Climate-driven landscape development

Physical and biogeochemical long-term processes in temperate and periglacial environments

Tobias Lindborg
Faculty of Forest Sciences
Department of Forest Ecology and Management
Umeå

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Swedish University of Agricultural Sciences
Umeå

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Abstract

Earth has experienced many glacial cycles over the ~2.5 million year long Quaternary period. During the latter part of the Quaternary, roughly the last 800,000 years, each cycle has been of duration ~100,000 years and has included extended periods of glacial conditions, with ice sheets in the northern hemisphere. In-between those periods, intervals with periglacial or temperate conditions in northern latitudes have occurred. Global sea level has, as a response to the formation and melting of ice sheets, fluctuated over 120 meters. Thus, the global climate cycles have been the main driver for the location of continental coastlines, environmental changes in the past as well as the resulting present-day landscapes. Recent human-induced climate change is now also affecting the landscape.

In this thesis, I examine the use of global climate models as input to exploring local landscape evolution over glacial cycles. An approach is proposed for landscape description that is designed for use in long-term safety assessments related to landscape development into the far future. The approach is illustrated by results of work that shows methods applied to a site-specific landscape development model using climate and climate-related data. Site-specific data is utilised to gain site understanding from which conceptual ecosystem models are developed for present day conditions, and to inform landscape narratives. Concentrations of elements are used to infer the characteristics of transport processes in the landscape over time. The results from the above studies are discussed in relation to the general hypothesis in this thesis; that by considering a few well-defined climate-related processes and using site understanding on local properties and processes, it is possible to reduce the uncertainties in future landscape developments for a specific site. Uncertainties include the abundance and distribution of ecosystems and associated properties related to processes governing the transport of matter. I conclude that relevant examples of historical and future landscape evolution for specific sites can be given that are useful for long-term assessments.

Keywords: Landscape development, biogeochemistry, climate, environmental change, catchment, ecosystem, mass-balance, organic carbon, shoreline displacement, permafrost.

Author's address: Tobias Lindborg, SLU, Faculty of Forest Sciences, Department of Forest Ecology and Management, SE-901 83 Umeå, Sweden.

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Sammanfattning

Under Kvartärperioden, d.v.s. de senaste 2,5 miljoner åren, har jorden genomgått flera glaciala cykler. Varje cykel har under de senaste 800 000 åren varit ca 100 000 år lång. Cyklerna har haft långa glaciala perioder med inlandsisar på det norra halvklotet. Mellan dessa glaciala perioder har varmare perioder med temperat klimat förekommit, som avbrutits av kallare periglaciala tundraklimat. Den globala havsnivån har som en respons på dessa glaciala cykler fluktuerat med mer än 120 meter. De globala klimatcyklerna har varit den huvudsakliga drivkraften bakom läget för kontinenternas strandlinjer, historiska miljöförändringar samt det landskap vi ser i dag. Den i detta sammanhang nyligen uppkomna antropogena påverkan i form av utsläpp av fossilt kol ska adderas till detta historiska mönster. Alla platser på jordytan är under konstant förändring, dels på grund av ovan beskrivna processer, dels fluviala och andra lokala processer. I denna avhandling undersöker jag hur globala klimatmodeller kan användas som indata till platsspecifika landskapsutvecklingsmodeller. Vidare så redovisas metodik och resultat från en platsspecifik landskapsmodell som använder klimatdata och klimatrelaterade data från en klimatmodell. Möjliga framtida platsspecifika landskap underbyggs med platsspecifika data och massbalansmodeller. Transportprocesser i landskapet över tid beskrivs med hjälp av koncentrationer för ett stort antal grundämnen. Resultatet diskuteras och stödjer avhandlingens tes; att med hjälp av ett fåtal väldefinierade klimatrelaterade processer, tillsammans med information om platsegenskaper och lokala processer, kan man minska de osäkerheter som finns i beskrivningar av framtida landskapsutvecklingar. Osäkerheter så som förekomst och distribution av ekosystem samt processer som styr ämnestransport i landskapet. Vidare så visar jag att relevanta exempel på historiska och framtida landskapsutvecklingar för specifika platser kan tas fram som är användbara vid långsiktiga bedömningar av platsegenskaper och elementtransport. Jag avslutar vidare med att konstatera att globala klimatscenarier tillsammans med platsförståelse är nyckelkomponenter i framtagandet av landskaps-beskrivningar för framtiden.

