A	Low
Bartsia alpina L.	Velvetbells	A	Low
Betula nana L.	Dwarf birch	A K	High
Betula pubescens subsp. *czerepanovii* (Orlova) Hämet-Ahti	Downy birch	A K	High
Betula pubescens x *nana* = *Betula intermedia* Thomas ex Gaudin		A K	Medium
Bistorta vivipara L.	Alpine bistort	A	Low
Bryophytes		A K	High
Carex bigelowii Torr.	Bigelow sedge	A K	Medium (A) Low (K)
Carex rostrata Stokes	Bottle sedge	K	High
Cassiope tretragona (L.) D.Don	Arctic bell-heather	A	Low
Cetraria islandica (L.) Ach.	Iceland moss	K	Low
Cladonia fimbriata (L.) Fries	Cup lichen	K	Medium
Cornus suecica L.	Swedish cornel	K	Low
Diapensia lapponica L.	Pincushion plant	A	Low
Dryas octopetala L.	White dryas, mountain avens	A	Low
Empetrum hermaphroditum Lange ex Hagerup	Mountain crowberry	A K	High
Equisetum spp. L.	Horsetail	K	Low
Eriophorum angustifolium Honck.	Common cotton-grass	K	Medium
Eriophorum spp. L.	Cotton-grass	A K	Low(A) High(K)
Eriophorum vaginatum L.	Hare's tail cotton-grass	K	Low
Geranium sylvaticum L.	Wild cranesbill	A	Low
Graminoids		A K	High
Juniperus communis L.	Juniper	A	Low

Scientific name	Common name	Field site	Abundance
Lichens		A K	High
Loiseleuria procumbens (L.) Desv.	Creeping azalea/ Mountain azalea	A	Low
Lycopodium spp. L.	Club moss	A	Low
Menyanthes trifoliata L.	Bogbean	K	Low
Nephroma arcticum (L.) Torss.	Arctic kidney lichen	K	low
Pedicularis spp.	Lousewort	A	Low
Phyllodoce caerulea L.	Blue mountainheath	A K	Low (A) Medium (K)
Pinguicula alpina L.	Alpine butterwort	A	Low
Pinguicula vulgaris L.	Common butterwort	A	Low
Pleurozium schreberi (Brid.) Mitt.	Schreber's big red stem moss	K	High
Polytrichum juniperinum Hedw.	Juniper haircap moss	K	Medium
Potentilla palustris (L.) Scop.	Marsh cinquefoil	A	Low
Ptilidium ciliare (L.) Hampe	Ciliated fringeworth	K	High
Rhododendron laponicum L. (Walhenb).	Lapland rosebay	A	Low
Rhododendron tomentosum Harmaja	Wild rosemary	K	Low
Rubus chamaemorus L.	Cloudberry	A K	Low (A) High (K)
Salix glauca L.	Glaucous willow	A	Medium
Salix lanata L.	Wooly willow	A	Medium
Salix lapponum L.	Downy willow	A	Medium
Salix spp L.	Willow	K	Low
Silene acaulis (L.) Jacq.	Moss campion	A	Low
Sphagnum spp. L.	Peat moss	A K	Low(A) High(K)
Trichophorum cespitosum (L.) Hartm.	Deer-grass, tufted bulrush	A K	Low (A) Medium (K)
Vaccinium microcarpum L.	Cranberry	K	Low
Vaccinium myrtillus L.	Bilberry	A K	Medium (A) Low (K)
Vaccinium uliginosum L.	Northern bilberry	A K	Medium (A) Low (K)
Vaccinium vitis-idaea L.	Lingonberry, cowberry	A K	Medium (A) High (K)
Viola lutea Huds.	Mountain pansy	A	Low

Multiscale Soil Carbon Distribution

in Two Sub-Arctic Landscapes

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Chapter 4 - Modelling soil respiration in a sub-arctic landscape

4.1 Abstract

1. A simple model based on field data was used to forecast (i) the response of soil respiration to rising temperatures for sub-arctic soils, and (ii) the resulting dynamics of soil C stocks under two sub-arctic vegetation types. Arrhenius and Q_{10} models were used to link soil respiration and temperatures.

2. Soils under a range of vegetation categories have contrasting moisture and temperature regimes, even under the same, or similar, macroclimatic conditions. Furthermore, soils under the same vegetation type can have different soil properties (for example C content or bulk density) as well as contrasting thermal and moisture regimes. Therefore, even when using the same parameters in the respiration models, they can react differently to a similar increase in mean soil temperature. This heterogeneity on small areas (m^2 to km^2) must be kept in mind when modelling over larger areas (10 km^2 to regional scale).

3 The birch forest soils are particularly sensitive to increased winter temperatures, which could increase the frequency at which the thawing point is reached. Here the modelled values for respiration nearly double for an increase in mean annual temperatures of 2°C. Birch forests may colonise tundra heath vegetation with climate warming, which may increase the potential for net C losses from soils in the sub-Arctic.

4.2 Introduction

Modelling soil respiration in arctic soils is a key to modelling responses of other components of the carbon (C) cycle to soil temperature increase (Elberling and Brandt, 2003). High latitude cold regions with important C stocks are judged particularly sensitive to temperature (von Lützow and Kögel-Knabner, 2009). As the Arctic is already undergoing changes at multiple levels and over several spatial and temporal scales (Callaghan *et al.*, 2005), it is important to link soil processes (and states) to robust models. However in systems as complex as the Arctic, the relationship between soil respiration and one of its main controls, soil temperature, can be masked under the feedbacks to temperature change from the different ecosystem components (Davidson and Janssens, 2006).

One approach to this complex issue can be to use empirically-measured soil parameters and abiotic conditions as the starting point, and then to model the effects of changing the interactions between soil C fluxes and local temperature conditions, for instance by limiting respiration to certain temperature ranges. In a similar process, highlighting differences over a small area (metre to kilometre) is key to understanding the processes underpinning changes over larger areas (kilometre to regional scale).

The two main arctic vegetation categories selected for this model are the sub-arctic tundra heath and birch forest. The field area of the Intensive Valley (IV) in Abisko (Swedish Lapland) is situated at the boundary tundra heath-birch forest ecotone (Sjögersten and Wookey, 2002a). The area used for this study is underlain by a diversity of soils, and includes a spectrum of vegetation communities (from forest to exposed heath and ridges) (see Chapters 1 to 3).

H_1: Hypothesis 1 states that this vegetation diversity is reflected in the thermal and moisture regimes of the soils and the sensitivity of their respiration rates to an increase in mean annual temperature. Once the contrasts in soil moisture and temperature for the different soils are known, the implications for soil respiration can be modelled. In this study, a simple soil model has been built based on data collected in the field. It encompasses relations between respiration and soil C stocks in soils under two sub-arctic vegetation categories, with temperature and moisture series as controls. Moisture is another control that can limit respiration, and may assume a primary role at both low and high moisture contents, due to water deficits and potential anoxia, respectively (Carlyle and Ba Than, 1988).

Several equations are available to link soil respiration and temperatures. Arrhenius and Q_{10} models (Arrhenius, 1889; Van't Hoff, 1898) are used to assess the potential influence of soil temperature changes on respiration. This echoes the numerous studies on the influence of the equation choice on soil respiration models and their limits (for example Arrhenius at low temperatures; e.g. Carlyle and Ba Than, 1988; Lloyd and Taylor, 1994; Davidson and Janssens, 2006).

H_2: The second hypothesis tested on these data is that the choice of model overrides the effects of soil parameters chosen, and landscape/ vegetation heterogeneity, and thus challenges ***H_1***.

As a correlation between soil properties and respiration exists in other Arctic soils (Dutta *et al.*, 2006), tundra heath and birch forest soils are used to study the sensitivity to temperature increase of soil respiration in soils under similar vegetation in different locations, and, conversely, of differing soils in similar locations. Moreover, organic matter (OM) components are varied in these soils (see Chapter 3) and properties such as the composition/quality of organic matter influence the soil respiration rate (Mikan *et al.*, 2002). ***H_3:*** Reflecting this, the third hypothesis tested states that this variety in soil compositions is linked with a contrast in soil responses to temperature change. In the model, using different soil parameters for soils under similar vegetations will have an influence on the simulated soil respiration, even when using similar model parameters for respiration. It follows that soils under contrasting vegetation covers will be even more varied in their responses to warming.

These contrasts in sensitivity of the soil respiration to temperature increase are of particular interest in winter. As well as the predicted increase in mean annual temperature in the Arctic (+2°C in arctic mean annual temperature for a +1°C increase in global mean annual temperature in 2040 (compared to 1981-2000); Kattsov *et al.*, 2005), winter warming of even greater magnitudes (+2-4 °C for the 2013-2020 period compared to global over Scandinavia between December and March; Kattsov *et al.*, 2005) could profoundly alter the depth and duration of snow cover (Wrona *et al.*, 2005). Higher temperatures in winter may raise soil temperatures closer to thawing point, resulting in an increase in the availability of liquid water during these periods (Wookey *et al.*, 2009). Following these facts and the discussion by Wang and colleagues (2010) of the soil temperature control of winter ecosystem (including soil) respiration, we hypothesise that soils that are more sensitive to winter temperature increase will have an enhanced soil respiration in winter with an increase in mean annual soil temperature (***H_4***). Interestingly (and, possibly, counter intuitively), milder winters may increase snow depth in some parts of the landscape, and this is likely to raise soil temperatures as well.

As the respiration increases and depletes available C, increases in temperature should result in depletion in the soil's labile and total C stocks (in the absence of new organic matter inputs). The rate and length of this process will depend on the size and composition of the soil C stocks calculated from the field data.

H_5: The last hypothesis is that as the model grows more complex, and more constraints are added when calculating the simulated soil respiration, estimated soil respiration should decrease, leading to a change in the soil C stock depletion trends.

4.3 Methods

4.3.1 Field sites

Two sub-arctic locations were used to study the distribution of soil C stocks, Abisko in Sweden and Kevo in Finland. However, data on soil temperature and soil moisture could only be collected for Abisko, so Kevo is not used in this modelling project. [*The site of Abisko is described in Chapter 2 and 3*]. Two sampling areas have been defined in Abisko: the Intensive Valley (IV) is a 500 m by 500 m area covering the transition between birch forest and tundra heath, while the Abisko Transect (AT) follows the main slope from the northern birch forest to the tundra heath over 2.9 km. The difference in elevation between either end of the transect is 200 m.

The IV is a heterogeneous area (Fig. 4.1 a) with cover ranging from forest copses and isolated mountain birch trees, through different types of heath, to barren exposed terrain and late snow beds (often lasting until mid-June). The vegetation categories present are linked to heterogeneous soil types and make this landscape a place of interaction between differing soil properties, vegetation types, topography/geomorphological settings, and climatic conditions. The areas covered by the different vegetation categories are given in Chapter 3.

The projected colonisation of tundra heath by birch forest in similar tundra-forest ecotones highlights soils under these two vegetation categories as likely to undergo many changes in the next decades (Callaghan *et al.*, 2005). These soils need to be treated separately when modelling C stocks and fluxes in this landscape. Using maps generated from aerial photographs of the IV, the landscape simulated in the model is dominated by tundra heath (76.1%) interspersed with birch copses and some birch forest patches at its northern margins (23.9%) (Fig. 4.1b). The present work focuses on tundra heath and birch forest; by way of illustrating this approach, other vegetation categories are added to the model later (the snow beds (5% of the area), Sedge and wetlands (7.4%) and Exposed heath (25%)) (Fig. 4.1 c and d). The tundra cover dominates over the forest cover in terms of percentage surface in the IV on the field (76.1% versus 23.9%, see Chapter 3). Consequently, in the model, the percentage surface area covered by the IV vegetation categories that are not modelled at a given stage is added to the tundra heath category (Fig. 4.1 a to c; for example bare areas).

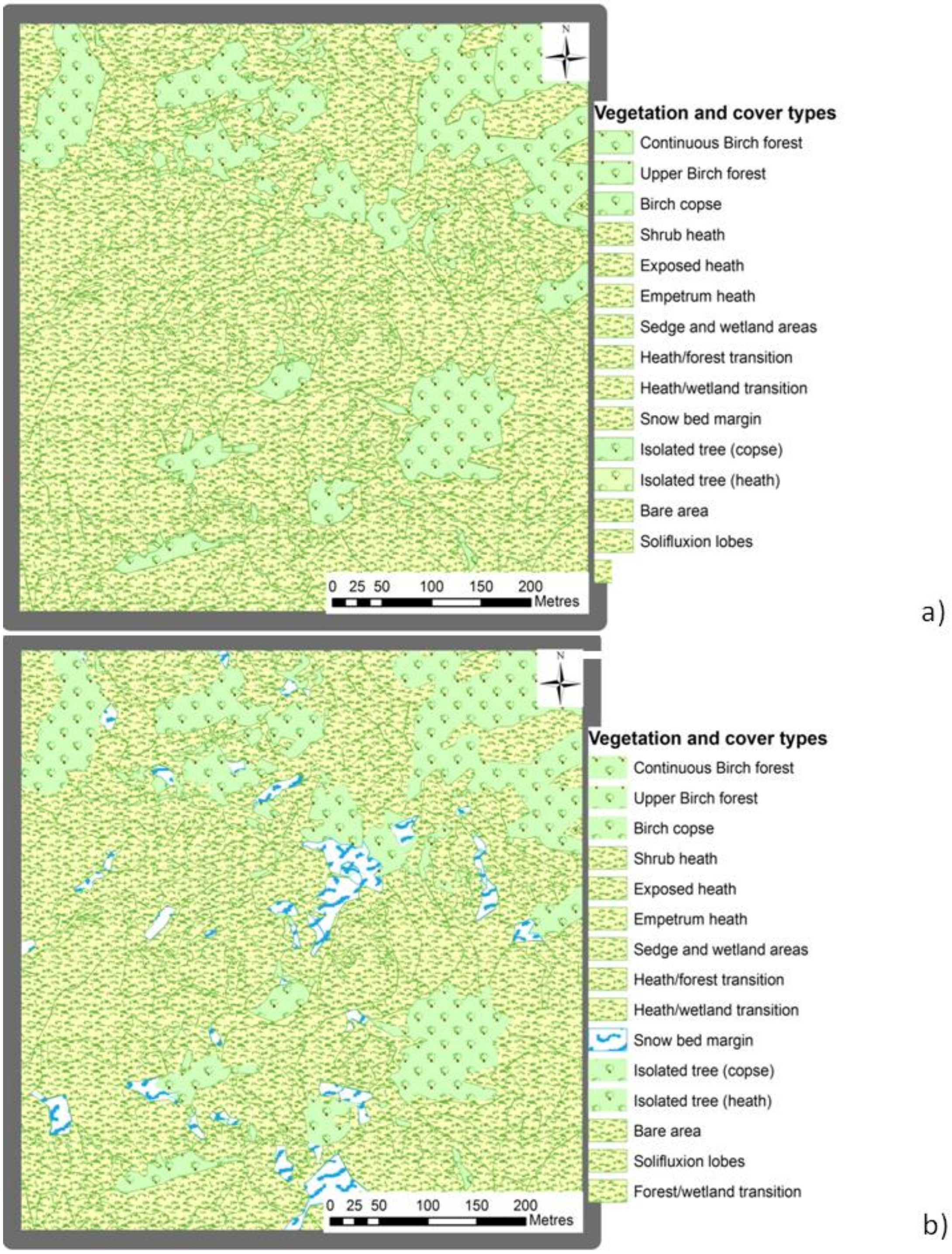

Figure 4.1: Map of the Intensive Valley area vegetation cover, with vegetation communities aggregated into broad "Tundra heath" and "Birch forest" components (a) and superimposing snow beds (b)[10]

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[10] I am grateful to Timothy Hill (ABACUS)for providing me with the aerial pictures which the maps are based on, and Ana Prieto-Blanco and Mat Disney for providing me with the DEM data; these were based on NERC data provided by B Huntley and R. Baxter

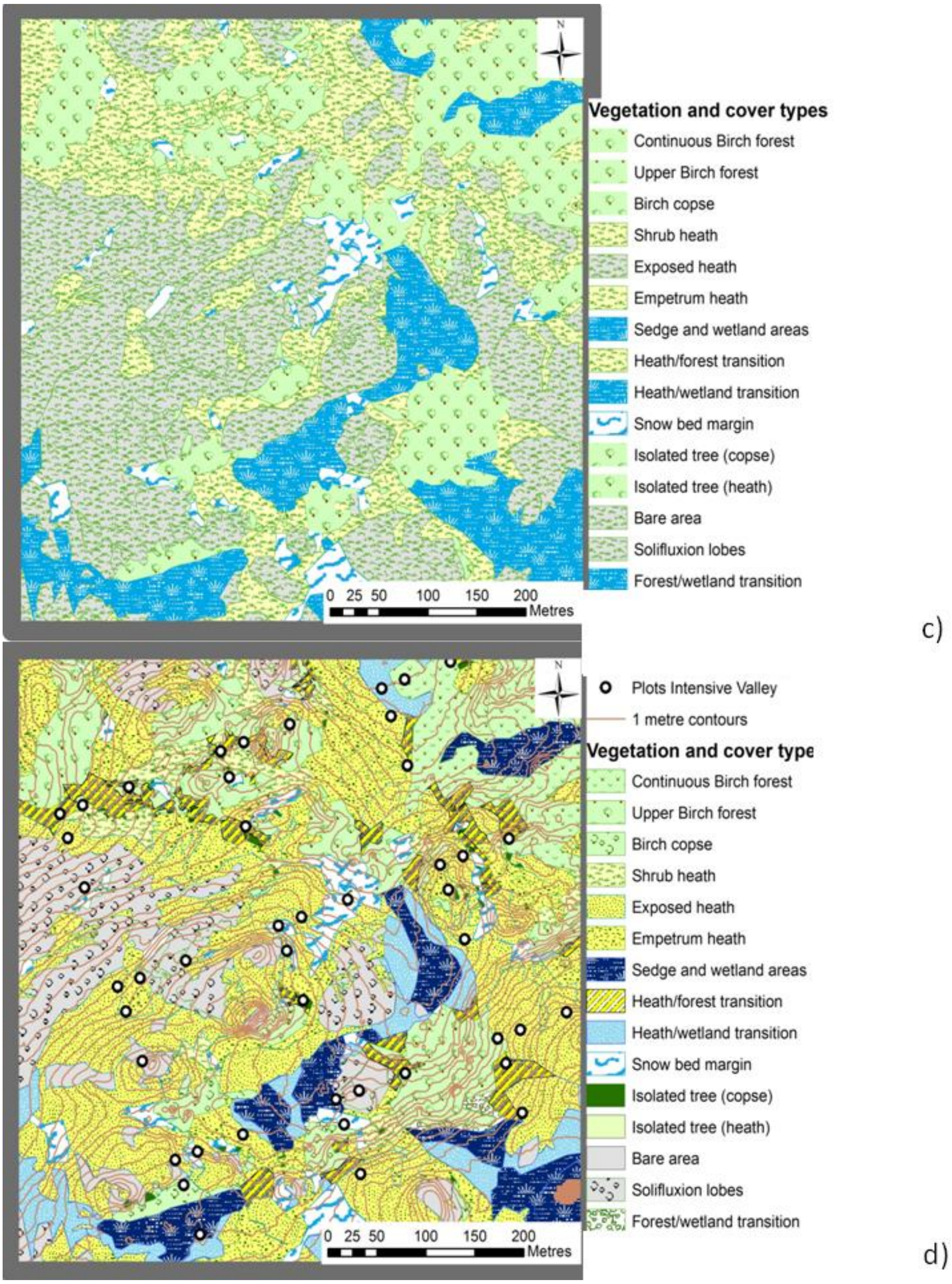


Figure 4.1: Map of the Intensive Valley area vegetation cover: broad "Tundra heath", "Birch forest", and snow beds communities are disaggregated to show "Exposed heath" and sedges and wetlands (c) and natural vegetation cover as mapped over the aerial photographs (d)

4.3.2 Data collected in this study

The characterisation of vegetation categories and the measurement of soil variables are described in the previous Chapters 2 and 3.

4.3.3 Moisture and temperature loggers

The moisture data were obtained between July 2008 and July 2009. Several plots of the IV and Abisko Transect (AT; described in Chapters 2 and 3) were used. The emphasis was put on birch forest and tundra heath plots. These two categories are the main vegetation covers in Abisko. A tundra heath plot was logged in the IV and another one located at the upper end of AT, to study the differences between soils under similar vegetation in different parts of the landscape. Two birch forests plots were chosen in the IV and AT with the same objective.

To accompany these, other plots with potentially heterogeneous thermal and moisture content regimes were logged in the IV. Shrub tundra is close to the main tundra heath category, with the presence of *Betula nana* and *Salix* bushes. Expansion of shrubs over tundra areas can result in changes in leaf litter decomposition, becoming more recalcitrant, and decreased winter snow cover, respectively a negative and a positive feedback to global warming (Cornelissen *et al.*, 2007; Wookey *et al.*, 2009). The exposed heath and small ridges in the IV, highest in their altitudes and exposition to the wind, were logged to study the influence of their topographic position on their soil moisture content and temperatures. On the other hand, wetland sedge areas are situated in depressions and possess soils with a high water content, which makes monitoring one of them a way to assess the upper limit of the soil moisture on this area. The simulated respiration for exposed areas and sedge wetland areas should represent the limits of the soil respiration ranges in Abisko. The snow beds are sheltered and accumulate deep snow acting as thermal insulator; some can be situated in birch forest and other close to exposed heath (Fig. 4.1).

The loggers deployed were eight Hobo Micro Weather Stations (Measurement systems Ltd, Newbury, UK), each coupled with two ECH_2O Soil Moisture Smart Sensors moisture probes (Decagon Devices, Pullman, USA). The two moisture probes were placed one metre apart. Complementing the moisture probes, for each Hobo station a 12-bit Temperature Smart Sensor temperature probe (Decagon Devices, Pullman, USA) was used for logging soil temperature at a depth of 5 centimetres. Following the failure of some of the Hobo probes, some of the temperature data were obtained with Tinytag loggers (Gemini Data Loggers, UK; Appendix 4.4). These did not permit to use more than one probe per station, so no moisture data were collected with these loggers.

In the following field season, supplementary temperature data were obtained for the transect birch forest and tundra heath plots at depths of 5, 10 and 15 cm.

4.3.4 Respiration equations

The first equations linking respiration and temperature via exponential relationships were proposed by Arrhenius (1889) and Van't Hoff (1898). The Arrhenius model used in this study and later simply referred to as "Arrhenius Equation", is:

$$R_S = A\ e^{-Ea\ /\ (R\ (T+w))} \qquad \textit{Equation 1}$$

Where R_S is the soil respiration rate (mol CO_2 m^{-2} s^{-1}), A is a pre-exponential factor (mol CO_2 m^{-2} s^{-1}), e is the Euler constant of the exponential function (2.178), E_a is the activation energy necessary to start the process (J mol^{-1}), R is the gas constant (8.3145 J K^{-1} mol^{-1}), T is the temperature in degrees Kelvin and w is the temperature increase tested in the warming simulation.

Van't Hoff (1898) introduces Q_{10} as the factorial increase in process rate (here the respiration rate) for an increase in temperature of 10°C.

The Q_{10} equation, referred to later as "Q_{10} Equation", is:

$$R_S = R_{S10}\ Q_{10}^{\ ((T+w)-10)/283.15)} \qquad \textit{Equation 2}$$

Where Q_{10} is the ratio between respiration rates for a temperature T+10 and temperature T, Rs is the respiration rate (mol CO_2 m^{-2} s^{-1}), R_{S10} is the respiration rate at 10°C, T is the temperature in degrees Kelvin, w is the degree increase tested in the warming simulation (degrees C or K) and 283.15 is the reference temperature 10°C in K.

Using the Arrhenius Equation, the Activation Energy (E_a) of the respiration process can be estimated. This can be an indication of the degree of adaptation of the microbial community to soil temperatures and of the ease with which C can be metabolised by this community (Mikan *et al.*, 2002; Sjögersten and Wookey, 2002a; von Lützow and Kögel-Knabner, 2009).

These basic equations do not encompass the complexity of soil, temperature and biotic and abiotic process interactions, and the Arrhenius Equation has been criticised for underestimating respiration at low temperatures (Lloyd and Taylor, 1994). A Q_{10} value of 2.5 is often used as standard for global soil respiration in climate models (Raich and Schlesinger, 1992). However, Q_{10} is variable depending on the depth of the soil, the temperatures (Kirschbaum, 1995), the properties of the soil organic matter, and the nature of the decomposer community (Carlyle and Ba Than, 1988).