Keywords: Landscape development, biogeochemistry, climate, environmental change, catchment, ecosystem, mass-balance, organic carbon, shoreline displacement, permafrost.

Author's address: Tobias Lindborg, SLU, Faculty of Forest Sciences, Department of Forest Ecology and Management, SE-901 83 Umeå, Sweden.

Preface

All the research and findings described in this thesis actually occurred. They all stem from the findings of others, together with my own experience of landscapes and ecosystems on this planet. Nevertheless, none of it would have happened without, what I understand to have been, pure luck. In hindsight, the luck was a result of fixed processes that determined the outcome. You should not mistake this kind of luck for randomness, coincidence or even free will. No, this luck was the kind that needed robust forcing factors.

Although the work presented here addresses scientific issues, I have put much effort into making the reasoning accessible to a layman. Regardless of your profession, remember that I may view the world with glasses that do not magnify the issues that lie in your path; rather I have allowed my eyes to wander instead over larger patterns, and to the spatial and temporal horizon. Some questions need such a broad approach and the cooperation of many. So, let me introduce to you the evolution of landscapes. Here the methods and knowledge derived from research on climate, geology, biogeochemistry, soil sciences, aquatic ecosystems, terrestrial ecosystems, hydrology and paleolimnology are merged and synthesised. Here begin the narratives of the past and the future, described in my thesis on climate-driven landscape development.

Stockholm 16 August 2017
Tobias Lindborg

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List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Becker, J.K., Lindborg T. & Thorne M.C*. (2014). Influence of climate on landscape characteristics in safety assessments of repositories for radioactive wastes. *Journal of Environmental Radioactivity*, vol. 138, pp. 192-204.

II Lindborg, T*., Brydsten, L., Sohlenius, G., Strömgren, M., Andersson, E. & Löfgren, A. (2013). Landscape development during a glacial cycle: modelling ecosystems from the past into the future. *AMBIO*, vol. 42, pp. 402-413.

III Lindborg, T*., Rydberg, J., Tröjbom, M., Berglund, S., Johansson, E., Löfgren, A., Saetre, P., Nordén, S., Sohlenius, G., Andersson, E., Petrone, J., Borgiel, M., Kautsky, U. & Laudon, H. (2016). Biogeochemical data from terrestrial and aquatic ecosystems in a periglacial catchment, West Greenland. *Earth System Science Data*, vol. 8, pp. 439-459.

IV Rydberg, J*., Lindborg, T., Solenius, G., Reuss, N., Olsen, J. & Laudon, H. (2016). The importance of eolian input on lake sediment geochemical composition in the dry proglacial landscape of western Greenland. *Arctic, Antarctic and Alpine Research*, vol. 48, pp. 93– 109.

V Lindborg, T*., Rydberg, J., Andersson, E., Löfgren, A., Johansson, E., Saetre, P., Sohlenius, G., Berglund, S., Kautsky, U. & Laudon, H. (submitted). Terrestrial and Aquatic Pools and Fluxes in a Periglacial Landscape: Carbon Budget Analysis for a Catchment in West Greenland.

VI Lindborg, T*., Rydberg, J., Lidman, F., Tröjbom, M., Berglund, S., Johansson, E., Kautsky, U. & Laudon, H. (manuscript). Mass-balance of 42 elements in a periglacial lake catchment in West Greenland.

Papers I-IV are reproduced with the permission of the publishers.

* Corresponding author.

Other papers associated with this thesis but not included:

- Johansson, E., Gustafsson, L-G., Berglund, S., Lindborg, T., Selroos, J-O., Claesson Liljedahl, L. & Destouni, G. (2015). Data evaluation and numerical modeling of hydrological interactions between active layer, lake and talik in a permafrost catchment, Western Greenland. *Journal of Hydrology*, vol. 527, pp. 688–703.
- Johansson, E., Berglund, S., Lindborg, T., Petrone, J., van As, D., Gustafsson, L-G., Näslund, J-O. & Laudon, H. (2015). Hydrological and meteorological investigations in a periglacial lake catchment near Kangerlussuaq, west Greenland – presentation of a new multi-parameter data set. *Earth System Science Data*, vol. 7, pp. 93–108, doi:10.5194/essd-7-93-2015.
- Kautsky, U., Lindborg, T. & Valentin, J. (Eds.) (2013). Humans and Ecosystems over the Coming Millennia: A Biosphere Assessment of Radioactive Waste Disposal in Sweden, *AMBIO*, vol. 42, pp. 381-526.
- Petrone, J., Sohlenius, G., Johansson, E., Lindborg, T., Näslund, J-O., Strömgren, M., & Brydsten, L. (2016). Using ground-penetrating radar, topography and classification of vegetation to model the sediment and active layer thickness in a periglacial lake catchment, western Greenland. *Earth System Science Data*, vol. 8, pp. 663-677.

The co-authorship of the papers reflects the collaborative nature of the underlying research. The contributions to the papers included in this thesis were as follows:

Paper I was written by Jens Becker, Tobias Lindborg and Mike Thorne. The strategy described was developed by the authors as part of IAEA MODARIA Working Group 6. Results in the paper rely on discussions and references from all participants in the Working Group with Tobias Lindborg as chairman. Examples of climatic implications for landscape development processes were written by Tobias Lindborg, who was also responsible for the development of conceptual models and illustrations.

Paper II was written by Tobias Lindborg with all co-authors taking an active part. Lars Brydsten performed the numerical modelling used in the landscape-modelling exercise. The overall methodology was fine-tuned over a 10-year period up until publication within the SurfaceNet project led by Tobias Lindborg.

Paper III was written by Tobias Lindborg with contributions from all co-authors. The site investigations and laboratory analyses were planned by Tobias Lindborg, who also led the field campaigns and instrumentation of the site. All co-authors contributed to the fieldwork as well as to constructing the published data-base in PANGAEA.

Paper IV was written by Johan Rydberg with Tobias Lindborg as active co-author. All authors took part in field sampling, analysis and discussions on results.

Paper V was written by Tobias Lindborg and Johan Rydberg with contributions from all authors. Conceptual model development and the field sampling program were led by Tobias Lindborg. Anders Löfgren, Peter Saetre and Eva Andersson were responsible for the biotic data collection and analysis. Emma Johansson made hydrological calculations and Johan Rydberg was responsible for lake sediment sampling and analysis. All authors were also involved in field campaigns, workshops and analyses and synthesis of data.

Paper VI was written primarily by Tobias Lindborg who also developed the conceptual model. Mats Tröjbom was responsible for the original concept and handling of the data base, as well as mass-balance calculations. Johan Rydberg, Sten Berglund, Fredrik Lidman and Mats Tröjbom analysed the results together with Tobias Lindborg. Emma Johansson contributed to the hydrological calculations. The sampling programme was developed by Tobias and Hjalmar Laudon.

1 Introduction

1.1 Background

Any assessment dealing with long-term landscape development, whether its historical or possible future evolution, must consider and characterize aspects of the environment that have the potential to change in time. The same importance and attention must also be given to the main drivers behind landscape changes. Depending on its goals and purpose, the assessment context may have different time-frames and spatial scales of interest. Work presented herein assesses one of the most extreme time-frames used in present-day societal assessments, namely the one used in long-lived radioactive waste assessments (Andersson et al. 2013). This type of assessment comprises at least some tens of thousands of years and can extend up to around one million years. This implies that global glacial cycles with their extreme changes in temperature between glacial and interglacial periods come into play. Furthermore, human-induced drivers of climate change and the need to understand resulting effects on, and sensitivities of, the natural system become an issue (e.g. IPCC 2013). The questions raised, and research needed, stem from decades of multidisciplinary research aiming to understand how radionuclides from a potential repository release might migrate and cause radiation exposures to humans and the environment in the far future (Lawson & Smith 1985; Commission of the European Communities 1988; National Academy of Sciences 1995; Japan Nuclear Cycle Development Institute 2000; Kautsky et al. 2013; 2015; 2016).