4.3.5 Soil and respiration model building

Though soil models are already available, building a new model has been preferred to using an existing one. This allows for controlling the complexity of the model and the parameters used to run it. Existing models can be focussed on study objects too different from arctic tundra soils, and in that case cannot be adaptated for this study. For example, Hadley Centre's coupled climate–carbon cycle general circulation model (GCM) HadCM3LC has a carbon cycle module, but is considering atmospheric and terrestrial interactions at a global scale, reducing soil carbon to a single pool. As does the Canadian Centre for Climate modelling and analysis Earth System Model (CCCmaESM1), which is targeting CO_2 exchanges between land, ocean and atmosphere (Jones *et al.*, 2005; Arora *et al.*, 2009). This project needs to consider both mineral soils (exposed areas) and highly organic soils (tundra heath), when soil models usually are more specialised; for example RothC targets arable soils and the model to Estimate Carbon in Organic Soils-Sequestration and Emission (ECOSSE) targets highly organic soils mainly (Jones *et al.*, 2005; Smith *et al.*, 2010). Even when they are simulating several pools and detailed soil processes, soil models' complexity entails practical obstacles such as the need for more processing time or capacity, or the need for more input data than were available (for example plant variables as the lignin to N ratio in CENTURY; microbial biomass in Roth-PC1 and in the HadCM3LC coupled with RothC, or water level and rain in ECOSSE; Hilinski *et al.*, 2001; Jones *et al.*, 2005; Jenkinson and Coleman, 2008; Smith *et al.*, 2010).

The model built for this study in Excel (Windows) is structured as a series of increasingly complex stages, though remaining a simple model focussed on soil processes. Each stage features more detailed soil pedons and increasing interactions between inputs, respiration and their controls. With this stepwise approach, the complexity needed to model accurately the soil processes can be assessed, by comparing the results obtained at the different stages.

4.3.5.1 Model stages

Table 4.1: Principal model stages characteristics: controls on respiration from temperature T, moisture M and soil profile characteristics

Stage	T	M	Soil profile and stocks
1	>0°C	Any	Simple $1m^3$ homogeneous column
2	>0°C	Any	Differentiated horizons, depths differ between soils
3	>0°C	Any	Recalcitrant organic matter stock can be used for respiration
4	Any	Any	Different temperature regimes at depth
5	Any	Any	Soil horizons are linked, respiration depends on the soil C stock size and type
6	Any	$0.35 m^3/m^3 > M > 0.05 m^3/m^3$	Moisture limits soil respiration

For each stage, warming increments of 0.25 from 0 to 2 (°C) are used to simulate future increases in the mean soil temperatures, which are forecast in this range for the next few decades (Callaghan *et al.*, 2005).

The stepwise approach consists in an increase in complexity for each stage, via the soil structure simulated and the processes included. Stage 1 (Fig. 4.2 a; Table 4.2) is the simplest, an undifferenciated soil column similar for both vegetation types. Stage 2 (Fig. 4.2 b; Table 4.2) is the simplest stage using the field data: the column has more realistic depths and several horizons, the data for the Intensive Valley and the Abisko Transect are used separately. Stage 3 (Fig. 4.2 c; Table 4.2) is based on the differentiation of the organic matter into labile and refractory fractions, completing the soil structure introduced in stage 2. Stage 4 (Fig. 4.2 d; Table 4.2) cancels the limits on respiration imposed when the temperature is inferior to 0°C. After the soil column, the influence of temperature is made more realistic, with the possibility of soil respiration in winter. These different thermal regimes are one of the main characteristics of the vegetation types introduced at these stages, along with a difference in soil profiles. Stages 5 (Fig. 4.2 e; Table 4.2) complements this structure with links between the different soil compartments, adding the transport of soil organic matter in the soil column. The last stage 6 is the more complex (Fig. 4.2 f; Table 4.2), introducing new types of soils with particular moisture regimes, the snow beds and the exposed heath. Moisture limitations are applied on respiration from all soil types.

At Stage 1 (Fig. 4.2 a), respiration follows directly the equation chosen. The only limitation is that temperature must be above 0°C to drive measurable respiration. This is not the case in soils as seen from Fig. 4.3's curves, but this limit is in place to simulate a simple model overlooking soil respiration in winter. Another simplification following the same approach is that the column of soil is considered a homogeneous block of $1m^3$ with no horizons and no differenciation in the OM types (Fig. 4.2. a).

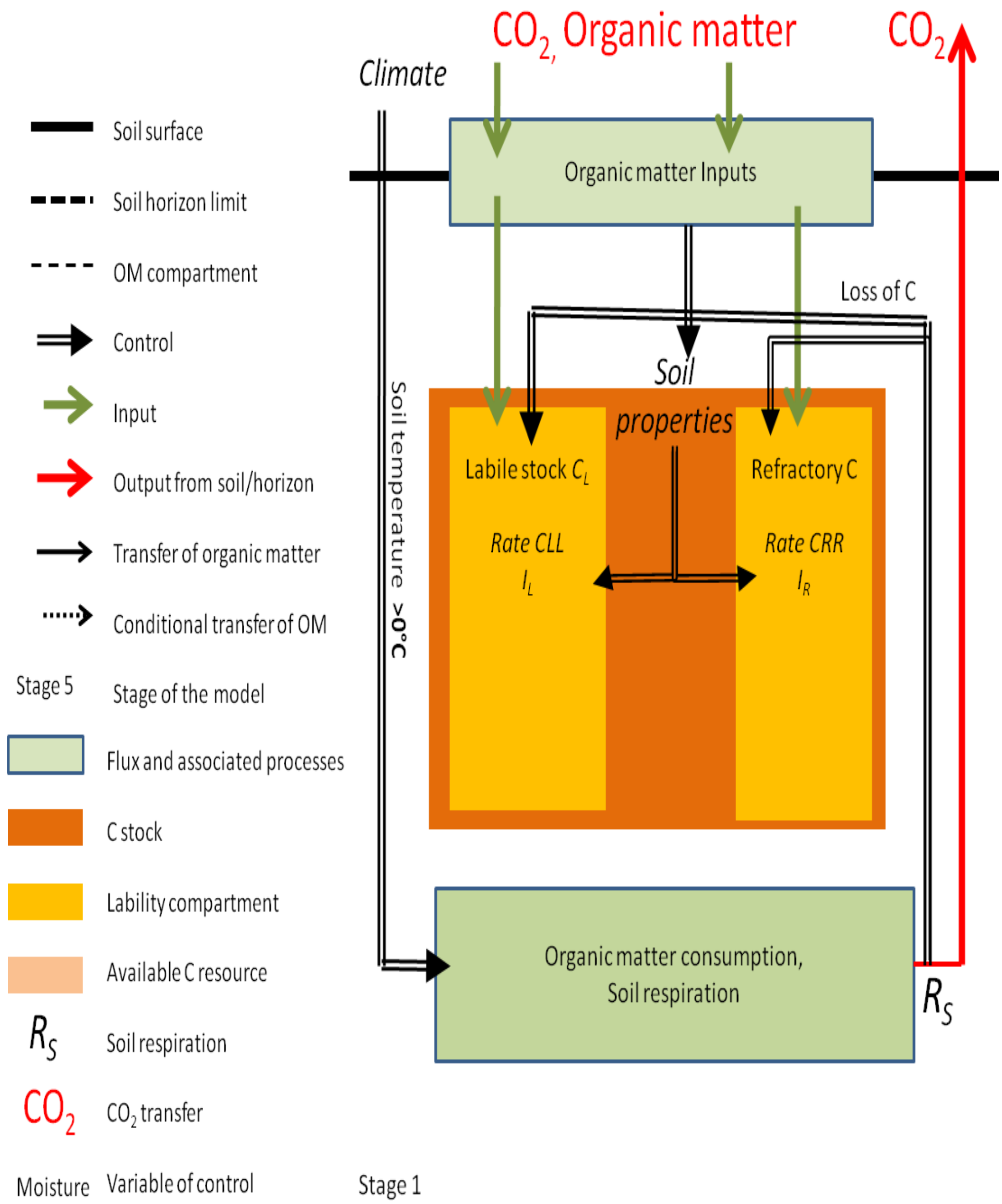
At Stage 2 (Fig. 4.2 b), data from this study's field surveys are used to simulate more realistic soil profiles: mean depths shallower than a metre, differentiation in soil horizons and presence of recalcitrant organic matter (Fig. 4.2 b; Table 4.2). This is a rough representation of the profiles as seen in the field, and shows the influence of the representation of the soil structure on the modelled respiration.

At Stage 3, the inputs are divided between recalcitrant and labile (Fig. 4.2 c). This means the previous inputs are not entirely available at this stage. If the labile stock is depleted, the respiration is fuelled by recalcitrant inputs and stocks, but at a diminished rate. This stage introduces a differentiation in the organic matter types, which are varied in the field (as seen in the micromorphological analysis results (Fig. 3.12-16 and 3.17). The feedback between stocks and inputs is introduced too.

At Stage 4, the soils are sub-divided into different soil thermal regimes at depth (one dataset per soil horizon; Fig. 4.2 d). After the division of the soil column at depth and between organic matter types, the division of the column between different thermal regimes gives a more realistic representation of the soil's thermally related processes. Significant metabolic activity in winter is also introduced by not limiting the respiration to temperatures above 0°C. A lower limit is not added, though very low temperatures (which severely limit the presence of liquid water in the soil matrix) constrain microbial activity and thus soil respiration (Mikan *et al.*, 2002; Elberling, 2003; Wang *et al.*, 2011).

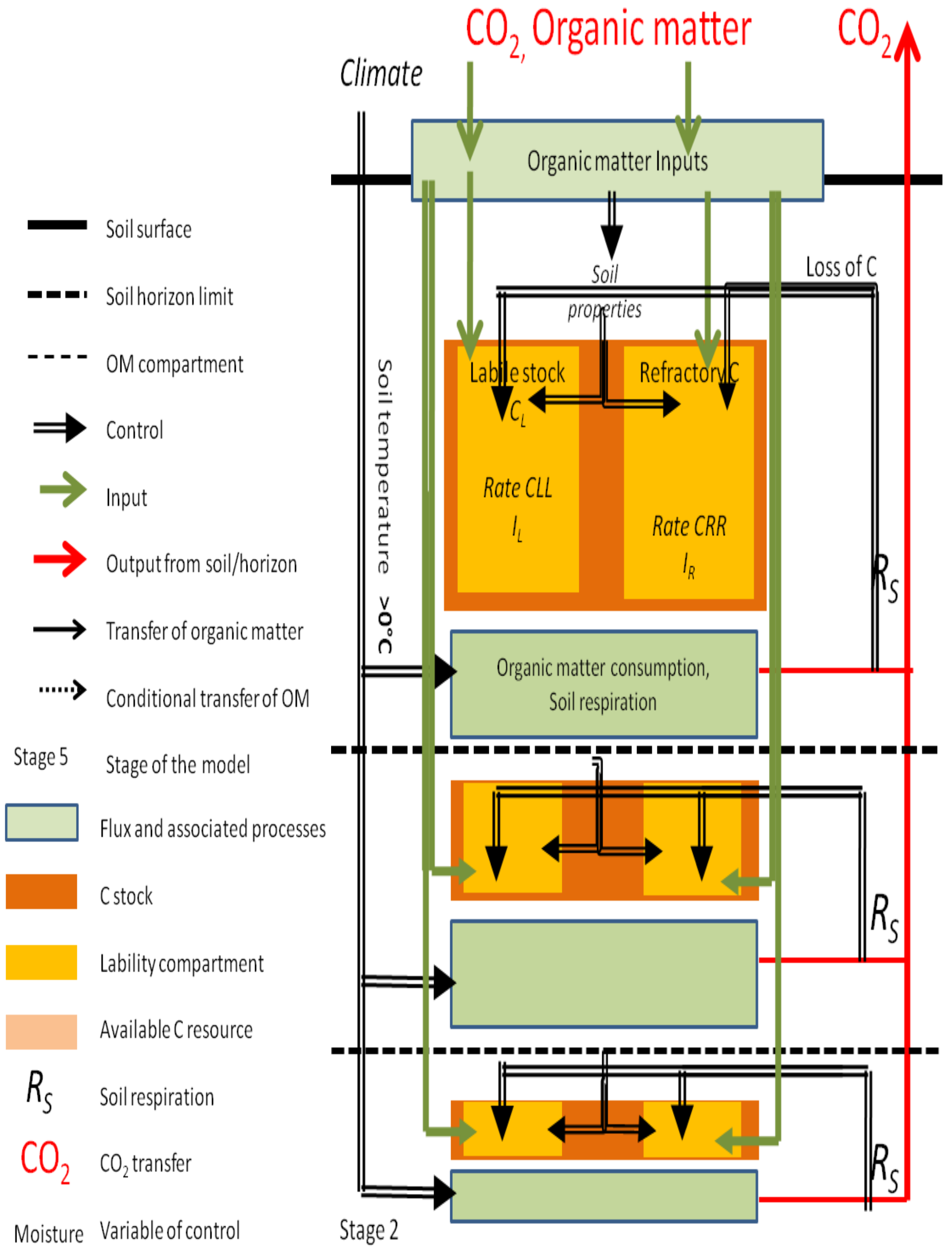
In Stage 5, respiration is still linked to C stocks, both labile and recalcitrant. If both are depleted, the labile stock (if there is one) of the soil horizon above can be metabolised (Fig. 4.2 e). The natural transport of organic matter between the soil compartments is introduced. It could be completed later by changing inputs mechanisms in the model, for example by taking into account the lateral transport of dissolved organic carbon.

Stage 6 (Fig. 4.2 f) introduces moisture constraints on the respiration at moisture levels between 5% and 35% (by volume), similar to the soils studied by Elberling (2003). In Abisko tundra heath and birch forest soils, low values in water content in August 2000 were significantly accompanied by lower soil respiration though soil temperature was more influential (Sjögersten and Wookey, 2002a). This stage contains the most complexity, with stocks, respiration and inputs linked throughout the soil compartments and their moisture and thermal conditions acting as controls. Further complexity could be introduced with other factors, for example: snow mechanisms, effects of freezing, and effects of the biological activity. These could complement this model, but are considered too complex for the aims of this chapter.



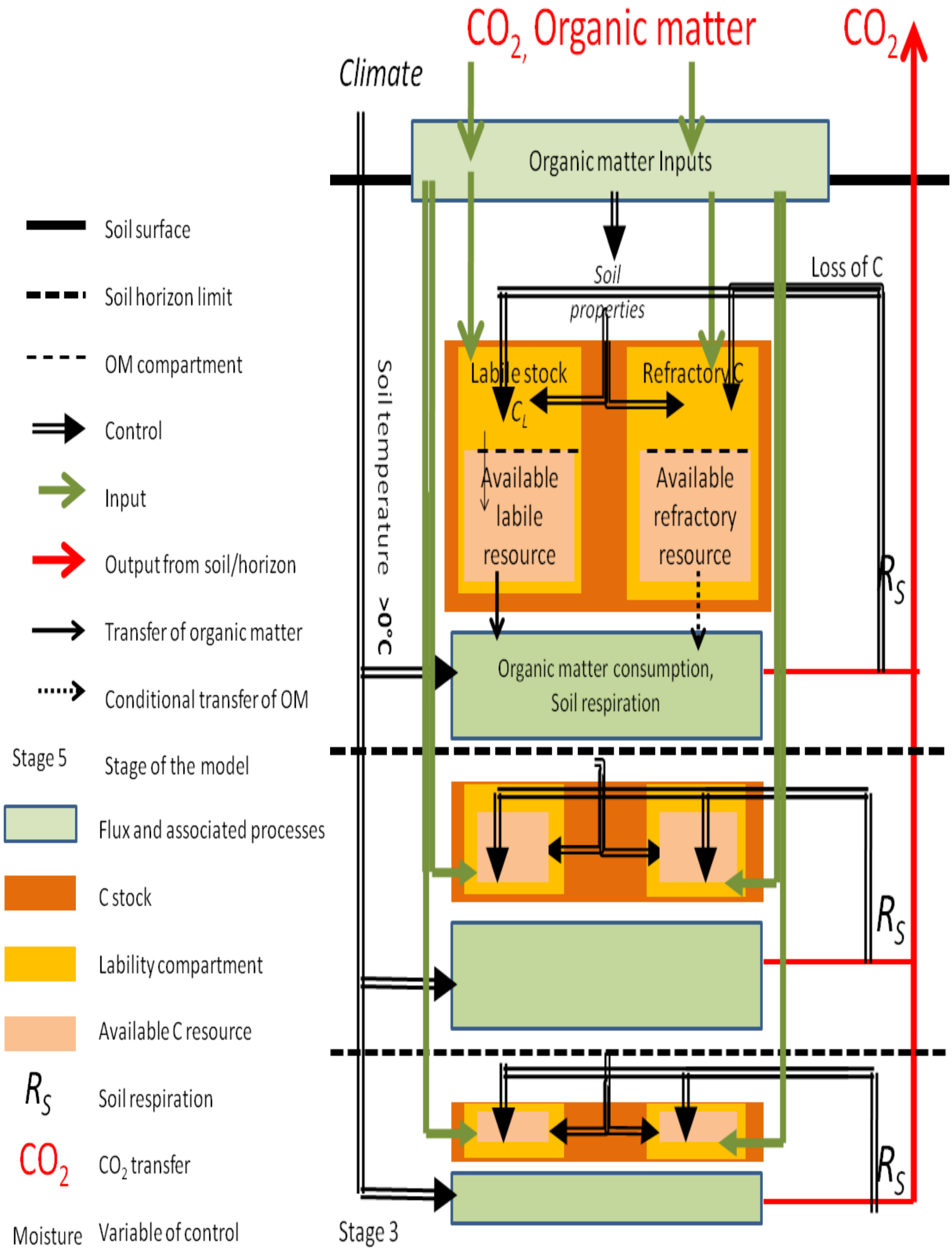
a)

Figure 4.2 a: Stage 1 structure with the inputs of CO_2 and organic matter going into the soil and ending up either in the labile or recalcitrant C compartment; the respiration rate is only function of the temperature; variables are explained in Appendix A4.1.



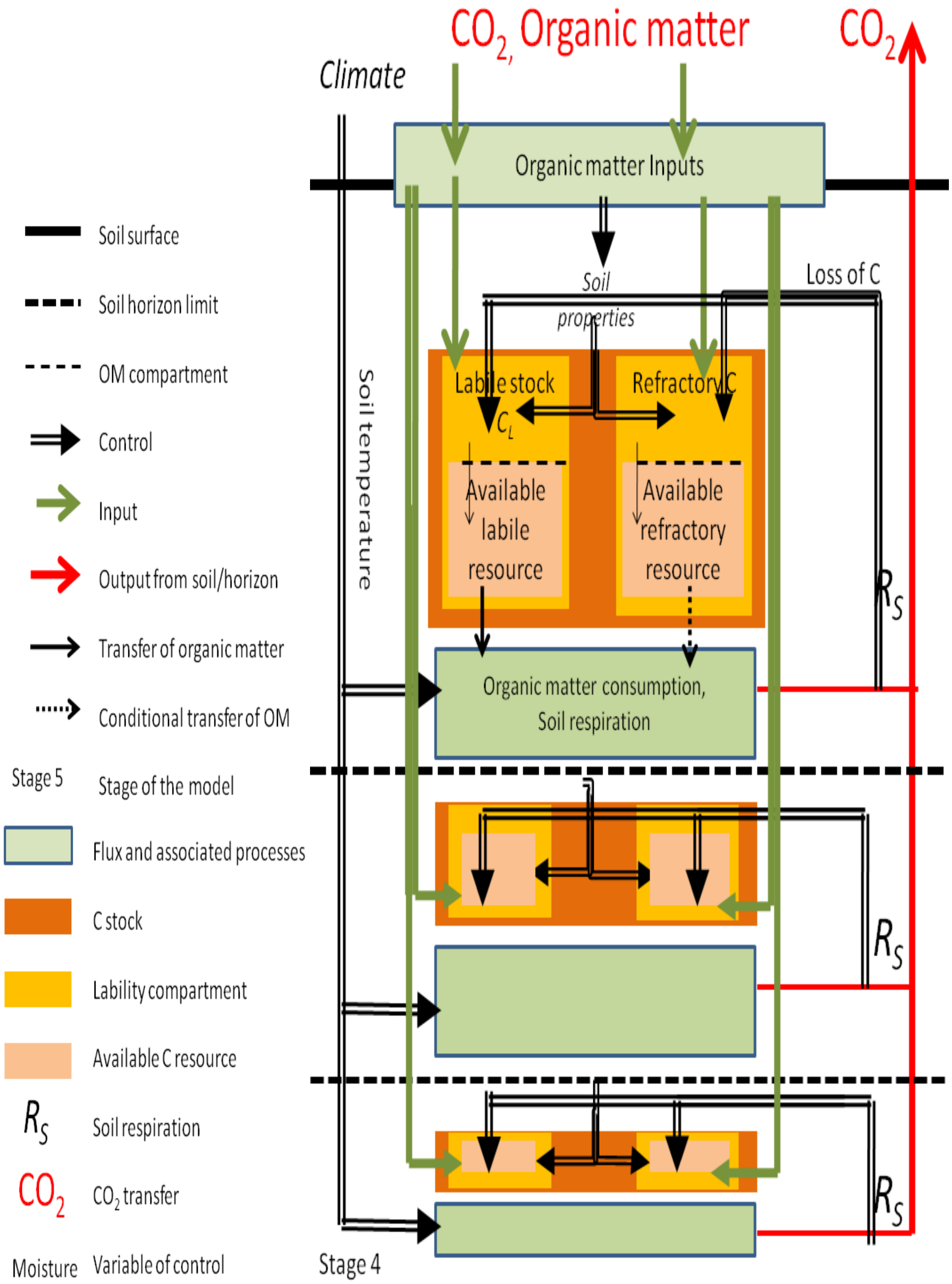
b)

Figure 4.2 b: Stage 2 structure with several soil horizons; the inputs of CO_2 and organic matter going into the soil and ending up either in the labile or recalcitrant C compartment; the respiration rate is only function of the temperature; variables are explained in Appendix A4.1



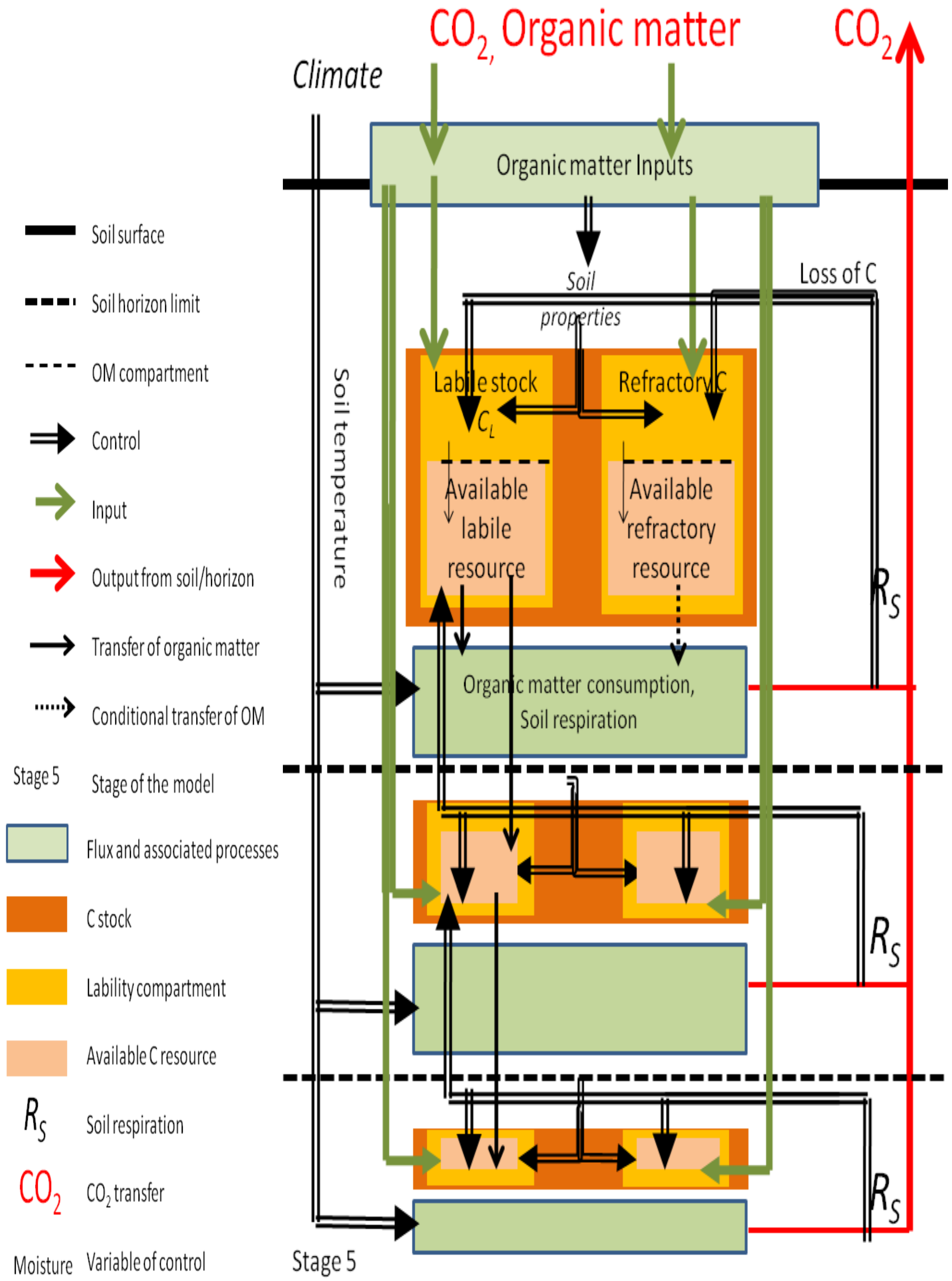
c)

Figure 4.2 c: Stage 3 structure with several soil horizons; the inputs of CO_2 and organic matter going into the soil and ending up either in the labile or recalcitrant C compartment; the respiration rate is only function of the temperature and can use the stocks of labile C; variables are explained in Appendix A4.1



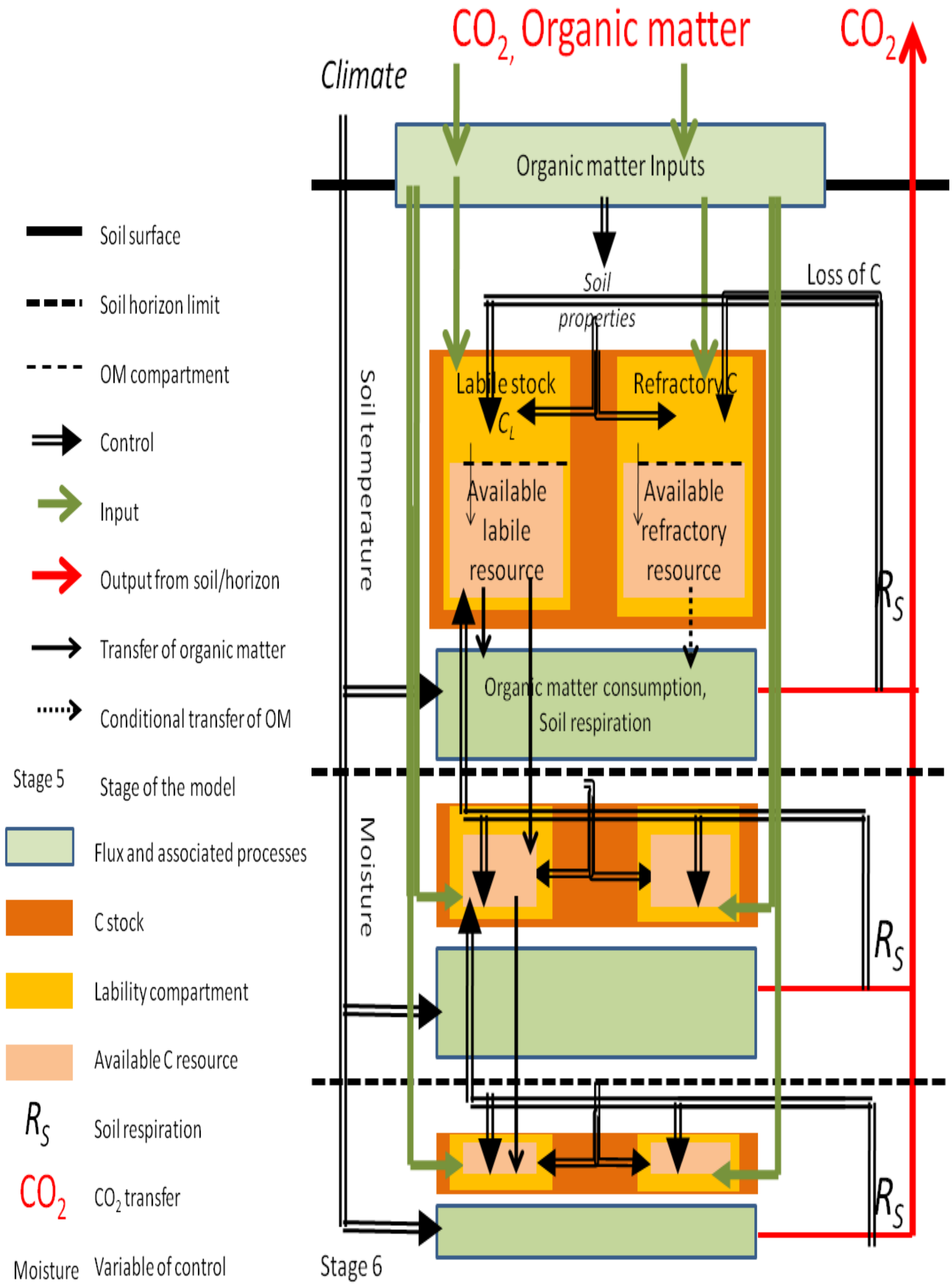
d)

Figure 4.2 d: Stage 4 structure with several soil horizons; the inputs of CO_2 and organic matter going into the soil and ending up either in the labile or recalcitrant C compartment; the respiration rate is only function of the temperature and can use the stocks of labile and recalcitrant C; variables are explained in Appendix A4.1



e)

Figure 4.2 e: Stage 5 structure with several soil horizons; the inputs of CO_2 and organic matter going into the soil and ending up either in the labile or recalcitrant C compartment; the respiration rate are function of the temperature and can only use the existing soil C stocks; variables are explained in Appendix A4.1



f)

Figure 4.2 f: Stage 6 structure with several soil horizons; the inputs of CO_2 and organic matter going into the soil and ending up either in the labile or recalcitrant C compartment; the respiration rate is function of the temperature and the moisture; variables are explained in Appendix A4.1

4.3.5.2 Soil column

The initial stage (Stage 1) simulates the whole area as a single homogeneous type of soil column and vegetation cover (Fig. 4.2 a; Tables 4.1 and 4.2). In effect, this mimics many coupled land-atmosphere climate models, such as the Canadian Centre for Climate modelling and analysis Earth System Model (CCCmaESM1), where the C is attributed to different pools but no depths distribution is described (Arora *et al.*, 2009), and the Hadley Centre's coupled climate–carbon cycle general circulation model (GCM) HadCM3LC before it is coupled with the Rothamsted RothC model (Jones *et al.*, 2005). These models do use different pools for the soil C that will be introduced at later Stages of the model (Fig. 4.2 b to f). Using several pools is advised but using several soil depths is not always mentioned (Knorr *et al.*, 2005). Stage 5 (Fig. 4.2 e) connects the different horizons by allowing the use of soil organic matter from the horizons above. This principle is used in models such as the Rothamsted Roth-PC1 (Jenkinson and Coleman, 2008) with more interactions between its components than the present model.

The homogeneity of the soil column in terms of organic matter lability in Stage 1 (Fig. 4.2 a) is similar to the simplifications made when upscaling soil properties over large areas based on the vegetation cover or soil type. This is necessary when large areas of the terrestrial Arctic are difficult to access and study (for example permafrost soils; Zimov *et al.*, 2006). The initial column measures one cubic metre to ease calculations. The initial composition is taken as being homogeneous in the three dimensions (no differentiated horizons) and all existing stocks and inputs of soil organic matter and C are readily available for respiration (i.e. labile). A distinction is made between birch forest and tundra heath as vegetation covers.

For stages 2 to 6 (Fig. 4.2 b to f), two series of values are used in the model, to represent the IV and the Abisko transect. These areas differ by their topographic position and the composition of their soil profiles. For each of these areas, most of the values used in the model come from the field data. However, as no incubation experiment could be realised, the thermodynamic parameters values are obtained from the literature. For the tundra heath and forest soils, they are considered similar in the IV and the AT. For the other soil types (snow beds, exposed heath and wetland soils), no specific values were found in the literature so they were attributed the forest values (forest snow bed) or tundra values (tundra snow bed, wetland, exposed heath) (Table 4.2). Horizons are differentiated and several respiration series are used for each soil.

Most soil parameters (bulk density, carbon content, stone content and depth) were obtained in the field studies (Table 4.2). Data on the lability and mean residence time of the labile and recalcitrant fractions come from ^{14}C experiments conducted on similar soils from Abisko by Hartley *et al.* (2011, in prep).

4.3.5.4 Inputs

At the initial stage, and for no increased temperature, the system is assumed (correctly, or not) to be in equilibrium. Therefore, the inputs corresponding to each of the data series intervals are a fraction of the initial total or labile C stock, according to the initial labile percentage and mean residence time of the OM.

4.3.5.5 Respiration

The respiration parameters for the Arrhenius Equation (Eq. 1) are different for the birch forest and tundra heath: both activation energy Ea and pre-exponential factor A are higher for the birch forest (from a study of similar Abisko soils by Sjögersten and Wookey, 2002a).

The respiration is first calculated for areas consisting only of birch forest or tundra heath. To simulate respiration for the IV at this stage, this landscape is simplified and parameterised as if it constituted entirely of birch forest and tundra heath (Fig. 4.1 a). Their proportions were previously estimated, through mapping based on aerial photographs, as being 23.9% birch forest and 76.1% tundra heath, for a total area of 0.35 km^2 (see Chapter 3). At stage 6 (Fig. 4.1 c and 4.2 f), the different vegetation categories cover respectively: 0.082 km^2 for the forest (23.87%); 0.064 km^2 for the tundra (18.43%); 0.002 km^2 for the snow bed situated in the forest (0.72%); 0.017 km^2 for the snow bed in the tundra heath (4.93%); 0.13 km^2 for the ridges (38.82%) and 0.048 km^2 for the wetlands (13.96%).

4.3.5.6 Relations between respiration, inputs and C stocks

The relations between soil C stock, soil respiration and C inputs to the soil are made more complex with each model stage. In Stages 1-2 (Fig. 4.2 a and b, Table 4.1 and 4.2) they are considered as independent, with respiration being only a function of the temperature, fixed inputs and C stocks receiving the inputs and losing the value of respiration from the labile stock.

From Stage 3 (Fig. 4.2 c), inputs are differentiated between labile and recalcitrant. Their values have been estimated from the lability percentage and mean residence times of the OM in these soils from Hartley and colleagues (2011, in prep). The residence times for the mineral horizons were not obtained in this study, so the values used here were obtained by the turnover time/depth curves for these soils, even if the progression in different soil horizons will differ. The resulting values give highly recalcitrant layers with turnover rates that can exceed 1000 years (Table 4.2). Thus, the "less recalcitrant" fractions of the mineral horizons are not made in fact of truly labile OM, and their respiration rates should reflect this. When the labile stock is depleted, recalcitrant inputs are then metabolised (von Lützow and Kögel-Knabner, 2009).

The layers should be further differentiated in their Arrhenius Equation parameters, as layers with lower decomposition rates and more complex organic structures, i.e. recalcitrant, are hypothesised to have higher sensitivity to temperature (Knorr *et al.*, 2005; von Lützow and Kögel-Knabner, 2009). Other models use the same parameters for all of their pools (Knorr *et al.*, 2005).

From Stage 5 (Fig. 4.2 e), the respiration is influenced by the quantity of labile and total C stock left in the horizons. If a stock is completely depleted, the respiration metabolises the available stock of the compartment above, if there is one. These conditions stay the same for Stage 6.

One of the objectives in linking soil respiration, C inputs and C stocks, is the estimation of the soil C stocks (labile and total) and fluxes dynamics over the next few decades to complement the study on C fluxes. This is done by taking out the annual cumulative respiration (g CO_2 m^{-2} yr^{-1}) from the C stocks while adding the annual C inputs. This is repeated over 50 years to get the trends in soil C stocks increase or depletion in the near future and estimate if the IV can be a C sink or a C source during this period. This simulation is based on the assumption that the inputs derived from the mean residence times and labile fraction in the soil are steady (system in equilibrium; as in Knorr *et al.*, 2005). If C effluxes and changes in labile C stock dominate on short timescales, the changes in total C stocks are driven by the behaviour of the recalcitrant OM (Knorr *et al.*, 2005).

4.3.5.7 Relation between moisture and respiration

Soil temperature and soil moisture are considered as the primary physical controls on soil respiration. Some studies of the influence of temperature on soil respiration assume soils with no moisture limitations (Lloyd and Taylor, 1994). A study by Elberling (2003) shows limitation to soil respiration in a tundra heath soil from Greenland for soil water contents lower than 5% and greater than 35% per volume. The equations governing the relation between soil moisture and respiration in these conditions are polynomial equations with specific factors (Elberling, 2003). These factors need to be estimated for each soil and consequently new laboratory experiments are needed to adapt these equations to Abisko soils. In the model, moisture control is added at Stage 6 as a simple condition in the respiration equation (Fig. 4.2 f): respiration only occurs for the 5-35 m^3/m^3 soil moisture content range. This is the only indirect way soil freezing is accounted for in the model, but more effects could be introduced in later versions. The moisture series used are the ones obtained from the 2008/2009 field season.

Table 4.2: Model parameters for Stage 1 (see text) tundra heath and birch forest simulation, for the other stages' IV tundra heath and birch forest soil profiles, and transect birch forest soil profiles

	Birch forest	Tundra heath	IV Birch organic	IV Birch eluvial	IV Birch illuvial	IV Tundra organic	IV Tundra mineral	Birch forest transect organic	Birch forest transect mineral
Arrhenius A (mol CO_2 m^{-2} s^{-1})	$7.62\ 10^{27}$	$2.33\ 10^{21}$	$7.62\ 10^{27}$	$7.62\ 10^{27}$	$7.62\ 10^{27}$	$2.33\ 10^{21}$	$2.33\ 10^{21}$	$7.62\ 10^{27}$	$7.62\ 10^{27}$
Activation energy Ea ($J.mol^{-1}$)	180267	145146	180267	180267	180267	145146	145146	180267	180267
Q_{10} factor	5.3	3.3	5.3	5.3	5.3	3.3	3.3	5.3	5.3
Bulk density ($g.cm^{-3}$)	0.66	0.32	0.18	0.56	0.36	0.58	0.98	0.48	1.8
Carbon content (%)	28	41.9	41.8	19.6	19.7	34.8	8.5	46.3	9.07
Rock content (%)	8	0	0	4.88	10.43	0	5	0	7
Depth (cm)	100	100	5	4	6.5	8	20	5.1	2.3
Labile fraction (%)	100	100	78.2	50	50	77.4	50	76.6	50
MRT (less recalcitrant) (years)	20	20	45	1075	1250	35	300	45	1075
MRT (recalcitrant) (years)	--	--	1075	1250	3000	300	600	1075	1500

Table 4.2: Model parameters for transect tundra heath profiles, for Stages 4 to 6 snow beds profiles and for Stage 6 Exposed heath and Sedges and wetlands soil profiles

	Tundra heath transect organic 1	Tundra heath transect organic 2	Tundra heath transect organic 3	Snow bed forest organic	Snow bed forest mineral	Snow bed tundra organic	Snow bed tundra mineral	Exposed heath organic	Exposed heath organic	Sedges and wetlands organic 1	Sedges and wetlands organic 2
Arrhenius A (mol CO_2 m^{-2} s^{-1})	$2.33\ 10^{21}$	$2.33\ 10^{21}$	$2.33\ 10^{21}$	$7.62\ 10^{27}$	$7.62\ 10^{27}$	$2.33\ 10^{21}$	$2.33\ 10^{21}$	$2.33\ 10^{21}$	$2.33\ 10^{21}$	$2.33\ 10^{21}$	$2.33\ 10^{21}$
Ea Activation energy ($J.mol^{-1}$)	145146	145146	145146	180267	180267	145146	145146	145146	145146	145146	145146
Q_{10} factor	3.3	3.3	3.3	5.3	5.3	3.3	3.3	3.3	3.3	3.3	3.3
Bulk density ($g.cm^{-3}$)	0.16	0.17	0.27	0.22	1.07	0.77	0.91	0.08	0.18	0.06	0.13
Carbon content (%)	44	48	41	40.12	2.58	30.4	12.3	49.25	20.9	50.3	45.3
Rock content (%)	0	0	0.1	0	1	0	1	0	20	0	0
Depth (cm)	3.75	3.75	12.2	10.8	12	12	8.3	2.8	3	11.5	18.5
Labile fraction (%)	82.8	82.6	50	78.2	50	77.4	50	50	5	100	20
MRT (less recalcitrant) (years)	35	200	500	20	1075	20	1075	20	50	30	150
MRT (recalcitrant) (years)	100	500	1500	100	2000	100	2000	50	1200	90	350

4.4 Results

4.4.1 Temperature and moisture datasets (*H_1*)

The heterogeneous cover of the IV is matched by the differences in thermal regimes at soil surface (5 cm) and at depth (10 and 15 cm). Quantifying soil thermal regime is important for identifying soils that may be especially sensitive to any increase in mean annual and winter temperatures. The curves for all depths and for the Intensive Valley and the Abisko Transect have been grouped by soil type (Fig. 4.3).

In winter, soils either experience a series of cold temperatures ‘peaks’ (tundra heath, exposed heath; Fig. 4.3 a, c) or a relatively stable temperature close to 0°C (riparian soils, snow beds, shrub tundra; Fig. 4.3 a, c, d). Most forest series show protracted relatively stable temperatures higher than -5°C, the only series showing greater contrast in temperatures (plot slightly more exposed) in winter still does not reach the extreme low temperatures of the tundra heath (Fig. 4.3 b). If temperatures remain in this range, even relatively small changes in temperature could have a disproportionally large effect on the amount of liquid water in the soil, and this will be critical for rates of decomposer metabolism, and thus soil respiration. This contrast between insulated soils and exposed ones is reflected in the temperatures’ frequencies distributions for these soils during the cold season (here defined as October through May; Fig. 4.4). Soils are either well insulated, with a high frequency of temperatures around 0°C (forest series, shrub tundra, snow beds; Fig. 4.4) or their temperature frequency distribution is skewed towards lower values (tundra series, exposed heath; Fig. 4.4). The presence of shrubs offers more insulation to soils and this type of tundra is found in more sheltered landscape positions (Fig. 4.1a) in contrast to the other tundra plots. The soils with high water content (riparian, wetlands; see Fig. 4.5) have temperatures between -5°C and 0°C too but their spread is more even than for the snow beds. The changes in temperatures in riparian and wetland soils are less buffered than for the snow beds (Fig. 4.3 c and 4.4).

Temperatures logged under similar vegetation types at different locations (here tundra heath plots and birch forest plots) present less differences than the inter-annual variation between series logged in the same soil (Fig. 4.3 a and b).

These differences in soil temperatures over a small area or distance (3.5 km^2 for the IV, 2.9 km for the transect), coupled with the differences in soil properties in soils under similar vegetation covers (Table 4.2) show the potential for differing reactions to a same increase in mean annual temperature.

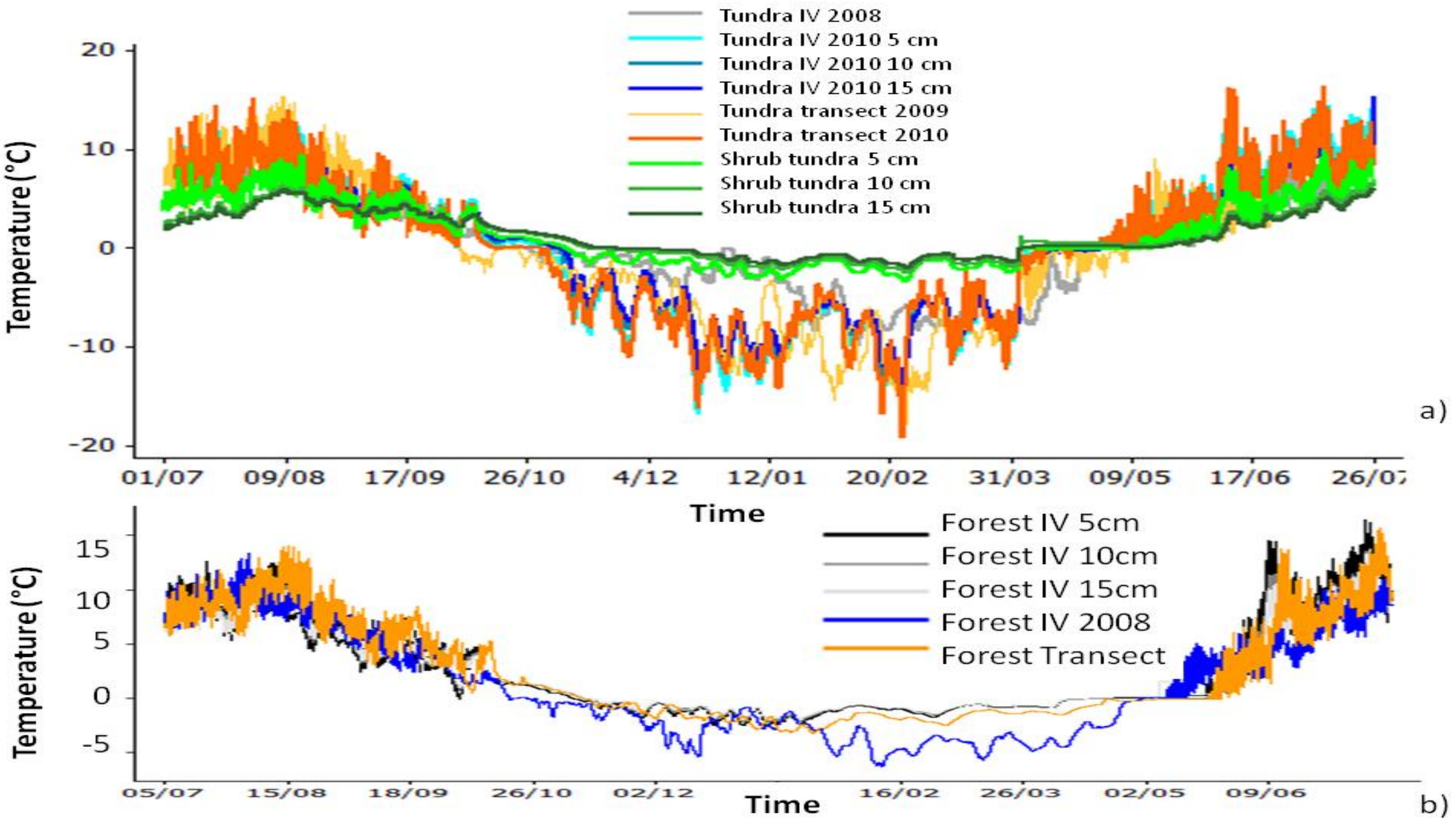


Figure 4.3: Temperature series (°C) for the tundra heath series (a) and birch forest series (b)

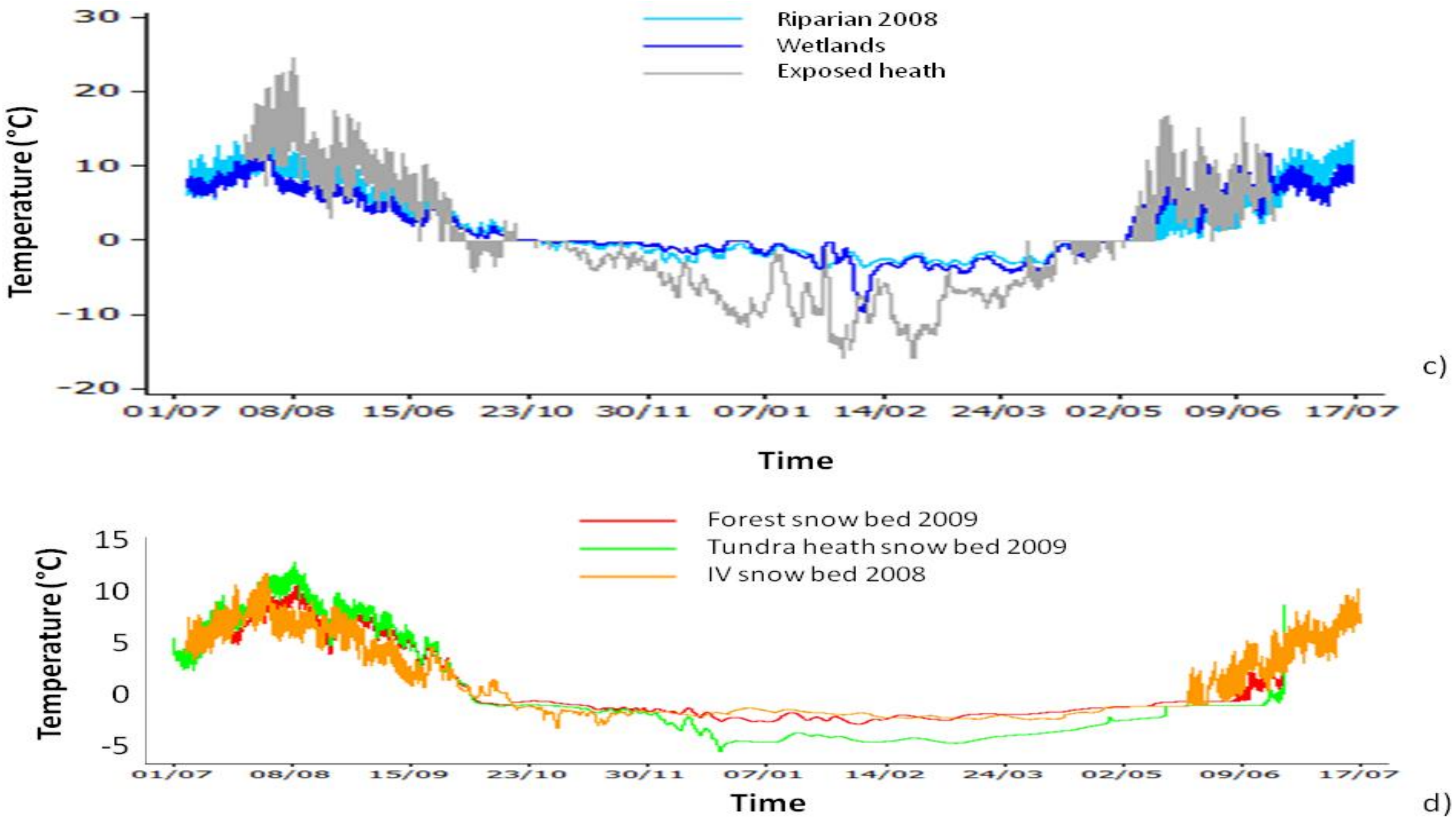


Figure 4.3: Temperature series (°C) for the exposed heath, riparian and wetlands series (c) and snow beds series (d)

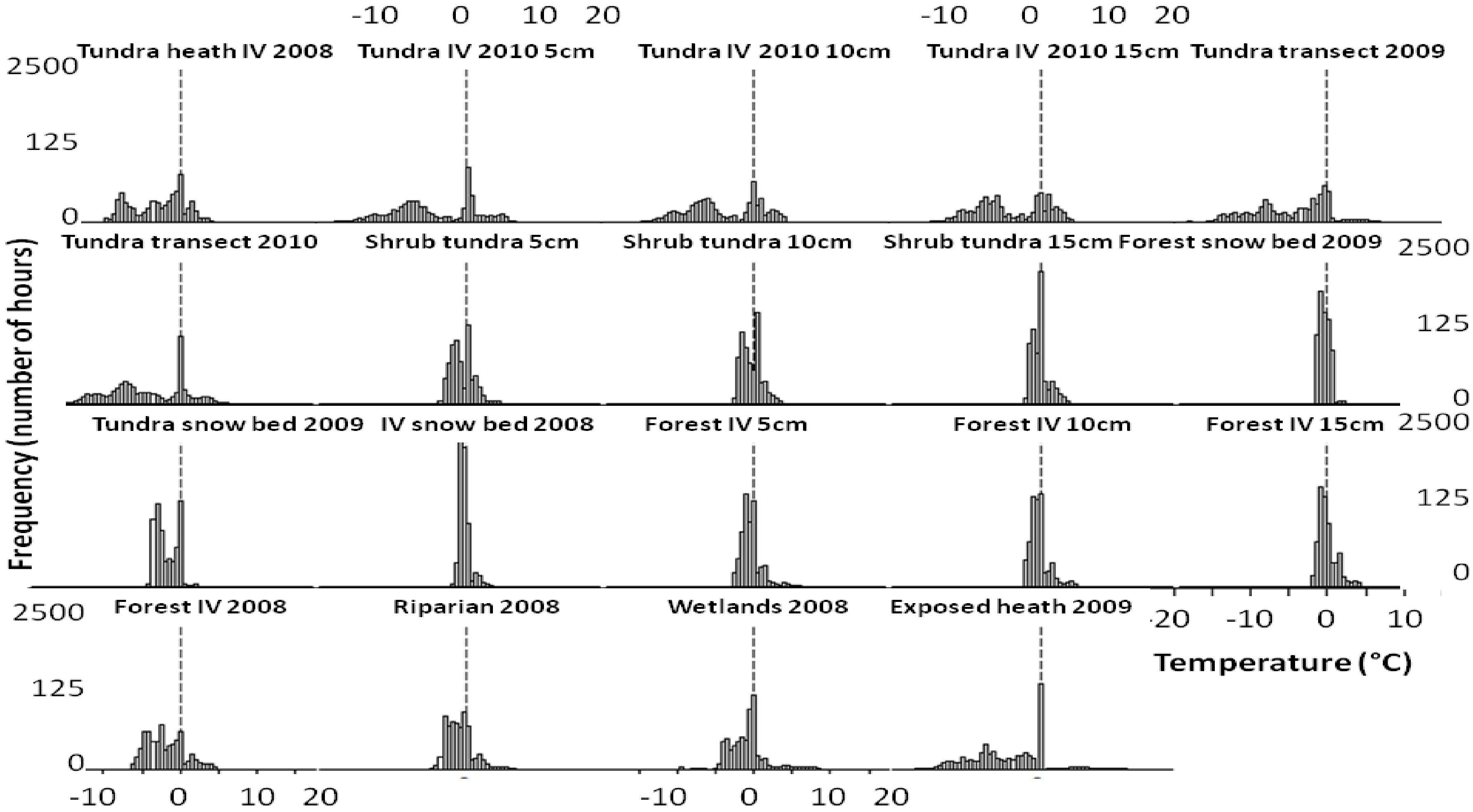


Figure 4.4: Frequencies in the -10 to 20°C temperature range for October through May for Abisko soils under different vegetation categories

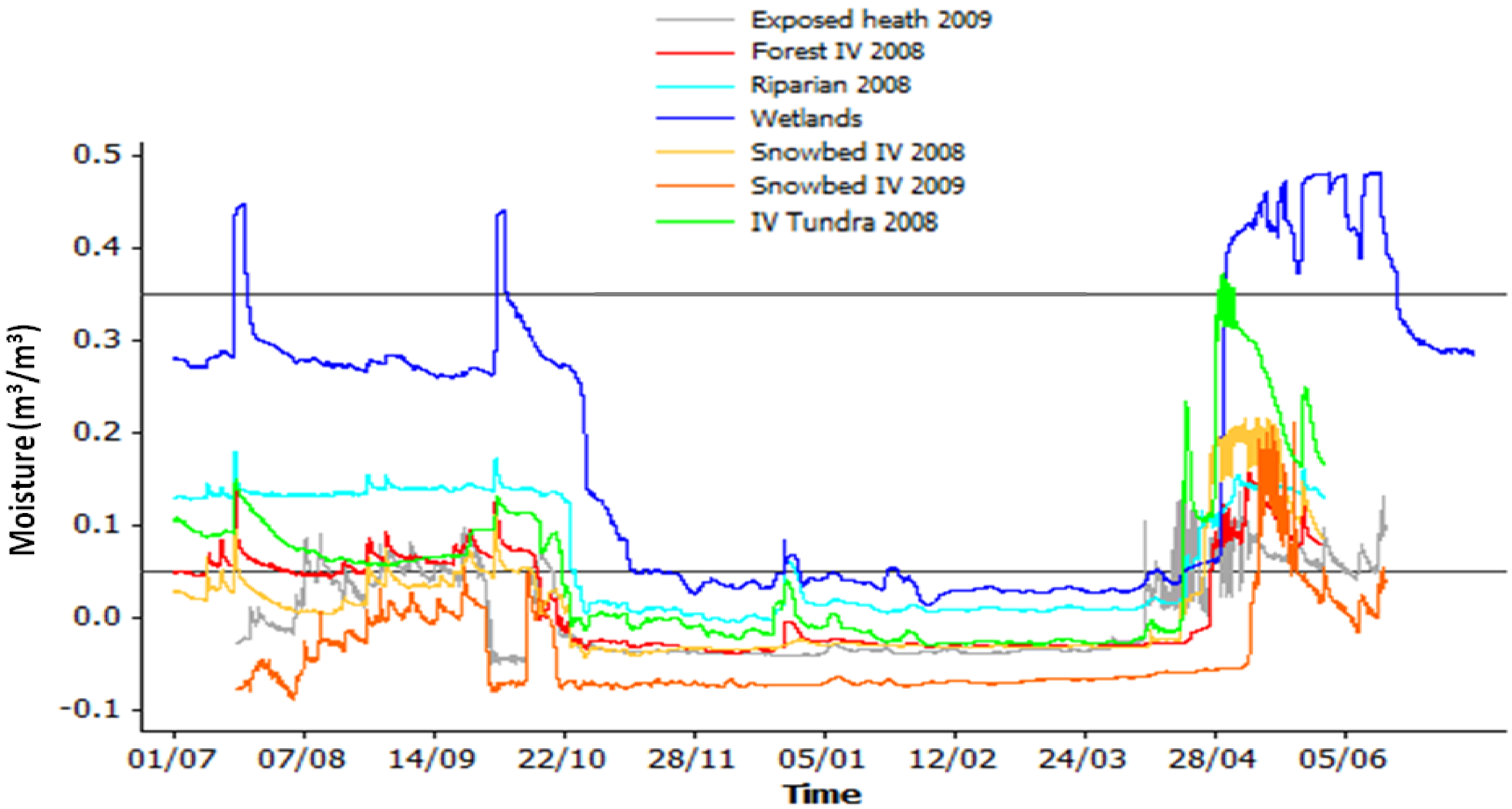


Figure 4.5: Moisture series (m^3/m^3) in the Intensive Valley for soils under different vegetation categories, with reference lines for the 0.05 m^3/m^3 and 0.35 m^3/m^3 thresholds

Moisture series of the different IV soils present common patterns (Fig. 4.5). The lowest moisture contents are found in August and during the winter (end of October-April) and the highest during the snow melt season (April-May). The ranges of moisture contents follow the characteristics of the soils. The tundra heath and birch forest are mesic plots and their moisture contents are between the higher values of the riparian and wetland soils and the slightly lower values of the exposed heath. The winter moisture contents for the snow beds are low as well in 2009. These soils keep a more stable water content, as the snow beds do not get the moisture peak present at the beginning of January for the other soils.

The negative values are due to the difficulties in getting accurate moisture contents in some types of soils and at low temperatures. The probes are recognised by the manufacturer itself as being less efficient in organic soils and at low temperatures, because of the potentially larger errors due to the influences of bulk density and volume of frozen water on the dielectric permittivity and volumic water content relationship (Yoshikawa and Overduin, 2005; Cobos, 2010).

4.4.2 Respiration equations and soil sensitivity to warming (*H_1, H_2, H_3*)

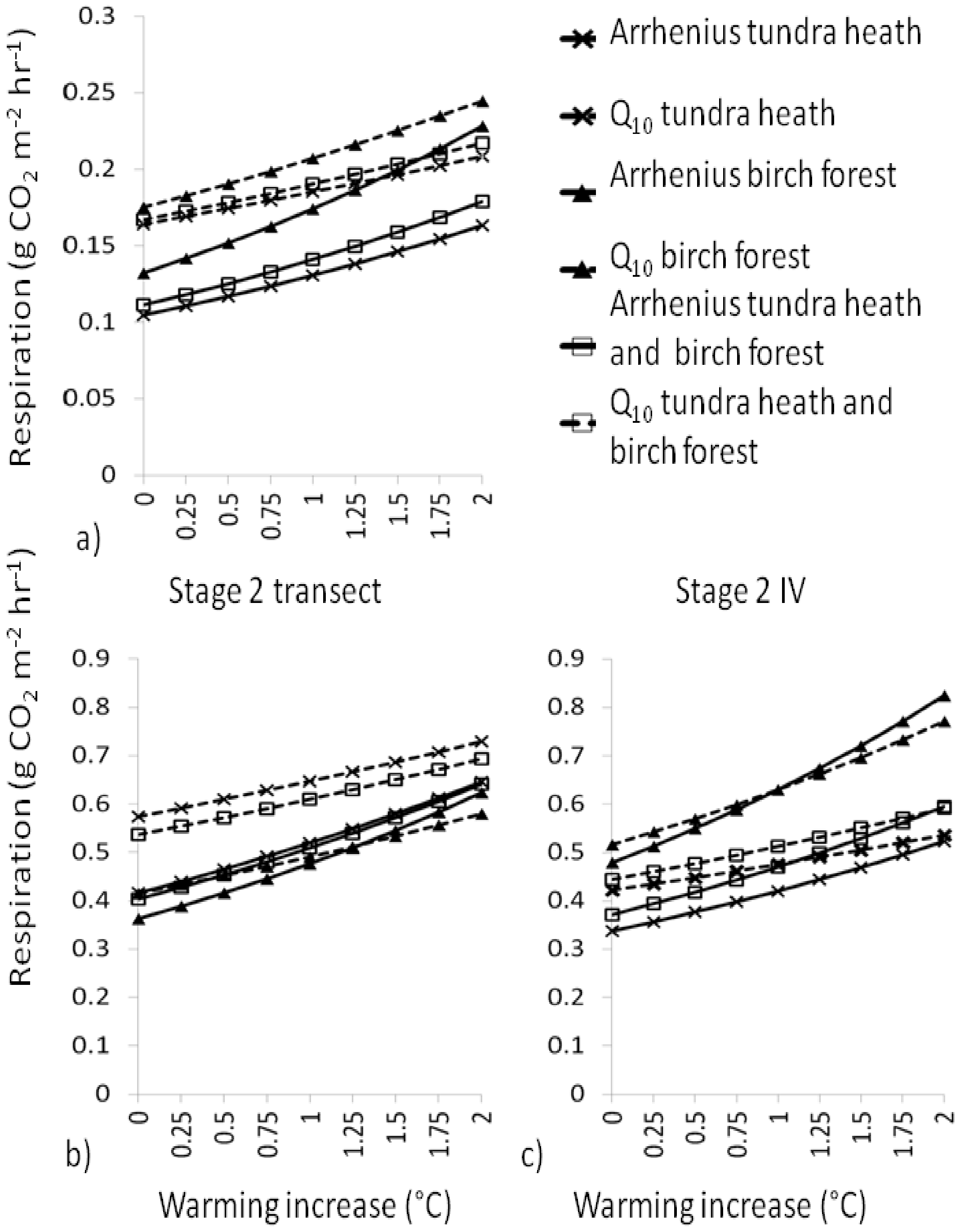


Figure 4.6: Annual average soil respiration (g CO_2 m^{-2} hr^{-1}) simulated for increases in mean soil temperature from 0 to 2°C for tundra heath and birch forest soils (Stage 1 (a)) and using parameters from the transect profiles (Stage 2 (b)) and IV profiles parameters (Stages 2 (c))

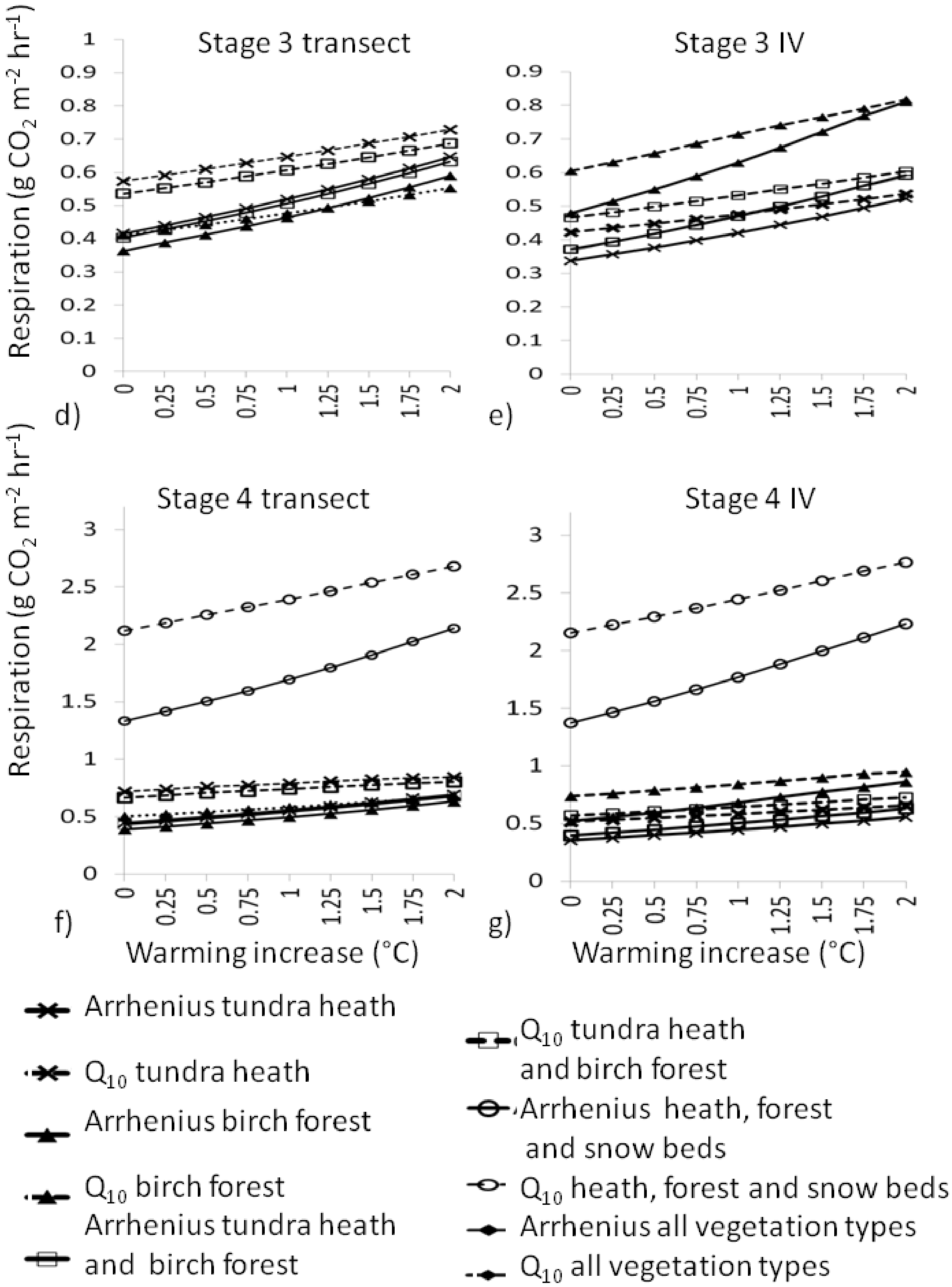


Figure 4.6: Annual average soil respiration (g CO_2 m^{-2} hr^{-1}) simulated for increases in mean soil temperature from 0 to 2°C for tundra heath, birch forest and snow beds soils using parameters from the transect profiles (Stages 3 (d), 4 (f)) and IV profiles parameters (Stages 3 (e), 4 (g))

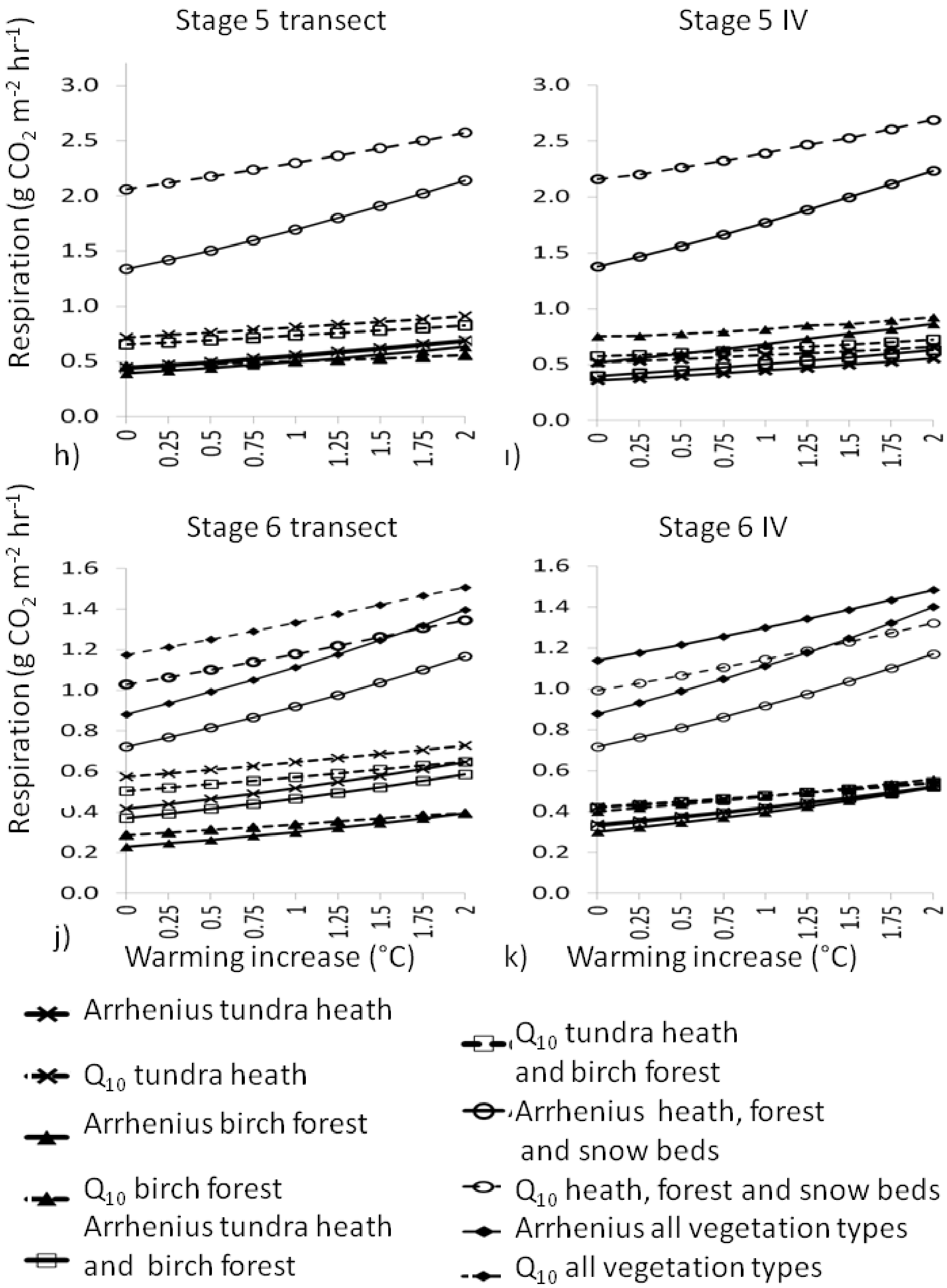


Figure 4.6: Annual average soil respiration (g CO_2 m^{-2} hr^{-1}) simulated for increases in mean soil temperature from 0 to 2°C for birch forest, tundra heath, snow beds, Exposed heath and Sedge and wetlands soils, using parameters from the transect profiles (Stages 5 (h), 6 (j)) and IV profiles parameters (Stages 5 (i), 6 (k))

The two equations (Eq. 1 and 2) used for calculating soil respiration affect the difference in average respiration (g CO_2 m^{-2} hr^{-1}) obtained after simulating increases in mean soil temperature from the present temperatures to +2°C (Fig. 4.6). If the values for mean respiration are higher for the Q_{10}, the rate of increase in response to warming is higher for the Arrhenius equation. An example is given by the Stage 3 IV birch forest data, where Arrhenius and Q_{10} estimates are similar at +2°C, despite much lower estimates for the present temperatures dataset at 0°C increase (Fig. 4.6 e).

At the different Stages of the model, the sensitivity to an increase in mean annual temperature follows the same exponential pattern whether using the Arrhenius Equation or the Q_{10} Equation (Eq. 1 and 2). However, the slopes of these curves linking increases in mean respiration to increases in mean annual temperature do change with the Stages, even when the same temperature and moisture data are used. The complexity of the model has an influence on the projected sensitivity of the soil to temperature change (Fig. 4.6).

4.4.3 Respiration series through the year and seasonality of the average temperature increase for a 2 °C warming (*H_1, H_3, H_4*)

Temperatures for the soil profiles used in the model are plotted alongside respiration data estimated with the Arrhenius and Q_{10} equations (Fig. 4.7). Within each stage, there is a difference between the results for the IV and the transect, pointing to a control by the soil properties and landscape position for soils under the same vegetation cover type (Fig. 4.7 h, i). In the IV the tundra heath values are lower, or similar to, the birch forest's (Fig. 4.7 e, g, i), but can be higher for the transect.

For all stages, respiration rates in birch forest are higher than for tundra heath in the IV (Fig. 4.7). At Stages 1 to 3, winter respiration is assumed to be negligible at all temperatures under 0°C from the respiration simulation (Fig. 4.7 a to d). Through Stages 4 to 6, winter respiration stays close to 0°C (Fig. 4.7 e to h). For both the Arrhenius Equation and the Q_{10} Equation, soil respiration changes mirror temperature changes (Eq. 1 and 2). Q_{10} values are higher than the Arrhenius values for the tundra heath and similar to the Arrhenius values for the birch forest. Arrhenius values have a greater range; each change in temperature seems more amplified than with the Q_{10} equation (for example the peak in July towards the end of the dataset; Fig. 4.7 e to l). Both methods show a plateau in respiration rates corresponding to a stable temperature during the snow melt period for tundra heath and birch forest (particularly in Fig. 4.7 e to l).

The other soils included in the model behave as the analysis of their winter temperature distribution predicted: the snow beds respiration curves are closer to the forest ones, and they have a significant activity in winter; tundra heath soils, which are less protected by snow, show more variability in their winter respiration rates (Fig. 4.7 h, m and n). However, as for the birch forest soils (Fig. 4.7 k), the introduction of limitations linked to a water content outside of the "optimum" range hinders respiration in winter as in summer (Fig. 4.7 o). Tundra heath soils do not show any such problems out of the winter period (Fig. 4.7 l). The Exposed heath and wetland categories have the potential for respiration rates similar to the other categories (Fig. 4.7 p); however, moisture limitations would impede this during most of the year.These contrasts are apparent when analysing the percentage increase in soil respiration during the year for an increase in mean temperature of +2°C using the Arrhenius equation. Forest soils are more sensitive, as respiration increases between 70% and 80% compared to between 50 and 60% for the tundra heath (Fig. 4.8 a to d). At later model stages (Fig. 4.8 e and f), winter respiration is included and is revealed as more sensitive to the increase in temperature than the summer respiration. The previously similar behaviours for birch forest and tundra heath of the percentage increase of soil respiration for increases in temperatures disappear. The tundra heath winter temperature is marked by spikes of intense cold whereas the birch forest temperature is more stable (and generally higher, see Fig. 4.3 a and b) and therefore the percentage increase reaches a plateau in winter. However, birch forest is still more sensitive to temperature increase as respiration nearly doubles for an increase of 2°C in the middle of winter (80% increase). The differences between tundra and forest snow beds appear stronger than with the respiration series for current temperatures (Fig. 4.7), with the forest snow bed closer to the forest series and tundra snow bed closer to the heath series.

Introducing limitations due to soil moisture changes (Stage 6, Fig. 4.7 k and l, 4.9 o to r) leads to limited respiration during most of the winter and short spans of summer. The complete closing of respiration mechanisms is a way to emphasise this, but it is a simplified mechanism. The next logical stage in this model would be to construct an equation for a more gradual decrease in respiration when the water content strays outwith the optimum range. Parameterising such a model would, however, require further experiments (for example soil incubation). Some results for this stage 6 are negative, for the exposed heath particularly. This shows than the current respiration rates could be higher than those resulting from an increase in mean annual temperature. The beginning of this decrease is seen in the birch forest series from stage 3 to 6: these stages see the introduction of a control on respiration rates via OM decreasing availability (Fig. 4.8 c to f).

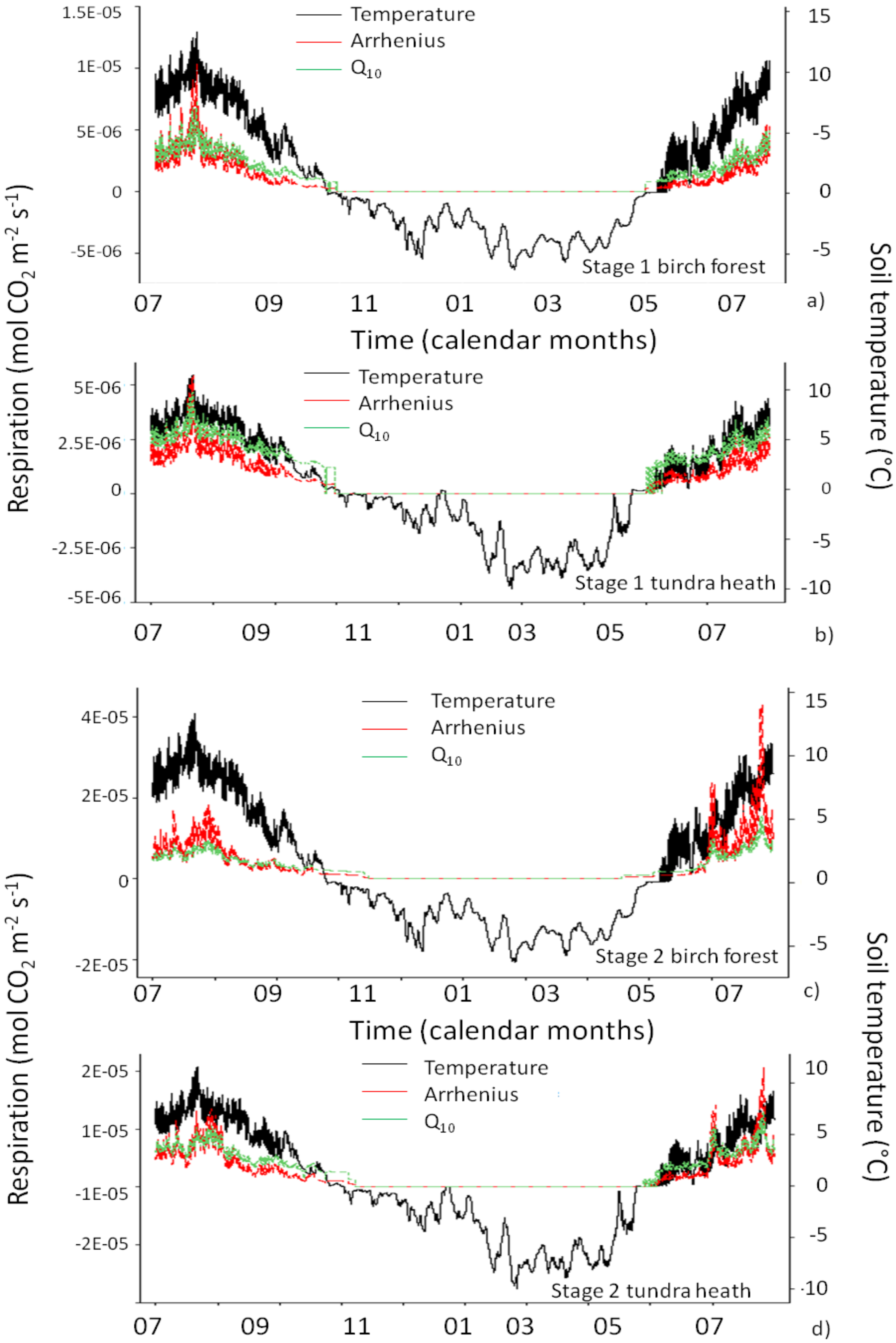


Figure 4.7: Soil respiration (mol CO_2 m^{-2} s^{-1}) estimated with the Arrhenius and Q_{10} equations for the birch forest (Stage 1, a), tundra heath (Stage 1, b), birch forest IV profile (Stage 2, c) and tundra heath IV profile (Stage 2, d) and associated temperature series (°C)

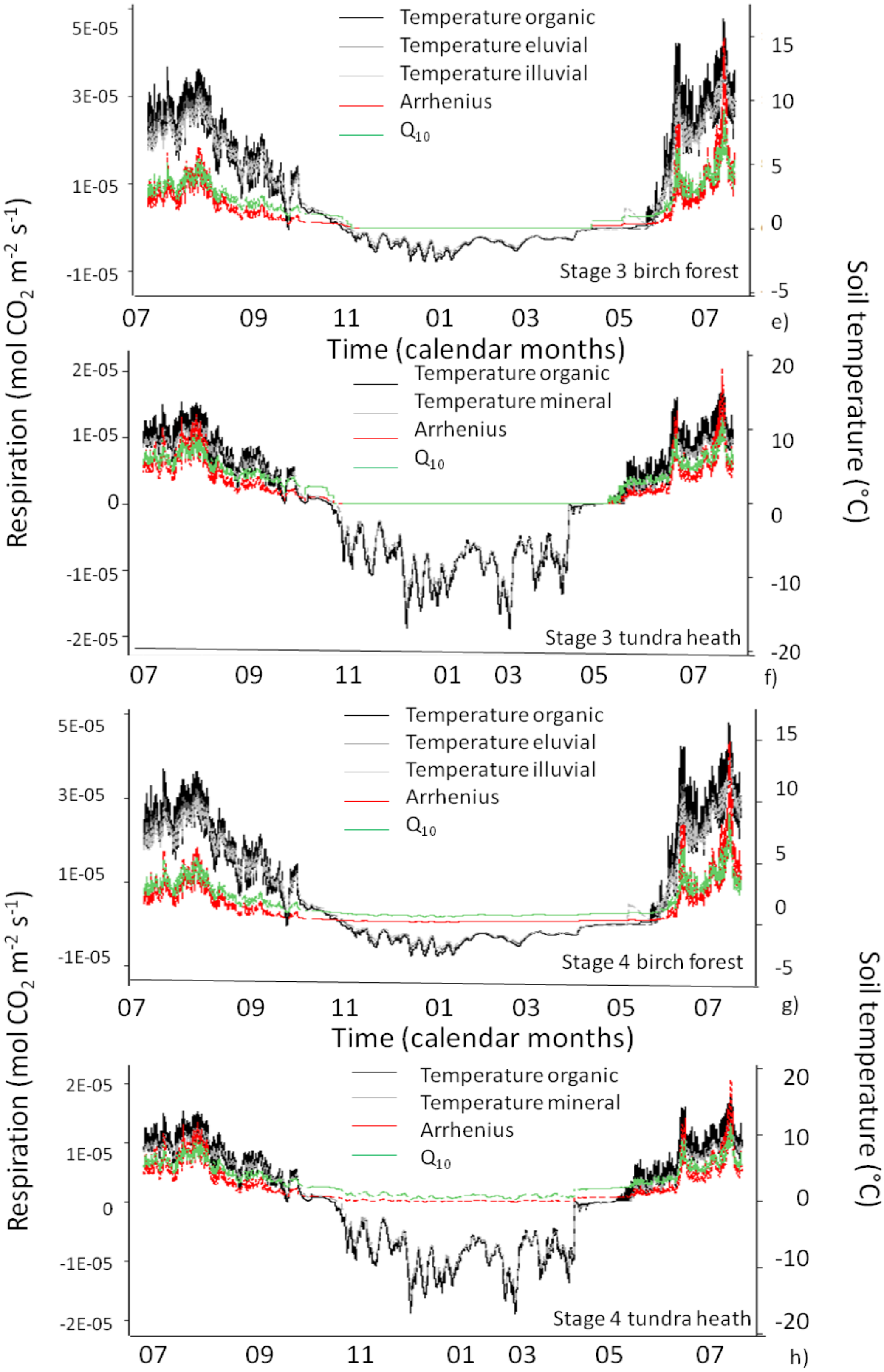


Figure 4.7: Soil respiration (mol CO_2 m^{-2} s^{-1}) estimated with the Arrhenius and Q_{10} equations for the birch forest IV profile (Stage 3, e, 4, g) and tundra heath IV profile (Stage 3, f, 4, h) and associated temperature series (°C)

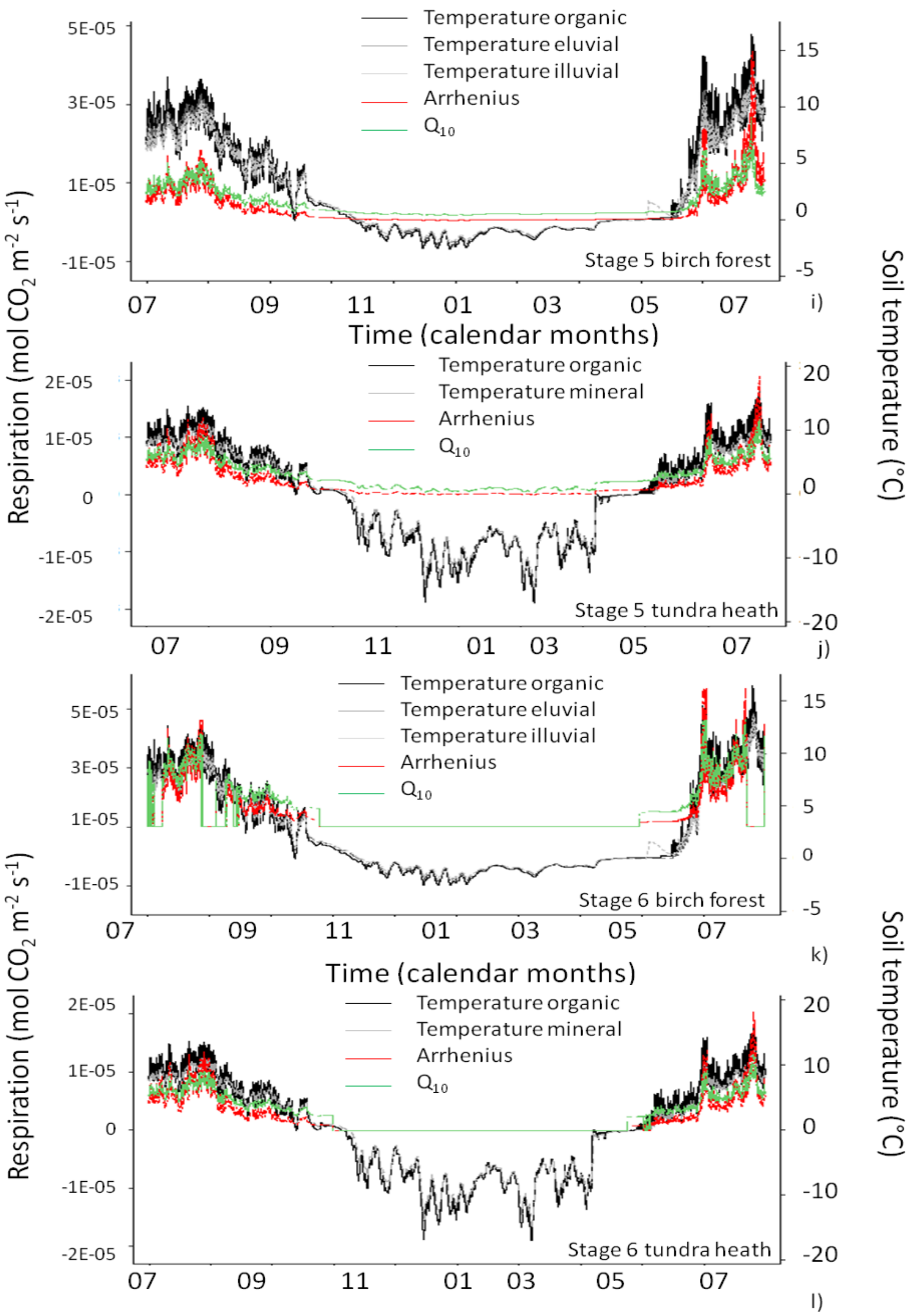


Figure 4.7: Soil respiration (mol CO_2 m^{-2} s^{-1}) estimated with the Arrhenius and Q_{10} equations for the birch forest IV profile (Stage 5, i, 6, k) and tundra heath IV profile (Stage 5, j, 6, l) and associated temperature series (°C)

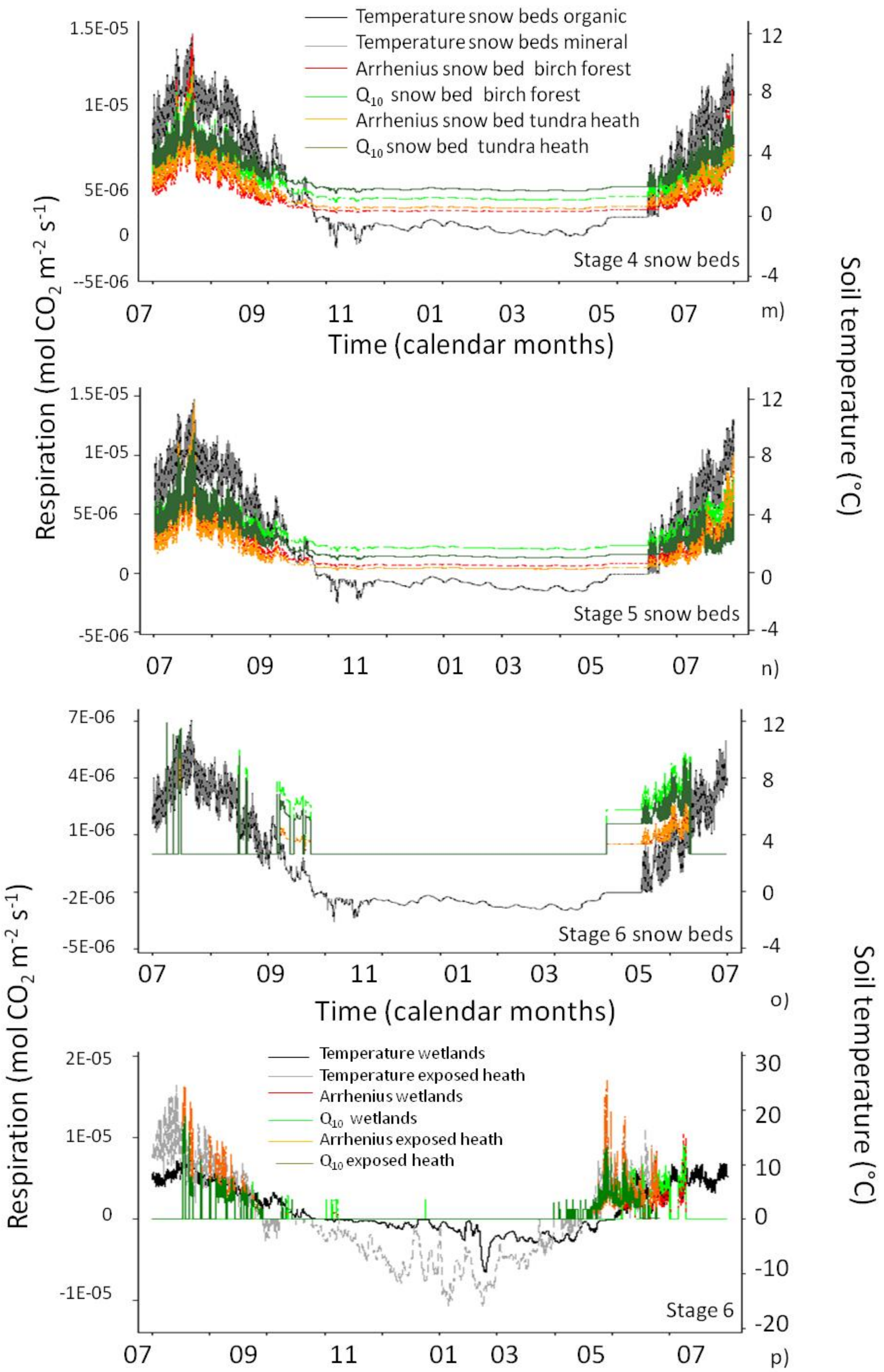


Figure 4.7: Soil respiration (mol CO_2 m^{-2} s^{-1}) estimated with the Arrhenius and Q_{10} equations for the snow beds profiles (Stage 4, m, 5, n, 6, o), Exposed heath and Sedge and wetlands soils (Stage 6, p) and associated temperature series (°C)

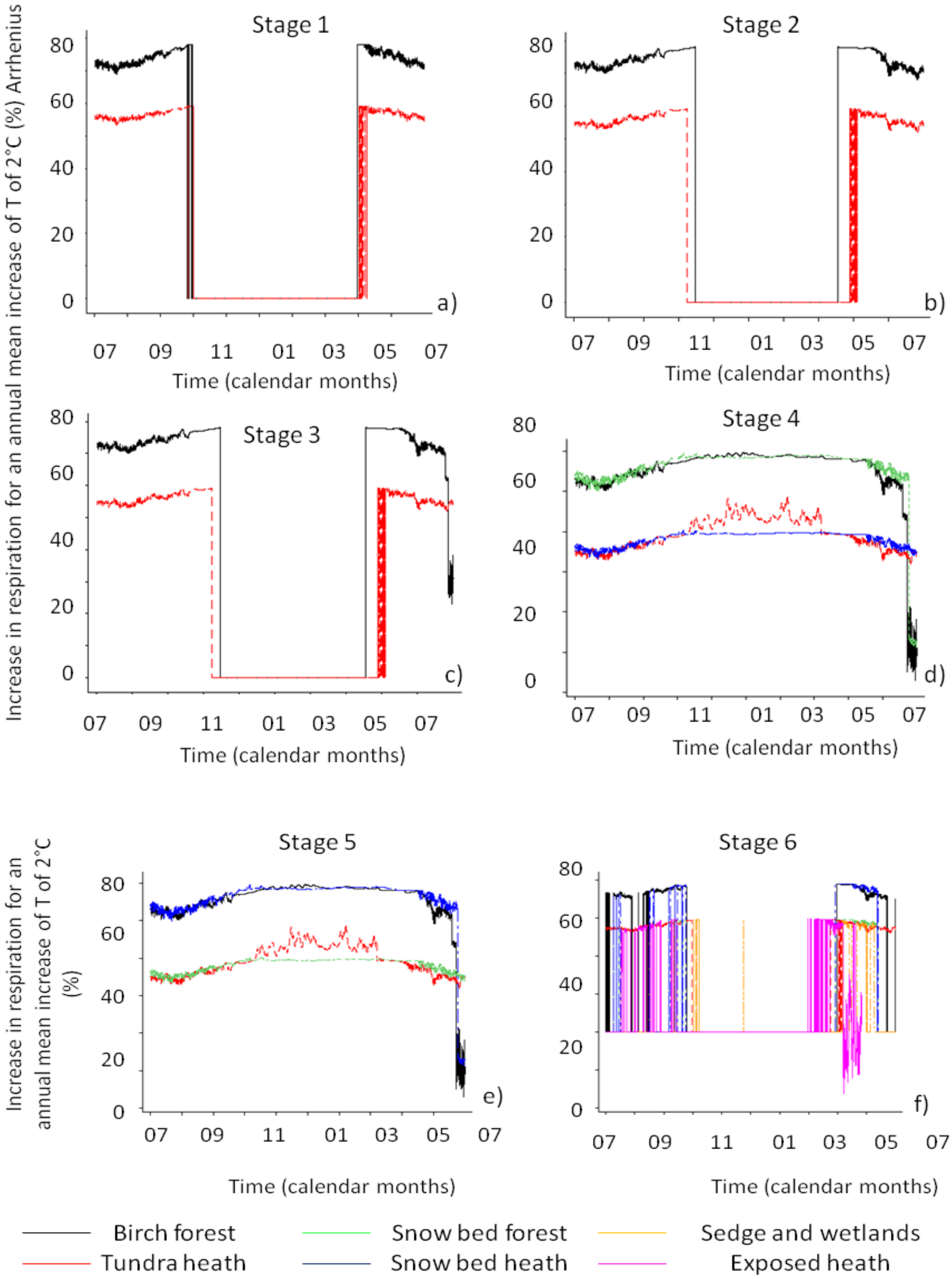


Figure 4.8: Percentage increase in soil respiration for the different soils estimated with the Arrhenius equation (Eq. 1), for a simulated increase in mean temperature of 2°C compared to present temperatures, for Stages 1 (a), 2 (b), 3 (c), 4 (d), 5 (e), 6 (f)

4.4.4 C stocks responses to warming (*H_5*)

Soil C stocks dynamics are forecast for present temperatures and for an increase in mean annual temperature of 2°C (Fig. 4.9). Under the conditions of Stage 1, stocks and inputs outweigh respiration and the resulting forecast is an increase of C stocks through time (Fig. 4.9 a and b). When the soil column is changed to field conditions for later stages, all the forecasts point towards a depletion of both labile and total C stocks (Fig. 4.9 c to v) if no changes in organic matter inputs are assumed (i.e. respiratory C losses exceed photosynthetic C gains). This happens earlier for the transect: for instance at stage 2 it takes 6 to 15 years (Q_{10}) to 16 to 21 years (Arrhenius) to deplete the total transect C stocks, with close results for 0 and +2°C increase (Fig. 4.9 e and f); for the IV: 40 years in current conditions and 25 for an increase of +2°C (Arrhenius); 21 to 33 years for Q_{10} (Fig. 4.9 c and d). These results are similar to those of Stages 3 and 4 (Fig. 4.9 g to n). Q_{10} results usually give a quicker total depletion. Including a moisture control at Stage 6 leads to a change in these patterns: using Arrhenius leads to not depleting the stocks completely if the temperature stays similar to today's conditions (Fig. 4.9 s and u); Q_{10} gives a total depletion in more than 40 years. An increase of 2°C in mean temperatures still leads to total depletion (Fig. 4.9 t and v).

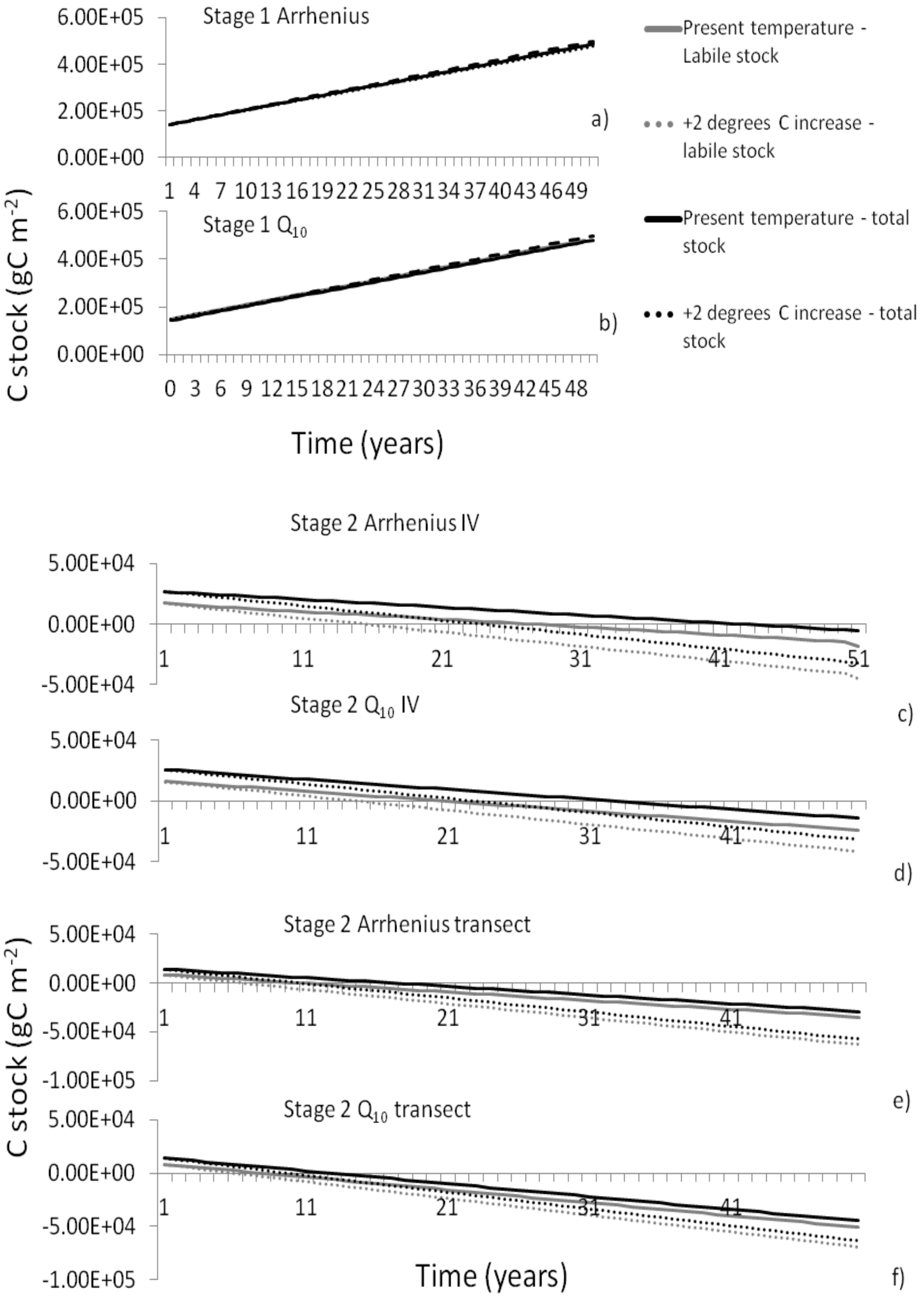


Figure 4.9: Labile and total C stocks depletion over 50 years with respiration calculated with the Arrhenius (Eq. 1) and Q_{10} (Eq. 2) equations for mean annual temperature increases of 0°C and 2°C; for the tundra heath and birch forest landscapes (Stage 1, a and b), using parameters from the IV profiles (Stage 2, c and d) and transect profiles (Stage 2, e and f)

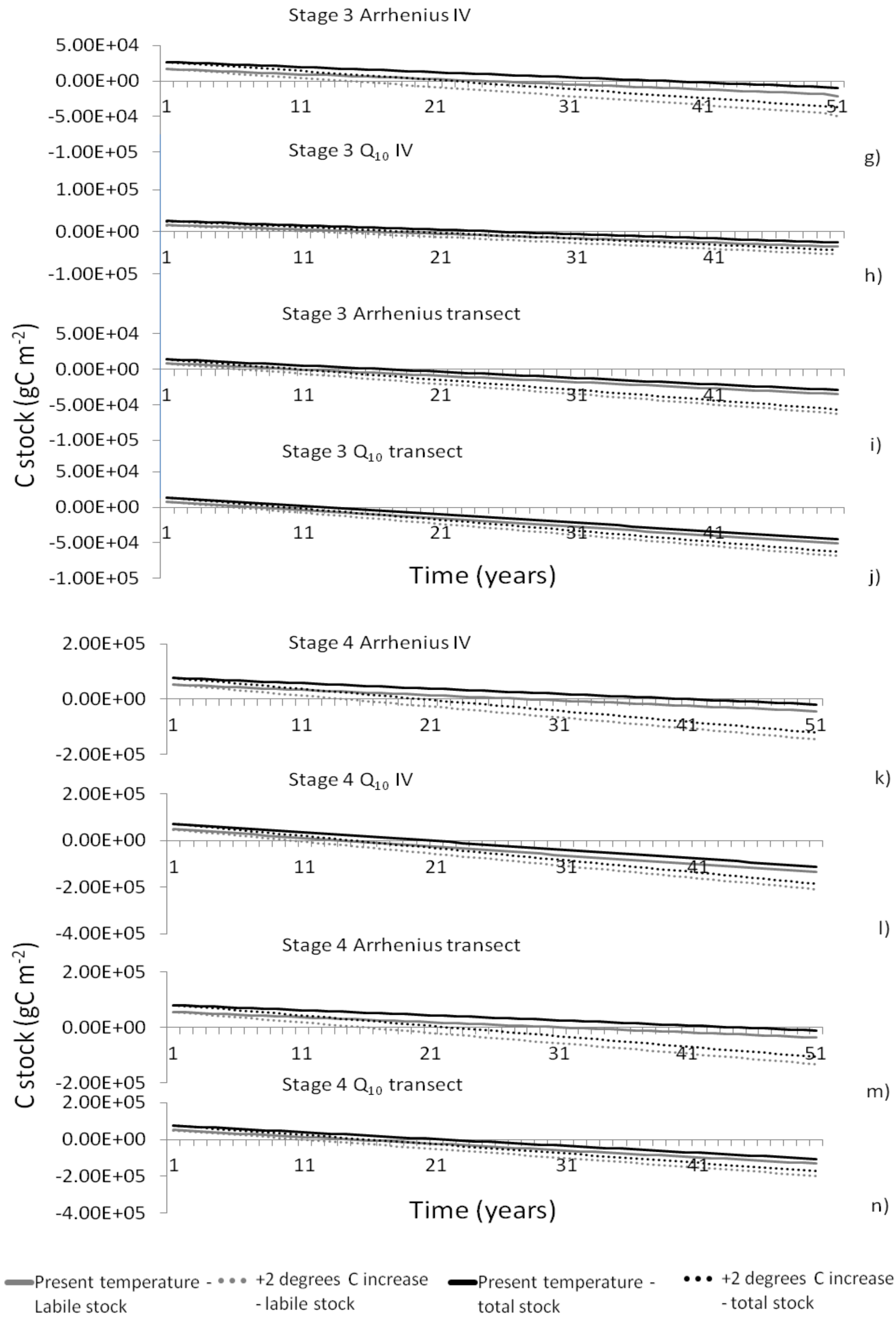


Figure 4.9: Labile and total C stocks depletion over 50 years with respiration calculated with the Arrhenius (Eq. 1) and Q_{10} (Eq. 2) equations for mean annual temperature increases of 0°C and 2°C; using parameters from the IV profiles (Stage 3, g, h and 4 k, l) and transect profiles (Stage 3 i, j and 4 m, n)

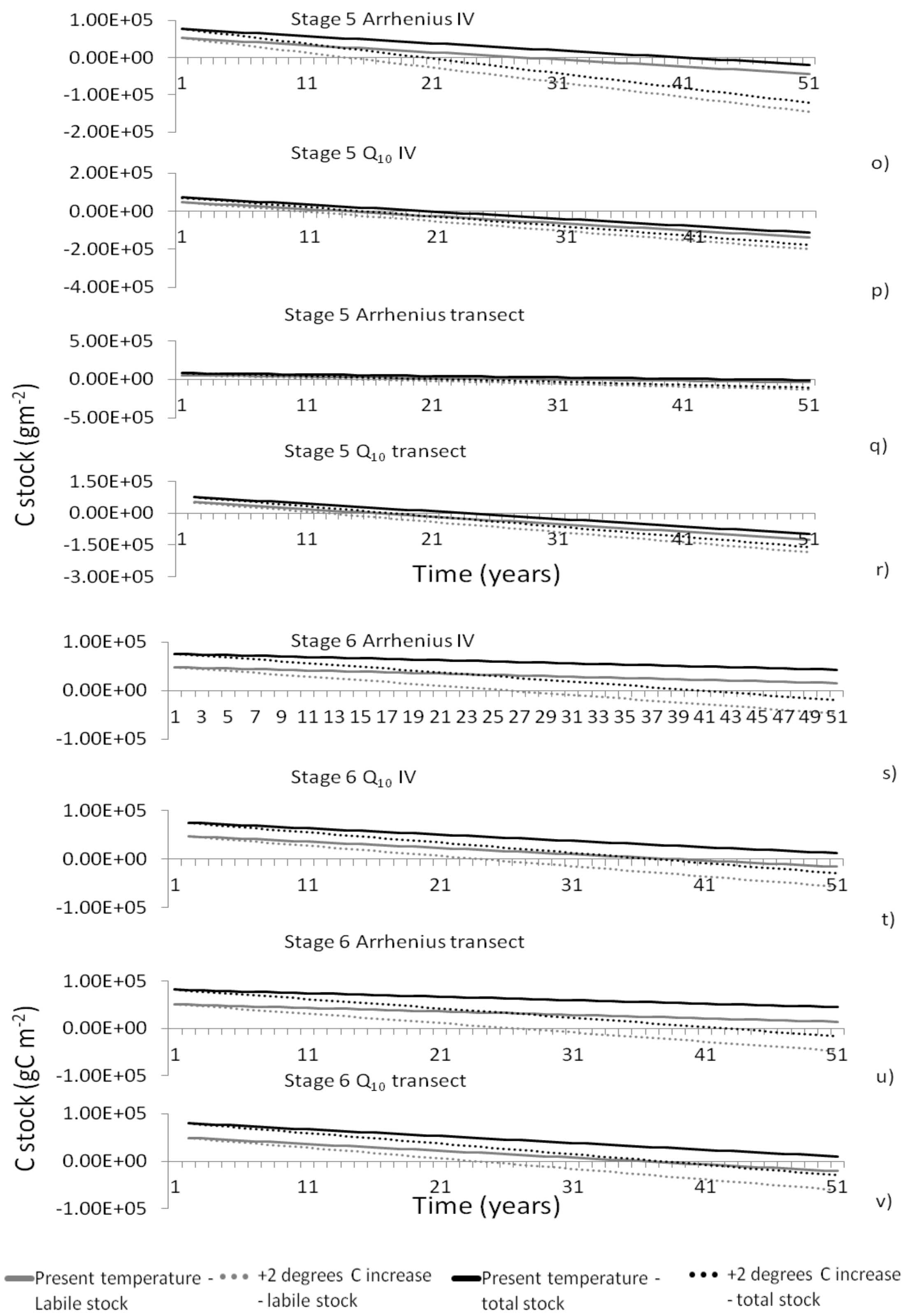


Figure 4.9: Labile and total C stocks depletion over 50 years with respiration calculated with the Arrhenius (Eq. 1) and Q_{10} (Eq. 2) equations for mean annual temperature increases of 0°C and 2°C; using parameters from the IV profiles (Stage 5 o p and Stage 6 s t) and transect profiles (Stage 5 q r and Stage 6 u v)

4.5 Discussion

4.5.1 Model structure

The different stages (Table 4.1) were established to explore the influence of different factors on soil respiration, and as a sensitivity analysis to estimate how the simulated respiration responded to increasing model complexity. The first stage is the closest to a "black box" model: no differentiation in the soil column, standard depth of 1 metre regardless of the reality of the field, and no consideration of the organic matter properties. The results obtained contrast strongly with the Stages 2-6 for the total and labile soil C stocks sizes, as the depths and labile fraction are exaggerated compared to field conditions and the soils are forecast as sinks of C for the next few decades (Fig. 4.9, Table 4.2). Soils with more realistic parameterisation are forecast as sources, even if the size and speed of C stocks depletion varies (Fig. 4.9). The results for the soil respiration during the year are similar to Stage 2, where respiration is still decoupled from soil C stocks. Using different soil parameters might seem to be only important if accompanied by coupling the respiration to the C stock values.

4.5.2 Moisture and temperature regimes of the contrasting vegetation categories (Stages 4-6; H_1)

The first two parameters that should be considered when studying this landscape are the vegetation and soil types modelled. The Intensive Valley is a heterogeneous area (Fig. 4.1) and soils such as those beneath the snow beds, wetlands and ridges are of particular interest as they will differ in substrate availability, soil thermal and moisture regimes, and, possibly, temperature-dependence of decomposition (von Lützow and Kögel-Knabner, 2009). Birch forest and tundra, discussed in more details in other sections, generally have mesic soils in this region and so do not present the full spectrum of thermal and moisture regimes of the Abisko field site.

On the highest points in the landscape, ridges and exposed heath soils are characterised by very shallow soils and the lowest moisture content (see Chapter 3; Fig. 4.5). They are not well insulated from changes in temperatures and cover high portions of the landscape (a third of what is considered as tundra heath is in fact exposed heath).

Wetland soil conditions are unsurprisingly characterised by the highest soil moisture (Fig. 4.6; Elberling *et al.*, 2004; Olsrud and Christensen, 2004) and so potentially impeded aerobic respiration in this model, as seen in Fig. 4.7 p. They develop in the depressions and consequently are more sheltered, but still present some variation in temperatures in winter (Fig. 4.3 c). The fact that respiration in soils such as the Exposed heath and wetlands is likely impeded by moisture conditions most of the year (Fig. 4.7) could have an impact on the overall landscape C budget (Fig. 4.9) and can not be neglected.

Snow beds are sheltered during winter and thus keep soils warmer than nearby heath or forest soils (Fig. 4.3 d, 4.4; Liptzkin *et al.*, 2009). They have a lower moisture content as moisture can be trapped in snow. Their temperatures stay close to 0°C and an increase in mean annual temperature could favour temperatures above the melting point in winter, as the snow beds situated in the forest are as sensitive as the nearby forest soils (Fig. 4.8).

However interesting these soils are, fitting them in the model is difficult without appropriate Arrhenius and Q_{10} parameters. Taking thermal parameters from studies on soil close spatially but different in composition is not an ideal method (see Chapter 3, Fig. 3.10-3.16 and 3.17 for the micromorphological slides' soil profiles photographs and analysis). Further measurements in the field, or from incubation experiments, are necessary to integrate them fully. Three possible methods (von Lützow and Kögel-Knabner, 2009) are the measurements *in situ* of losses from bulk soil C stocks, measurements in laboratory from field incubation (Sjögersten and Wookey, 2002a; Fang *et al.*, 2005) and experimental heating of soil columns and measurement of soil respiration (Hartley *et al.*, 2008).

4.5.3 Soil moisture measurements and use in modelling (Stage 6)

Soil moisture is recognised as an important factor acting on soil respiration (Grogan and Jonasson, 2005; Davidson and Janssens, 2006). It is tied to complex processes in arctic soils throughout the year (snow cover, snow melt input, freeze-thaw processes) and can not be neglected as a proxy for these annual events. Low values for water-filled pore space restrict the mobility of soil organisms (micro- and mesofauna, bacteria and fungi; Swift *et al.*, 1979 b).

A first *caveat* to the use of soil moisture is the reliability of the soil probes, which are recognised by the manufacturer itself as being less efficient in organic soils and at low temperatures (Yoshikawa and Overduin, 2005; Cobos, 2010). This shows in this study as some moisture curves suggest data with negative values for volumetric water content (Fig. 4.5); it is likely that the range of these data have been displaced to lower values because of problems with the probes. This means that thresholds for the optimum range of soil moisture could have to be adjusted for each soil.

For now the consequence of a moisture content outside of the 5-35 m^3/m^3 range is a complete stop to soil respiration (Fig. 4.7 and 4.8). This is not a realistic situation, and the next step in introducing more complexity to the model is to link a soil moisture content out of this range to a decrease in respiration according to an *ad hoc* equation. The paper from which the moisture thresholds have been taken (Elberling, 2003) presents a polynomial equation for the behaviour of respiration in these conditions. It is not an absence of respiration under 5% and over 35% soil moisture content, but a progressive decrease. However, it could not be adapted in the present work as soil-specific parameters need to be measured. This would require further experiments in the laboratory on Abisko soils, but it is the key to adjust the model for important processes in arctic landscapes.

Similarly, the soils studied here do not contain any permafrost, which should be considered for use in any model of arctic soils due to its importance in terms of present C stocks and potential CO_2 release under climate warming scenarios (Zimov *et al.*, 2006; Hugelius and Kuhry, 2009; Hugelius *et al.*, 2011b).

4.5.4 Sensitivity to temperature changes for birch forest and tundra heath (all stages, H_1, H_4)

Behaviours for the summer period are similar for birch forest and tundra heath concerning the patterns and sensitivity of respiration rates to an increase in mean annual temperature (Fig. 4.6 and 4.8). Their moisture curves during the year present the same pattern (Fig. 4.5). The main difference between birch forest and tundra heath soils is their temperature and respiration patterns during the winter. Here winter lasts from mid-October (stabilisation of soil temperatures around 0°C or less) to mid-May (snowmelt for most soils; snow beds can persist until June).

Winter soil respiration is now widely studied in arctic soils and can amount to a significant proportion of the CO_2 respired yearly by arctic soils (Grogan and Jonasson, 2006; Larsen *et al.*, 2007). This is partly due to the length of the winter period and partly because significant snow-packs can maintain soil temperatures close to, or above, freezing point, where liquid water remains available in small quantities to support metabolic processes (Liptzkin *et al.*, 2009; Wookey *et al.*, 2009).

Tundra heaths, as exposed heaths, attain soil temperatures below -15°C (Fig. 4.3 a). The soils of the mountain birch forest stay warmer during the winter (Fig. 4.3 b) than nearby heaths (minimum -5°C) as they can favour snow accumulation (Grogan and Jonasson, 2006). Soils with similar ranges of temperatures in winter are the snow beds and shrub tundra, for which the presence of trees and shrubs help maintaining a thick snow cover in winter (Wookey *et al.*, 2009). Though the winter respiration rates of the birch forest soils are low, they are also more sensitive to a small increase in temperature around the freezing point than tundra heath soils (Fig. 4.6 and 4.8). The importance of birch forest soils is likely to increase as forest could colonise areas of tundra heath, warming temperatures favouring tree line migration and, potentially, ‘priming’ the decomposition of extant recalcitrant soil organic matter (Callaghan *et al.*, 2005; Hartley *et al.*, 2010; Kuzyakov, 2010; Hartley *et al.*, 2011). This is similar to the possible release of the soil C stocks of frozen birch forest in discontinuous permafrost under warming conditions (Goulden *et al.,* 1998).

4.5.5 Soil under the same vegetation type but in different locations (Stages 2-6; H_3)

The transect birch forest and tundra heath soils have different sensitivities to changes in temperatures than their IV counterparts, as seen with the use of the Arrhenius and Q_{10} Equations in warming scenarios on soil respiration rates and C stocks calculations (Fig. 4.6 and 4.9). Similar soils under similar vegetation cover but in different topographical positions react differently to the same increase in temperature, which is a fact to acknowledge when upscaling soil properties and respiration data across large spatial and temporal scales (Wrona *et al.,* 2005).

The soils of the transect are more "typical" tundra heath and birch forest soils while the Intensive Valley is an area of transition between these two vegetation covers. The temperature response curves for both forest plots are otherwise similar (Fig. 4.3 b), however the C stocks of the transition birch forest are smaller compared to the more established birch forest transect soils. This supports the theory that these soils could be in a different state of equilibrium relative to their C stock evolution (Wutzler and Reichstein, 2007).

The transition area is less likely to be in the equilibrium condition assumed in the model. With any advance of birch forest over tundra heath in the Arctic, as a possible result of temperature increase (Callaghan *et al.*, 2005), the study of similar ecotone areas is particularly important. They could easily be overlooked if they appear as part of the main tundra heath/birch forest cover. The different vegetation cover components occupy small and disconnected areas that can only be detected under the kilometre scale (Fig. 4.1). This ‘mosaic’ pattern of soil and plant communities is not unique to the Abisko area, and is a feature of the broader circum-polar ecotone between boreal forest and arctic tundra, especially in areas of gentle relief (for example across Scandinavia, in the Ural mountains, and western Canada; Sjögersten and Wookey, 2009; Kammer *et al.*, 2009; Olthof and Pouliot, 2010).

4.5.6 C stocks forecasting (All stages, H_5)

Calculating soil C dynamics and stocks sizes over the next few decades (Fig. 4.9) tests the relations between soil respiration, C inputs in the soils and C stocks entered in the model. The difference between the results for Stage 1 and Stages 2-6 shows the importance of the soil parameters chosen for the different soil profiles. Stage 1 presents a high increase in stocks for the forest and tundra landscape for profiles with a standard 1 m depth and only labile C (Fig. 4.9 a). For the Stages 2 to 6, the results of the forecasts for soils parameterised with empirically-measured characteristics/properties are a total depletion in few decades (Fig. 4.9 c to v). This happens in similar modelling using several C pools (Knorr *et al.*, 2005). However, the use of moisture limitations slows this tendency and C stocks are not depleted when estimated with the Arrhenius equation (Fig. 4.9 s to v). This can be due to some soils’ high sensitivity to using moisture conditions: exposed heath and wetlands. Even the birch forest soils showed a slower increase in respiration rate for any increase in temperature when the depletion of the labile C stock was adjusted to influence respiration rates (Stages 3-6; see Fig. 4.8 c to f). This supports the hypothesis (***H_5***) that adding constraints on soil respiration can decrease significantly its rates (Fig. 4.8; Fig. 4.9 s to v). This points to the importance of the sources of inputs neglected in this model (from plant: roots, leaves and stems; Swift *et al.*, 1979 c; Grogan and Jonasson, 2005; Davidson and Janssens, 2006). These would certainly slow even more but maybe not change the tendency to decrease of C stocks, which is expected as losses due to respiration are generally hypothesised to be more sensitive to temperature change than NPP across temperatures experienced in these environments (von Lützow and Kögel-Knabner, 2009). Moreover, recent work by Hartley and colleagues (2008) strongly suggests that soil respiration in this region does not acclimate to changes in temperature and the initial decrease would not be stopped by microbial adaptation to new conditions. Inputs should as well be modulated throughout the year instead of being added in a steady flow. Inputs types are also distinct in the ease of decomposition (Sjögersten *et al.*, 2003).

These difficulties could result from the assumption that the soils are in equilibrium, which is a weakness inherent in most pool-based soil models (Wutzler and Reichstein, 2007). Experiments in the field to sample and quantify all the types of C inputs throughout the year are necessary, but time-consuming as well as methodologically challenging. Another improvement would be the use of continuous quality distributions of soil organic matter (Bruun *et al.*, 2010), which would enable a better estimation of stocks and organic matter quality along the profile, and so permit a better monitoring and modelling of C inputs and stocks in these soils.

4.5.7 Other factors to include in further runs

Vegetation variables have not been considered in this model, even if variables such as net ecosystem production are used in C fluxes studies (Sjögersten and Wookey, 2009). However, dynamics of Gross Primary Production (GPP), NEP and net ecosystem exchange are complex and beyond the scope of this model (Lovett *et al.*, 2006).

Another weakness of this model is its focus on soil heterotrophic respiration, neglecting other components of ecosystem respiration such as roots ('autotrophic') respiration, and mycorrhizas (which are difficult to classify either as heterotrophs or autotrophs) present in these soils (Grogan and Jonasson, 2005; Wookey *et al.*, 2009). Respiration can be understood as being mainly microbial in this model, with preferential use of the more easily decomposable fractions of labile OM before the use of recalcitrant OM, and the limitation of soil respiration by too much or too little soil moisture. Adding a faithful representation of the different soil pools and microbial/microfaunal interactions, a coupling with CH_4, controls on substrate availability and a microbial pool (von Lützow and Kögel-Knabner, 2009), and other nutrients cycles (N, P) would improve the inputs and C stock dynamics simulated in these soils, and help with appending further soil types, such as the sedge wetlands. It could help studying the priming effect in birch forest soils as well (Kuzyakov, 2010).

4.6 Conclusion

This simple model focussing on soil respiration does not yet encompass all the soil processes and so can be improved by adding more controls and feedbacks. More datasets collected with the aim of improving the model could give insights into the processes linking C inputs, stocks, soil respiration and its controls, in the context of sub-arctic soils at the tundra heath and birch forest ecotone. However, basic simulations already highlight the sensitivity of soil respiration to any increase in mean soil temperatures. The Birch forest soils in Abisko have the potential for a rapid release of C under warming winter conditions. Similar soils under this vegetation type, or soils under the tundra heath vegetation, can differ between themselves in term of soil properties and C stocks. Thus, even simple models should use profiles from diversified locations.

Appendix 4.1: Equations and conditions by model stage

A4.1.1 Respiration equations for all stages

Arrhenius: $R_S = A\ e^{-Ea\ /\ (R\ (T(i)+w(j))}$ Equation 1

Where R_S is the soil respiration rate (mol CO_2 m^{-2} s^{-1}), A is a pre-exponential factor (mol CO_2 m^{-2} s^{-1}), e is the Euler constant of the exponential function (2.178), Ea is the activation energy necessary to start the process (J mol^{-1}), R is the gas constant (8.3145 J K^{-1} mol^{-1}) and $T(i)$ is the temperature in degrees Kelvin at interval i. $w(j)$ is the degree increase tested in the warming simulation.

Q_{10}: $R_S = R_{S10}\ Q_{10}{}^{((T+w)-10)/10)}$ Equation 2

Where Q_{10} is the ratio between respiration rates for a temperature T + 10 and temperature T (degrees C or K): $Q_{10(i)} = R_{s(i,,T)}/R_{s(i,T-10)}$, Equation 3

Rs is the respiration rate (mol CO_2 m^{-2} s^{-1}), R_{S10} is the respiration rate at 10°C calculated with equation 1, T is the temperature in degrees Kelvin, w is the degree increase tested in the warming simulation. 283.15 is the reference temperature 10°C in K.

A4.1.2 Derived respiration variables for all stages

Average respiration rate for the hours of activity:

$R_{SE} = \Sigma R_S(i)\ /n*\ 60t\ *c_2\ /h_e$ Equation 4

Where R_{SE} is the average respiration rate for the hours of exchange (g CO_2 m^{-2} hr^{-1}), R_{Si} the respiration rate for each interval i (mol CO_2 m^{-2} s^{-1}), n the number of logging intervals, t is the interval duration in minutes, c_2 is the molar mass of CO_2 (g mol^{-1}) and h_e is the number of hours of exchange.

The average respiration for all hours of the logging season, $R_{SA,}$ is obtained by replacing h_e by h, calculated h is the number of hours of the logging season obtained with $h = n * t / 60$ Equation 5

Cumulated respiration per year: $R_{SY} = \Sigma R_S(i) * 60t * c_2 * y / h$ Equation 6

Where R_{SY} is the cumulated respiration rate for the year (t CO_2 m^{-2} yr^{-1}), $R_S(i)$ the respiration rate for each interval i (mol CO_2 m^{-2} s^{-1}), t the interval duration in minutes, c_2 the molar mass of CO_2 (44.009 g mol^{-1}), y the number of hours in a calendar year (8760) and h the number of hours of the logging season.

Average respiration per area: $R_A = R_{SA} * a$ Equation 7

Where R_A is the average respiration rate for the area (g CO_2 hr^{-1}), R_{SA} the average respiration rate for all hours (g CO_2 m^{-2} hr^{-1}), a the surface extent of the vegetation category considered (m^2).

Cumulated respiration per area per year: $R_{AC} = R_{SY} * a$ Equation 8

Where R_{AC} is the cumulated respiration rate for the year per area (g CO_2 yr^{-1}), R_{SY} is the cumulated respiration rate for the year (g CO_2 m^{-2} yr^{-1}), a the surface extent of the vegetation category considered (m^2).

A4.1.3 C inputs

Input at equilibrium: $I = I_L + I_R$ with Equation 9

$I_L = L/100 * C_{L0} / M_{RTL}$ Equation 10

and $I_R = (100-L)/100 * (D-C_{L0}) / M_{RTR}$ Equation 11

Where I (g C m^{-2} yr^{-1}) is the C input if the system is in equilibrium, I_L (g C m^{-2} yr^{-1}) is the labile C input if the system is in equilibrium, I_R (g C m^{-2} yr^{-1}) is the refractory C input if the system is in equilibrium, for a soil comprised of L % of labile C in an initial stock C_{L0} (g C m^{-2}) with a mean residence time of M_{RTL} (years), and of a refractory fraction of C with a mean residence time M_{RTR} (years). D is the initial total soil C stock (g C m^{-2}). I is only calculated for the initial time t = 0, afterwards I_R and I_L are the ones used though always linked to I.

A4.1.4 Inputs rates

Labile rate: $C_{RL} = C_{L0}/M_{RTL}$ Equation 12

Where C_{RL} is the labile C stock turnover rate (g C m^{-2} yr^{-1}), C_{L0} is the initial labile stock (g C m^{-2}) and M_{RTL} the mean residence time of labile organic matter (years).

Refractory rate: $C_{RR} = (D_0-C_{L0})/M_{RTR}$ Equation 13

Where C_{RR} is the refractory C stock turnover rate (g C m^{-2} yr^{-1}), D_0 is the initial total C stock (g C m^{-2}), C_{L0} is the initial labile C stock (g C m^{-2}) and M_{RTR} the mean residence time of refractory organic matter (years).

A4.1.5 C stocks:

Initial labile stock: $C_{L0} = B_D\, C\, L\, d\, (1\text{-S})\, s$ Equation 14

Where C_{L0} is the labile soil carbon stock (g C m^{-2}), d is the depth of sampling (cm), B_D is the bulk density (g C cm^{-3}), C is the carbon content (%), L is the labile fraction of the soil carbon stock (%), S is the rock content (%). s (=10 000) is the conversion factor from g C cm^{-2} to g C m^{-2}. Results can be converted in t C ha^{-1} by dividing by 100.

Fraction of the labile C stock out: $C_{LL}(i) = 100\, (C_{L0} - C_L(i))\, /\, C_{L0}$ Equation 15

Where $C_{LL}(i)$ is the fraction of the initial labile C stock lost at this time interval (%), C_{L0} is the initial labile C stock (g C m^{-2}), and $C_L(i)$ is the labile C stock at interval i (g C m^{-2}).

Total initial stock: $D_0 = B_D\, C\, d\, (1\text{-}S)\, s$ Equation 16

Where D_0 is the soil carbon stock (g C m^{-2}), d is the depth of sampling (cm), B_D is the bulk density (g C cm^{-3}), C is the carbon content (%), S is the rock content (%). s (=10 000) is the conversion factor from g C cm^{-2} to g C m^{-2}. Results can be converted in tC ha^{-1} by dividing results by 100.

Fraction of the total C stock out: $D_L(i) = 100\, (D_L(i) - D_L(i\text{-}1))\, /\, D_0$ Equation 17

Where $D_L\, (i)$ is the fraction of the initial total C stock lost at this time interval (%), D_0 is the initial total C stock (g C m^{-2}), and $D(i)$ is the total C stock at interval i (g C m^{-2}).

Total C stock: for the first interval in time: $D(1) = D_0 + c_2\ I_L(1) + c_2\ I_R(1) - c_2\ R_S(1)$ Equation 18

Afterwards for each interval i: $D(i) = D\ (i\text{-}1) + c_2\ I_L(i) + c_2\ I_R(i) - c\ R_S(i)$ Equation 19

Where D_0 is the initial total C stock (g C m^{-2}), $D(1)$, $D(i\text{-}1)$, $D(i)$ are the total C stocks at intervals 1, *i* and at the interval before *i* respectively (g C m^{-2}), *c* the molar mass of CO_2 (44.009 g mol^{-1}), $I_L(1)$ (g C m^{-2} yr^{-1}) is the labile C input for interval 1, $I_R(1)$ (g C m^{-2} yr^{-1}) is the refractory C input for interval 1, $I_L(i)$ (mol CO_2 m^{-2}) is the labile C input for the logging interval *i*, $I_R(i)$ (mol CO_2 m^{-2}) is the refractory C input for the logging interval *i*, $R_S(1)$ is the respiration rate for the first interval (mol CO_2 m^{-2} s^{-1}), $R_S(i)$ the respiration rate for each interval *i* (mol CO_2 m^{-2} s^{-1})

A4.1.6 C flux and temperature:

C flux: for all stages, C flux: $C_f = R_s(i) – I(i)$ Equation 20

Where C_f is the C flux (mol CO_2 m^{-2} s^{-1}), *Rs* is the respiration rate (mol CO_2 m^{-2} s^{-1}), $R_S(i)$ the respiration rate for each interval *i* (mol CO_2 m^{-2} s^{-1}), $I(i)$ (mol CO_2 m^{-2}) is the C input for the logging interval *i* if the system is in equilibrium, adapted from input *I* (equation 9).

Temperature increment: the files are designed so that calculations for all warming increase intervals are done simultaneously, and a formula ensures the right increment is used at each interval: $w(j) = w(j\text{-}1) + w_v$ Equation 21

Where w(j-1) is the previous temperature increase increment in K/°C, and w_v the increment value.

A4.1.7 Conditions specific to the stages

Stage 1:

Conditions on respiration:

→ Temperature must be above 0°C/273.15 K

→ Function of the temperature only

Equation: Arrhenius, Q_{10}, for temperature *T(i)* (°C) and increase in temperature *w* (K)

C inputs:

→ Considered as 100% labile

→ Function of the mean residence time of the labile fraction only

Equation is that of I_L.

C stocks:

→ Only labile OM at this stage so D(i) = C_L(i)

→ Function of the initial soil properties and of the C inputs and respiration (considered as a loss)

→ The stocks cannot be negative.

Stage 2

Conditions are the same and equations for respiration, inputs and C stocks are the same. The difference with stage 1 is the introduction of horizons for each soil. The synthesis for the soil is made by adding the fluxes and stocks for each horizon. The variables not intrinsic to the soil, as the number of respiration hours, are calculated by weighing each soil horizon by its depth compared to the total soil depth.

Stage 3

Conditions on respiration:

→ Temperature must be above 0°C/273.15 K

→ If the labile stock is so depleted that it cannot fulfil the respiration needs, the refractory stock can be used at a different rate.

Inputs are still calculated as only labile. The only refractory stock that can be used is the existing one. Inputs and C stocks equations stay the same as previous stages.

Stage 4

Conditions on respiration:

→ No limits on temperature values and winter activity

→ The refractory input is available for consumption too.

→ If the labile stock is so depleted it cannot fulfil the respiration needs, the refractory stock can be used at a different rate.

Inputs: as defined by their equations

C stocks as previously

Stage 5:

Conditions on respiration:

→ No conditions on temperature

→ Transfer of labile organic matter is possible between soil horizons

→ Respiration is dependent on the size on the horizons labile and total C stock, and of the labile C stock of the horizon above it

Stage 6:

The moisture condition (M as the soil water content in m^3/m^3) is added in the equation but the other terms are unchanged compared to stage 5.

Conditions on respiration:

→ Introduction of the soil moisture conditions: activity between 5% and 35% water content per volume only

→ No conditions on temperature

→ Transfer of labile organic matter is possible between soil horizons

→ Respiration is dependent on the size on the horizons labile and total C stock, and of the labile C stock of the horizon above it

Appendix 4.2: Model equations list

$R_S = A\ e^{-Ea / (R\ (T(i)+w(j))}$ Equation 1

$R_S = R_{S10}\ Q_{10}^{\ ((T+w)-10)/283.15)}$ Equation 2

$Q_{10(i)} = R_{s(i,,T)}/R_{s(i,T-10)}$ Equation 3

$R_{SE} = \Sigma R_S(i) /n * 60t * c_2 /h_e$ Equation 4

$h = n * t / 60$ Equation 5

$R_{SY} = \Sigma R_S(i) * 60t * c_2 * y /h$ Equation 6

$R_A = R_{SA} * a$ Equation 7

$R_{AC} = R_{SY} * a$ Equation 8

$I = I_L + I_R$ Equation 9

$I_L = L/100 * C_{L0} /M_{RTL}$ Equation 10

$I_R = (100-L)/100 * (D-C_{L0}) / M_{RTR}$ Equation 11

$C_{RL} = C_{L0}/M_{RTL}$ Equation 12

$C_{RR} = (D_0-C_{L0})/M_{RTR}$ Equation 13

$C_{L0} = B_D\ C\ L\ d\ (1\text{-S})\ s$ Equation 14

$C_{LL}(i) = 100\ (C_{L0} - C_L(i)) / C_{L0}$ Equation 15

$D_0 = B_D\ C\ d\ (1-S)\ s$ Equation 16

$D_L(i) = 100\ (D_L(i) - D_L(i-1)) / D_0$ Equation 17

$D(1) = D_0 + c_2\ I_L(1) + c_2\ I_R(1) - c_2\ R_S(1)$ Equation 18

$D(i) = D\ (i-1) + c_2\ I_L(i) + c_2\ I_R(i) - c\ R_S(i)$ Equation 19

$C_f = R_s(i) – I(i)$ Equation 20

$w(j) = w(j-1)+wv$ Equation 21

Appendix 4.3: Model nomenclature

A	pre-exponential factor (mol CO_2 m^{-2} s^{-1})
a	surface extent of the vegetation category considered (km^2)
a_T	total area of the site (km^2)
B_D	bulk density (g C cm^{-3})
c	molar mass of C (12.011 g mol^{-1})
c_2	molar mass of CO_2 (44.009 g mol^{-1})
C	carbon content (%)
C_f	C flux (mol CO_2 m^{-2} s^{-1})
$C_L(1)$	labile C stock at logging interval 1 (g C m^{-2})
$C_L(i\text{-}1)$	labile C stock at logging interval *i-1* (g C m^{-2})
C_{L0}	initial labile C stock (g C m^{-2})
$C_L(i)$	labile C stock at logging interval *i* (g C m^{-2})
$C_{LL}(i)$	fraction of the initial labile C stock lost at logging interval *i* (%)
C_{RL}	turnover rate of the labile C stock (g C m^{-2} yr^{-1})
C_{RR}	turnover rate of the refractory C stock (g C m^{-2} yr^{-1})
d	depth of sampling (cm)
$D(i)$	total C stock at interval *i* (g C m^{-2})
$D(i\text{-}1)$	total C stock at interval *i-1* (g C m^{-2})
$D_L(i)$	fraction of the initial total C stock lost at logging interval *i* (%)

D_0	initial total C stock (g C m^{-2})
e	Euler constant of the exponential function (2.178)
E_a	activation energy necessary to start the process (J mol^{-1})
h	number of hours of the logging season
h_e	number of hours of respiration during the logging season
I	total yearly C input if the system is in equilibrium (g C m^{-2} yr^{-1})
$I(1)$	C input for interval 1 (mol CO_2 m^{-2} s^{-1})
$I(i)$	C input for the logging interval *i* (mol CO_2 m^{-2} s^{-1})
I_L	total yearly labile C input if the system is in equilibrium (g C m^{-2} yr^{-1})
$I_L(1)$	labile C input for interval 1 (mol CO_2 m^{-2} s^{-1})
$I_L(i)$	labile C input for the logging interval *i* (mol CO_2 m^{-2} s^{-1})
I_R	total yearly refractory C input if the system is in equilibrium (g C m^{-2} yr^{-1})
$I_R(1)$	refractory C input for interval 1 (mol CO_2 m^{-2} s^{-1})
$I_R(i)$	refractory C input for the logging interval *i* (mol CO_2 m^{-2} s^{-1})
L	labile C (%)
M	soil water content (m^3/m^3)
M_{RTL}	mean residence time of the labile fraction of C (years)
M_{RTR}	mean residence time of a refractory fraction of C (years)
n	number of logging intervals
Q_{10}	difference in respiration rate between temperature T+10 and temperature T
R	gas constant (8.3145 J K^{-1} mol^{-1})

R_A	average respiration rate for the area (g CO_2 hr^{-1})
R_{AC}	cumulated respiration rate for the year for the whole area (g CO_2 yr^{-1})
Rs	respiration rate (mol CO_2 m^{-2} s^{-1})
$R_S(1)$	respiration rate for the first logging interval (mol CO_2 m^{-2} s^{-1})
$R_S(i)$	respiration rate for each logging interval *i* (mol CO_2 m^{-2} s^{-1})
R_{S10}	respiration rate at 10°C or 283.15K
R_{SA}	respiration for all hours of the logging season (g CO_2 m^{-2} hr^{-1})
R_{SE}	average respiration rate for the hours of exchange (g CO_2 m^{-2} hr^{-1})
R_{SY}	cumulated respiration rate for the year (g CO_2 m^{-2} yr^{-1})
S	rock content (%)
s	conversion factor from g C cm^{-2} to g C m^{-2} (=10 000)
t	logging interval duration in minutes
T	temperature in degrees Kelvin
$T(i)$	temperature in degrees Kelvin for interval i
w	temperature increase tested in the warming simulation (K)
$w(j)$	temperature increase tested in the warming simulation (K) for increment j
w_M	maximum temperature increase tested in the simulation (K)
w_v	increment value (K) or (°C)
y	number of hours in a calendar year (8760)

Appendix 4.4: Setup of the soil moisture and temperature loggers

The HOBO station and associated loggers (a) and Tinytag logger with temperature probe (b) were used in this project. The loggers were carefully wrapped and the cables protected (c) before being set in the field (d). The surface soil layer has been put back into place above the loggers (e). Despite the care taken to protect the loggers, some did not last until the end of the field season because of waterlogging (f).


a)

b)


c)


d)


e)

f)

Chapter 5- Synthesis

This project's aim was defined as the characterisation of soil C stocks and their distribution at the field scale, in order to evaluate robust sampling approaches and appropriate spatial scales needed when surveying arctic areas to estimate circumpolar C stocks. Despite some technical problems and limitations, this project has given an account of the present soil C distribution in two sub-arctic field sites from the micrometre to the kilometre scale. The natural variability of the soil C distribution at the scales sampled being too important to be efficiently reduced to an average value on its own, any average has to be accompanied by data on the range of soil C stocks and on the vegetation and soil diversity on the site sampled. Neglecting these would always mean a loss in information on the depths of the profiles or on the soil properties heterogeneity. As upscaling is done to help forecast changes over large areas, this objective would be poorly supported by using data without the underlying natural distribution characteristics.

This synthesis chapter is constituted of a review of the methodology, a presentation of some issues encountered during the project and an overall synthesis of the results.

5.1 Methodology summary

5.1.1 Fieldwork and sampling strategy

The field sites have been chosen for their links to current research projects and ecological issues (See section 1.3.1). Being 360 km apart, the sites were close enough to be compared, while being far enough to feature contrasting topography, vegetation covers and climatic conditions (Chapters 1 and 2; vegetation in Appendix 1 of Chapter 3). Moreover, existing datasets for Abisko and Kevo were available through the ABACUS project (Arctic Biosphere Atmosphere Coupling at Multiple Scales; ABACUS, 2010). These sites complemented one another as the apparent simplicity of Kevo could highlight relationships masked by the complexity of Abisko's land cover (Fig. 2.1 and 3.3).

Three field campaigns were conducted in Abisko and one in Kevo. The fieldwork for this project was framed by temporal and material constraints. Therefore, more time and means were allocated to the fieldwork in Abisko, a more complex site, spanning larger areas than Kevo and necessitating more time to sample the soils and vegetation types present. However, this choice limited the time spent in Kevo and prevented the use for this field site of all the techniques implemented in Abisko, such as the micromorphological sampling (Chapter 3) and the temperature and moisture logging (Chapter 4).

In Abisko, sampling was concentrated in a heterogeneous birch forest-tundra heath ecotone area, the Intensive Valley (IV), already used in several research projects (Spadavecchia *et al.*, 2008; Williams *et al.*, 2008) and along the Abisko Transect (Fig. 2.1). The IV area permitted to study soils under the same climatic conditions at similar altitudes, thus showing the importance of vegetation cover and topography at scales around 1 m to 100 m for soil properties and soil C stocks. The Abisko transect follows an altitudinal gradient and thus spans the whole transition between established birch forest and extended tundra heath (Fig. 2.1). Kevo presents mostly a hydrological gradient between the waterlogged mire border and the mesic birch forest (Fig. 2.1), thus a simple transect, the Kevo Transect (KT), was sufficient to cover its variability.

The sampling intervals were adapted for each of the sampling schemes. The IV being a 500 m by 500 m square area, cyclical intervals alternating from 25 to 100 m covered this distance with enough plots for statistics. Too many plots would have required too much time on the field and in the laboratory. The Abisko transect covering 3 km, intervals smaller than 50 m would have needed too much work and bigger intervals would have missed information from the field. The Kevo transect being shorter, cyclical intervals taken from the IV were divided by 2 to get enough coverage. For the IV and the Kevo transect, the cyclical pattern was used for the sampling, as this technique is meant to cover more scales with less plots.

The vegetation categories, as used in Chapters 3 and 4, were defined after the field survey. This yielded 11 vegetation categories for the Intensive Valley, but only two for Kevo. In Kevo, the transition area between mire border and birch forest had to be agglomerated with the mire border category; as otherwise, there would not have been enough plots in either category for reliable statistics.

As the sampling schemes were applied without targeting the vegetation present, they could miss some of the vegetation types scattered in the field. It is important to know the characteristics of these neglected vegetation types and their associated soil profiles, to assess the quality of information provided by applying the scheme over a heterogeneous landscape. To complete the sampling scheme of the Intensive Valley, a sedge wetland plot was added, as it was missing from the plots defined by the sampling scheme (Fig. 2.1). This vegetation type presents particular soil temperature and moisture conditions and can react differently to an increase in air temperature compared to the main vegetation types, the birch forest and the tundra heath (Chapter 4). Apart from this need to add the sedge wetland plot, the cyclical grid applied to the Intensive Valley did cover most of the heterogeneity of vegetation types in this area (Chapters 2 and 3).

5.1.2 Data analysis

Once the field data were available, geostatistics were used with the aim of mapping the distribution of soil C stocks. Maps were produced for the soil C stocks and other variables (Chapters 2 and 3). However, the analysis of the data by the building of semi-variograms did not return useful results (Chapter 2). The first semi-variogram generated for the soil C distribution pointed towards a high variability for distances under 25 m. This was confirmed by the second semi-variogram, calculated with different software. This variability hindered the use of geostatistics for comparison between several variables. Consequently, for the analysis of links between vegetation and soil properties, the methods chosen use the datasets without using the plots coordinates (Chapter 3).

Next to the quantitative study allowed by the analysis of soil samples, a qualitative analysis was conducted on micromorphological samples (Chapter 3). The carbon analysis has indicated the distribution of the carbon, and the micromorphological analysis helped in linking this distribution with the organic matter quality and its potential for decomposition in a warming climate. These samples were obtained by a parallel sampling in the same plots as the carbon stock sampling, in five locations along the Abisko Transect (Chapter 3). The number of samples was limited due to the time and costs involved with these techniques. The samples were kept whole, to obtain thin sections for micromorphological analysis. These keep the structure of the soil, and are thin enough to be studied by microscopy. Image analysis was conducted on these slides, using the cyclical sampling scheme to select areas of 1.5 mm by 1.5 mm to describe. A complete analysis of the slides was not possible in the time available, and using the same schemes as for the field scales permits continuity in the approaches used across the scales.

5.1.3 Modelling

Once the analyses of field data and relationships between vegetation and soil were done, they were used to forecast via a model the soil respiration rates corresponding to these sub-arctic soils, in the present conditions and for increases in the mean annual temperature (Chapter 4). These estimates were done for IV and AT soils; no temperature or moisture data were available for Kevo. The model used for these simulations was built for the present work. This approach allows for a better control of the parameters included and the complexity level of the model. A stepwise approach was designed to get levels of increasing complexity, to highlight which parameters have to be included in similar models. Limitations on the respiration rates were placed for some temperature and moisture ranges, to use these variables as controls (Chapter 4). Further versions of the model could include controls and parameters that were not added for lack of data and because of the decision to keep the model simple for this project (e.g. microbial processes). A simple model shows more readily what basic information is needed when estimating respiration rates after such a field survey.

5.2 Methodological conclusions from the sampling and analysis campaigns and the proof of concept modelling of soil respiration

5.2.1 Sampling design and geostatistical methods

Applying cyclical sampling to analyse the distribution of soil C is a new approach. In the Intensive Valley (IV) area in Abisko, it did lead to highlight the heterogeneity of plant cover and soil C stock under contrasting vegetation types (Chapters 2 and 3). It did cover eleven out of sixteen land cover categories present on this field site and does better than linear transects at producing a representative sample of vegetation and soil types (Table 2.3). The choice of this sampling design was, however, taken with the objective of streamlining sampling/analysis but retaining robust and objective coverage of landscape position. This objective was not met: geostatistical analysis conducted in Chapter 2 failed to return any definite result about the spatial distribution of the soil C stocks and the abiotic and biotic controls on it. This could be due to the natural high variability in the C stocks distribution in this field site, for instance compared to the apparent simplicity of the Kevo Transect's (KT) soil C stocks distribution. It may also reflect the fact that there is no strong overriding pattern or control of soil C distribution in this environment (i.e. no single soil-forming factor assumes clear dominance). It should be noted, however, that Burrows and colleagues (2002) conceived cyclical sampling to address such fine scale variability for LAI distribution. The real cause of this lack of results could be the relatively limited number of values available (45 plots), compared to the studies of LAI that were used as a basis to implement the scheme (more than 300 plots: Burrows *et al.*, 2002). Similarly, another project conducted in the IV to analyse the variability of LAI used more than 5500 measurements (Spadavecchia *et al.*, 2008). LAI measurements are faster non-invasive techniques compared to the necessarily limiting protocol of soil sampling and this well-illustrates a fundamental problem in C cycle research; above-ground processes and vegetation C stocks are (relatively) amenable to rapid sampling, with high replication, compared with soil properties. The latter remain, however, just as important to quantify and understand.

The study of the stocks and the fluxes are complementary in the study of the present and future C cycle. The measurement of C stocks must be precise and extensive, as the fluxes are usually at one or two orders of magnitude less. Therefore, the monitoring must give an account of less than 10% difference in the changes in stocks. Given the difficulties to monitor the stocks, this means that changes must rather be taken from fluxes measurements on sites and laboratory experiments (Trumbore, 2000). ^{14}C and C isotopes can be used as indicators of changes over time (Hartley *et al.*, 2011).

A more complete coverage could help validate extrapolations used for calculating C stocks, which sometimes cover very large areas while assuming homogeneous distribution of C in the three dimensions (Zimov *et al.*, 2006) or use a case study to extrapolate on other areas (Harden *et al.*, 1992). The uncertainties about future responses of the tundra to global warming will only be solved by increasing the number of measurements and their spatial and temporal coverage, as much as the fieldwork conditions allow it. Otherwise, if the data remain scarce the inventories of C stocks will certainly continue to underestimate C stocks in certain environments (Harden *et al.*, 1992). Moreover, these data are a basis on which societal decisions about anthropic C emissions have to be regulated (Huntington *et al.*, 2005b).

5.2.2 Moisture and temperature measurements

The moisture and temperature measurements were intended to cover both the inter-annual variability of soil temperature and moisture in Abisko and as many of the vegetation communities as possible. The eight HOBOs loggers would have been redeployed each year, with two or three as controls on the same plots and the others in vegetation or landscape units which had not been logged before. However, in the first year, three of the loggers were so damaged by water that data collection was impossible (Appendix 4.4). Replacing them was not possible due to their high cost. After the second field campaign, only two HOBOs were left. The Tinytag loggers were used as a good complement to these measurements since they did not encounter any problems. The temperatures series obtained with the HOBOs and the Tinytags were similar. However, only the HOBOs were equipped with soil moisture probes, which limited the moisture dataset to only five series instead of the 24 expected. This had consequences for the soils model (Chapter 4) that could only encompass the soils for which these datasets were available (birch forest, tundra heath, exposed heath, sedge and wetlands and snow beds). There was only one paired set of data over the two field seasons (snow beds); consequently, no analysis of the annual variability of soil moisture and temperature could be conducted. This type of problem can only be solved by using material adapted to the field conditions, which are particularly harsh. As noted in Chapter 4, the probes can have their own limitations and have trouble logging soil moisture in arctic conditions (Yoshikawa and Overduin, 2005; Cobos 2010). Therefore, one should expect a certain amount of faulty material, corrupted datasets and enough material deployed on the field to compensate these shortcomings.

Despite these setbacks, the data obtained highlighted the variety of soil physical conditions on the Abisko site and permitted to simulate the differing behaviours of the soil types in front of an increase in soil temperature (Chapter 4).

5.2.3 Soil respiration model

The model was originally conceived for the R software and programming language, but the impossibility to code some of the loops used in the model lead to choose Excel and its easy input interface as a basis for the modelling exercise. The R software treats each dataset as a list of values, and consequently can not go back to the previous step, for example when using the C stock value of the previous interval in time (t-1) to calculate the soil respiration of the present interval (t). The adaptation of the model to a programming language is a priority as it would be a necessary step if later works necessitate coupling it to other models to broaden its uses. A change in model format, while keeping the basic equations and relations between the model components, would facilitate the addition of parameters such as microbial biomass and substrate availability (Lovett *et al.*, 2006; Lipson *et al.*, 2009; von Lützow and Kögel-Knabner, 2009), which are at the heart of soil respiration processes (Sjögersten and Wookey, 2002a; Wang *et al.*, 2011).

Another limit to the use of this model is the lack of appropriate thermodynamic data for soils that cover only small patches (here not the birch forest or tundra heath soils). No Q_{10} or Arrhenius parameters values were found in the literature for the snow beds soils in Fennoscandia. Snow beds are studied for the processes involving their deeper snow cover and warmer temperatures in winter (Hiller *et al.*, 2005; Björk and Molau, 2007). In this study, the soil properties values for the snow beds were measured from the soil sampling, but the Arrhenius and Q_{10} parameters had to be taken from the tundra heath and birch forest soils studies (Sjögersten and Wookey, 2002a).

Some of the model's mechanisms need to be improved. The main problem was the lack of a fitted equation for the respiration response to limitations in soil moisture. Several studies give estimates of the temperatures under which microbial respiration is impaired (Mikan *et al.*, 2002; Wang *et al.*, 2011), but equations given for the decrease of respiration in these conditions are site and soil-specific (Elberling, 2003) and could not be adapted to the Abisko soils. A targeted study of inputs rates and of soil respiration under limited soil moisture needs to be conducted for each of the soil types of Abisko used in the model.

A last *caveat* to the use of this model is the assumption that moisture and temperature are the controls driving soil respiration rates. Studies usually give a correlation between temperature and/or soil moisture and soil respiration (Mikan *et al.*, 2002; Sjögersten and Wookey, 2002a), but not all of the soil respiration is explained by these two factors. Gross Primary Production plays a part as well as soil microbial biomass and substrate availability (Käkohnen *et al.*, 2001; Loranty *et al.*, 2011), soil organic matter quality (Mikan *et al.*, 2002; Neff and Hooper, 2002), snow cover depth (Wang *et al.*, 2010) or the presence of permafrost (Michaelson and Ping, 2003).

5.3 Validity of upscaling field survey results

5.3.1 Differences in field sites

Abisko and Kevo are situated 360 km apart, which is a small distance compared to the scale of the Arctic region (Fig. 1.1 and 1.2). This is far enough for the two field sites to be different for a great number of parameters: vegetation categories and plants species distribution (Table 3.3 and Appendix 3.1), soil profiles (Fig. 2.3 and 2.4), C stocks ranges and distribution (Table 2.2) and soil properties (Fig. 2.6). The relationships between the soil variables themselves differ (Fig. 2.7).

Approaches that agglomerate results over large areas to provide estimates for the whole Arctic would overlook these contrasts. One example is the CAVM map (CAVM team, 2003; Walker *et al.*, 2005), which definitions for vegetation categories put Abisko and Kevo both in the S2 low shrub tundra category. The definition of the Arctic used to produce this map does not encompass ecotones such as the birch forest to tundra heath transition. C stocks estimates made by the collaborative efforts to characterise the C cycle at the Arctic scale suffer from the same bias (Prentice *et al.*, 2001; Callaghan *et al.*, 2005).

A study of the respiration sensitivity of Kevo soils to warming, using the same model and assumptions as for the Abisko soils (Chapter 4), would be a strong point of comparison of the behaviours of these differing soils in the future climatic conditions in the Arctic.

5.3.2 Heterogeneity of soil C distribution over small areas

The heterogeneity of the soil C stocks both in the IV and in the AT complicates geostatistical analysis as discussed above. Upscaling the observations made on the field to larger areas (10-100 km^2) is compromised by the high variability of soil C stocks over small areas (cm^2 to km^2). An average value was found when aggregating stocks for several plant communities according to the presence or absence of trees (Table 3.4). As Abisko is a heterogeneous landscape, a replication of the sampling in a similar area a few kilometres away would be needed to confirm this result.

As the soil C distribution considered is in three dimensions, another factor of variability is the soil profile depth. Comparisons between sites are made with values in g C m^{-2}, implying a standard depth is used. However, representing the deep C-rich sedge and wetland soils and the shallow birch forest soils with the same depth is a loss in information as to the natural variability of the distribution of soil C. This is important as the depth of the soil influences CO_2 release (Schimel *et al.*, 2006).

Individually forest soils have lower C stocks and smaller soil profiles (Fig. 2.3). Hence, the similar values of average soil C stocks for soils with trees and treeless soils can be due to the aggregation of tundra soils. Some of the other soils in the treeless category lower its average C stocks value due to their small C stocks (Exposed heath, unvegetated areas) (Table 3.4). Masking the variability in soil C stocks and soil depths by using a value of 2.3 kg C m^{-2} (Table 3.4) for the whole site can be useful to upscale the present C stocks values and distribution patterns. As these soils are in a transition area likely to undergo great changes with the advance of trees over some, or many, of the open heaths, ridges and sedge wetlands (Sjögersten and Wookey, 2009; Hartley *et al.*, 2010), this estimate ought to last for the next decades. It should be revised regularly by renewing the soil sampling and vegetation cover data. It does provide a value against-which to compare future stocks (especially if the same sampling schemes and methodologies are applied). In this regard there is a tangible legacy of this work as a reference point against which to assess change.

For now, upscaling results from ecotone areas such as Abisko seems highly complex and these results will be more useful over small areas where vegetation categories can be distinguished (l0s of km^2). Sites like Kevo may seem better candidates for upscaling as it has only two main vegetation categories and the transition between the two is sharper than for Abisko (Fig. 2.1). However, the landscape component that has the smallest surface extent, the mire to birch forest transition area can easily be overlooked at larger areas when agglomeration of categories is necessary for an easier mapping. It is also the one with the deeper soils and more important C stocks (Fig. 2.4). Maps of the soil C stocks variability at finer scales should accompany maps of soil C stocks over large areas (e.g. Ping *et al.*, 2008). There should be an emphasis on the heterogeneity of ecotone areas, to help forecast future CO_2 release from this soil.

5.3.3 Linking field survey and remote sensing: the search for a proxy of the soil C stocks distribution

The objective of Chapter 3 was to quantify the strength of relationships between vegetation categories, vegetation properties such as the LAI and NDVI, and soil C stocks and soil properties. The different techniques used (statistical analyses, (Fig. 3.4 and 3.5), simple scatterplots, (Fig. 3.6, 3.7, 3.8), kriged maps (Fig. 3.10)) did not highlight a clear relationship between the LAI/NDVI and vegetation categories, permitting to substitute one for the other. No sound relationship was found either between the soil C stocks/soil properties and the vegetation categories or between the soil C stocks/soil properties and the LAI/NDVI. The conclusion that must be drawn from this is that using one of the easily-measured vegetation property to indirectly measure soil C stocks and associated soil properties is not possible in these sites. This is in line with results at the global scale in major world ecosystems (Fig. 5.1, from data in Anderson, 1992; Anderson, 1991). These data are not the latest estimates, but the pairings of C stocks and living biomass and Net Primary Production values provide an insight into their relationships. There is no clear pattern emerging by plotting soil C stocks against these vegetation variables. Consequently, remote sensing of vegetation properties is not enough to estimate underground soil C stocks.

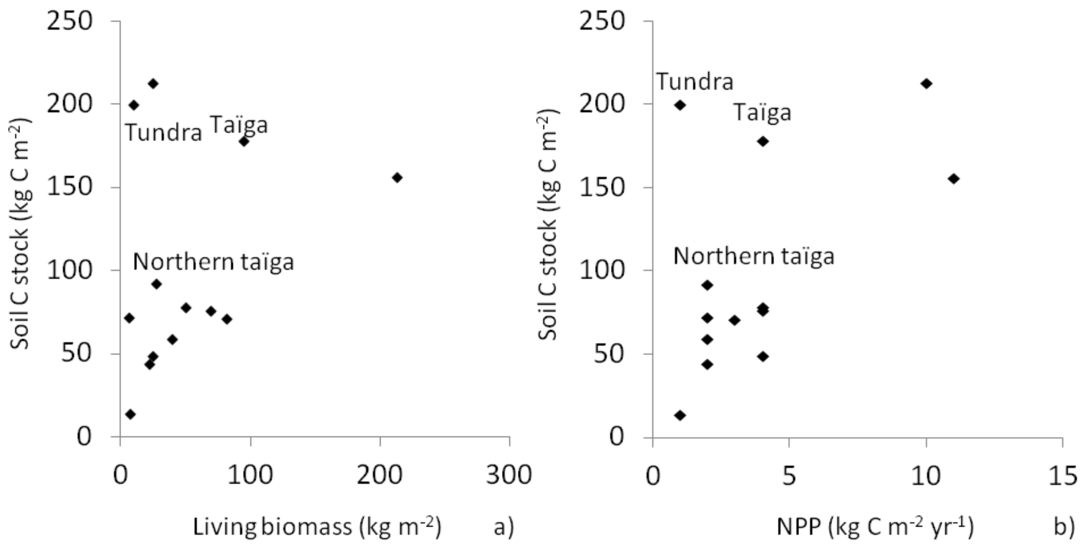


Figure 5.1: Scatterplots of the data of Anderson (1992) for soil C stocks against living biomass (a) and soil carbon stocks against Net Primary Production (NPP)

5.4 Links between topography, soil and vegetation

5.4.1 Abisko Transect versus Intensive Valley

As discussed in the previous section, relations between soil and vegetation properties are not straightforward (see also the schematic diagram in Chapter 1, Fig. 1.5). To overlay the influence of topography, soils under similar vegetation categories but in different landscape positions have been used. In Abisko, the birch forest soils and tundra heath soils have been sampled along a transect spanning an altitudinal gradient (AT), and in an area of the birch forest-tundra heath ecotone (IV). The soil C stocks and profile depths are highly variable for both sampling schemes (Fig. 2.3, 2.5). Soil variables ranges are more similar between the two Abisko sites (IV and AT) areas than with Kevo (Fig. 2.6), but are not identical. These differences in soil C content, bulk density and depth are used in the soil respiration model. Soil temperature data are similar for both sites, the main control being the vegetation category rather than the appartenance to the transition area or the plots at either end of the transect (Fig. 4.3). Differences between results for the IV soils and AT soils are linked to the soil properties and so landscape position rather than climatological conditions. When plotting the average soil respiration estimates for increases in mean annual temperature of 0 to 2°C, AT and IV soils exhibit differing behaviours. AT tundra heath soils have the higher respiration rates compared to the forest, while results for IV show higher respiration rates for the birch forest. Forecasting the depletion in soil C stocks gives faster depletion rates for AT (Fig. 4.8).

Overall, the topographical factor has to be taken into account with the soil C distribution variability and vegetation cover variability, for modelling present C stocks and fluxes and their future in a warmer Arctic.

5.4.2 Birch forest and tundra heath ecotone

The transition between birch forest and tundra heath in the Abisko field site is hard to define as the presence of trees inside the tundra heath area blurs the boundary between the two vegetation categories (Fig. 2.1, 3.3). These isolated trees are important, as a sign that the treeline is mobile in this landscape (Van Bogaert *et al.*, 2011). The forecast advance of birch forest over tundra heath means the arrival of trees over soils with horizons, C stocks (Fig. 2.3), organic matter composition (Fig. 3.17) and a temperature sensitivity (Chapter 4) differing from the forest soils, i.e. there will be an increasing mis-match between soil properties and vegetation community. One of the likely consequences of this colonisation is the priming of old organic matter from the tundra heath soils (Callaghan *et al.*, 2005; Hartley *et al.*, 2010; Kuzyakov, 2010). Here the IV birch forest soils, in the transition area, have higher respiration rates than the tundra heath soils, and a higher increase in winter soil respiration in response to warming (Fig. 4.8). The AT birch forest soils have a different behaviour, which may be a sign of these soils not being at equilibrium in their C and organic matter budget (Wutzler and Reichstein, 2007).

5.4.3 Other soil types and vegetation communities

Throughout this work, the importance of accounting for the diversity in soil properties and vegetation communities has been illustrated. Minor landscape components in terms of spatial cover yield some of the most important C stocks and deepest soils (Fig. 3.3, Table 3.4). During this project, particular emphasis was put on the snow beds, sedge and wetlands and exposed heath soils as they are the soils for which moisture and temperature data were available (Chapter 4).

Situated in the landscape depressions, the sedge and wetland soils have high water content and important C stocks in Abisko and Kevo (Fig. 2.4, Table 3.4). The particular moisture conditions lead to limited aerobic respiration (Yavitt *et al.*, 2005) and so they release less CO_2 than other soils in the modelling of soil respiration (Fig. 4.7). Lafleur and colleagues (2005) did however highlight that some waterlogged soils are more sensitive to the air temperature than water-table level, so these soils have to be monitored as well.

A soil type differing greatly from the wetlands soils is the exposed heath soil on the highest part of the landscape, shallow and with only a small C content (Table 4.2). These soils do release CO_2 despite their small C stock (Fig. 4.7) and as they cover 25% of area of the IV (Table 3.4), their contribution can not be neglected.

The exposed heath soils can be identified by remote sensing, but the snow beds are more difficult to locate. They have deeper snow cover in winter, but in the forest, their difference in vegetation cover is only visible in the understorey (Table 3.3) and so hidden from LAI recognition (van Wijk and Williams, 2005). The modelling exercise of Chapter 4 gives an indication of the possible release of CO_2 from the snow beds soils if they react to warming in the same way as the surrounding soils. However, a key characteristic of the snow beds –the fact that they provide a shelter/insulation to both plants and soil organisms during winter (Sonesson and Callaghan, 1991) suggests that they will react completely differently from forest and heath soils. Their C stocks are higher than neighbouring tundra and forest soils and their soil composition (Fig. 2.3 and 3.17) and their nutrients' cycles also differ, while their microbial communities respond to different stimuli than the forest and heath faunas (Lipson *et al.*, 2009; Liptzkin *et al.*, 2009). Therefore, there is a real need to study these soils' thermodynamic regime in more details so they can be compared to other soils and their sensitivity to warming modelled more accurately.

5.4.4 Future of the C stocks

The simulation of soil C stocks into the future, for an increase in mean temperature of 2°C, reveals an acceleration of the soils C stocks depletion that is already happening in the present conditions (Fig. 4.9). These simulations are however based on a simple model, which does not take into account controls as the microbial biomass or inputs of organic matter (Lovett *et al.*, 2006; Lipson *et al.*, 2009; von Lützow and Kögel-Knabner, 2009). The other data gathered for this study focus on the present condition of the soil C stocks rather than their future. However, a few comments can be made on this topic:

- The birch forest and tundra heath soils have differing sensitivities to temperature increase in different parts of the same field site. These soils are likely not in a state of equilibrium (Wutzler and Reichstein, 2007); changes in soil composition are already happening.

- As already mentioned, the treeline of Abisko is not fixed (van Bogaert *et al.*, 2011) and trees are already present in tundra heath areas (Fig. 3.3). Trees can use older organic matter through rhizosphere priming (Kuzyakov, 2010).

- There is a high variability in the soil C stocks distribution and differing soil moisture and temperature regimes in the IV. Some soils are more sheltered and keep warmer temperatures in winter as well as being more sensitive to temperature increases (birch forest and forest snow beds soils) compared to heath soils. It is likely that as these soils' respiration rates respond differently to soil warming and experience different temperatures throughout the year, the response to warming will not be the same everywhere on the site.

For these reasons, the most likely scenario is that warming will favour the advance of trees over the tundra heath areas, mobilising organic matter from these soils. However, this will be unequal across the landscape and some C stocks will be protected for longer. Soils with an already low C stock, such as the exposed heath, would release less CO_2 than soils under shrub heath, so the strength of this new source could vary through the landscape. Defining which type of tundra heath will be colonised is a step in forecasting these changes, as the amalgamated "tundra heath" category gathers soils with substantially contrasting soil profiles.

As already stated, to be verified these hypotheses need to be supported by solid datasets spanning the next few decades and so are beyond the temporal scope of this thesis. They should be taken into account when upscaling the responses of one soil type over large areas, as multiple local conditions linked to vegetation types, soil properties and topographical situation will play in the future of soil C stocks.

5.5 Synthesis and future research directions

The main findings of this project answer to the interrogations presented at the beginning of this thesis:

- The main aim of this project has been achieved by giving an account of the present soil C distribution in two sub-arctic field sites, from the micrometre to the kilometre scale. The natural variability of the soil C distribution is important, for example from 0.01 to 18.8 kg C m^{-2} for the 0-4 cm depth in a 2.5 km^2 area of Abisko.
- An average value of 2.3 kg C m^{-2} has been derived for both forest and treeless areas and could be used for further works, bearing in mind the limitations associated with the context of this estimation. This similarity needs to be confirmed by replicating the IV sampling in similar ecotone areas. This value has to be associated to sufficient information on the depths of the profiles or on the soil properties heterogeneity. As upscaling is done to help forecast changes over large areas, this objective would not be efficiently supported by using data without the underlying natural distribution characteristics.
- This common value for forest and treeless areas is an answer to another issue. The aim of linking these scales to larger areas via remote sensing is not attained, as vegetation categories and their properties as the Leaf Area Index do not show strong enough relationships with soil C stocks to be of any use in predicting the soil C distribution. A common value for treeless and forest areas (with all due caution) is a shortcut for mapping C distribution for all vegetation categories, until technologies such as the Near Infra-Red Spectroscopy are sufficiently developed to monitor C stocks at depth.

- Components occupying a small surface can contain high stocks of C, such as the wetland areas in Abisko and mire borders in Kevo. Other categories differ from neighbouring vegetation areas by particular conditions, for example snow beds by their higher snow accumulation in winter and contrasting soil horizons or exposed areas by their shallow soils. The simulated respiration rates and behaviours following soil temperature increase are different for each of these soil categories. Therefore all landscape components warrant a peculiar interest during the field survey, and any simulation of soil respiration in these landscapes should integrate as much as the landscape diversity as possible.
- With this picture of a very heterogeneous soil C distribution from the microscale to the kilometre scale on the field sites, and at a scale of several hundreds of kilometres between the field sites, the validity of upscaling results from a few field sites to large areas is put into question. Averaging a few values over very large areas is a necessary shortcut in the Arctic, as the lack of accessibility reduces the number of potential field sites. So a solution to this issue, for the projects aiming at estimating the soil C stocks size in the Arctic, is to estimate in parallel the likely variability of soil C stocks in these areas and be especially attentive to the ecotone areas.
- As expected, birch forest and tundra heath soils differ in their compositions and sensitivities to warming. The forecast advance of forest soils over tundra heath areas could release important C stocks both (i) directly due to accelerated decomposition following warming, or changes in snow depth and distribution, and (ii) due to root/litter priming of the decomposition of existing soil organic matter. This is happening in a heterogeneous area and it is likely that the responses to these

new conditions will be as varied as the vegetation cover of the sites, and should be assessed by further monitoring campaigns.

Several research suggestions have been mentioned in the previous discussion topics and are summarised here with others:

- Using the cyclical sampling scheme gives a good coverage to map soil C stocks and properties. However, its use for geostatistical modelling needs some development to make it robust enough with a limited number of samples. Using grids similar to the IV's in other birch forest-tundra heath ecotones areas would provide validation or not to the use of an average value for soils C stocks in aggregated vegetation communities.
- Micromorphology thin sections produced interesting observations on the composition of soil profiles under contrasting vegetation categories. A regular spatial sampling for micromorphology would be demanding in terms of time and logistics, but could provide more insights into the composition and variability of soils from the microscale to the kilometre scale.

The model used in this project needs development to represent accurately C cycle processes in these landscapes. Moisture and temperatures relations in the model need to be improved. Adding data on organic matter inputs and specific parameters for the wetlands, snow beds and exposed heath soils would be a good way to test the sensibility of these soils to temperature increase.

For upscaling purposes, the variability of soil C stocks is masked under average values for similar vegetation types. While this is done for practical reasons, a good way to acknowledge this variability would be the mapping of soil C stock variability and of transition areas in the arctic landscapes around the treeline.

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