Over such extended periods of time, it is obvious that the evolution of a landscape can never be fully described or understood. This is, however, not the goal of this work. Instead, I present herein a physically constrained approach that can be used when arguing for possible site-specific landscape futures that exhibit specific physical and biogeochemical patterns because of the effects of long-term climate forcing on the environment in combination with biotic and abiotic landscape succession in shorter timeframes within specific climates.

In this thesis and associated papers, I discuss different methods for identifying and characterizing present and possible future landscapes. I further examine processes affecting landscape evolution and effects on element cycling for temperate and periglacial climate conditions. The methods and results are presented in a spatial hierarchy going from global-scale processes down to specific sites and local properties. Parts of the research and analysis presented in this thesis were performed in association with a safety assessment of a repository for spent nuclear fuel at the Forsmark site in Sweden. Other parts arose from international cooperation within the International Atomic Energy Agency (IAEA). Complemented by research conducted on a site in Greenland, a stepwise strategy together with results is presented that shows a way to reduce uncertainties in future landscape behaviour for specific sites. This, in turn, can enhance the confidence in calculations made in safety assessments of long-term waste storage and other long-term societal assessment needs related to specific sites.

1.2 Landscape evolution and glacial cycles

Landscapes are dynamic and any area on the surface of the Earth is subject to continuous change. Large-scale processes, such as denudation, sedimentation, shoreline displacement and natural biotic succession are interrupted locally by small-scale and short-term disturbances, such as fire, land use, erosion and flooding. Global climatic variations are the main drivers of, or controls on, many of these processes (Zachos et al. 2001). Effects of variations in global climate and related processes at a regional scale (Kleman et al. 1997; Stroeven et al. 2016), on permafrost growth and thaw characteristics (Washburn 1979; French 2007), and on shoreline displacement (Mörner 1979; Påsse 2001; Brydsten 2006; Brydsten et al. 2009; Whitehouse 2009) are well understood. Also, even though all processes that lead to ice-sheet formation and deglaciation, and control the rates of these processes, may not be fully understood (Helmens et al. 2014; Patton et al. 2017), the spatial and temporal pattern can be described.

Geological records show that over the past 2.5 million years, the Earth's climate has varied between short interglacial periods with warmer climate to longer glacial periods characterized by fluctuating colder climates, and growing ice sheets at high northern latitudes as well as in Antarctica (Imbrie et al. 1992; Raymo and Nisancioglu 2003; Lisiecki and Raymo 2005). Earth's orbital cycles (Milankovich 1941) together with feedback mechanisms in the ocean-atmosphere-geosphere/biosphere system (Archer et al. 2009), and in recent time, anthropogenic influences (e.g. Lord et al. 2015) have resulted in the historical pattern seen in paleorecords (Bradley 2014) and the present warming of the globe (IPCC 2013).

Kopp (2009) calculated that during the last interglacial, the Eemian which occurred some 125,000 years ago, global sea level was about 6.6 meter higher than today due to a 1-2˚ C warmer global average temperature (3-5˚ C in polar regions). Even though many issues related to the responses and sensitivities of the climate system are still uncertain (Archer et al. 2009), the pattern of climate fluctuations in the past, the linkage to Milankovich cycles, and the understanding of recent anthropogenic influences due to greenhouse gas emissions, constrain future global climate scenarios. Future climate scenarios defined under specific assumptions as to future fossil fuel usage and land-use change and make the variability assessable.

Hence, understanding of the dynamics of past climate evolution and variability is essential to assessing future climate evolution relevant to site-specific, long-term assessments. However, information on past climate conditions may not provide a sufficient basis to determine the timing of future climate changes, or define future global climate responses to increased CO_2-levels in the atmosphere.

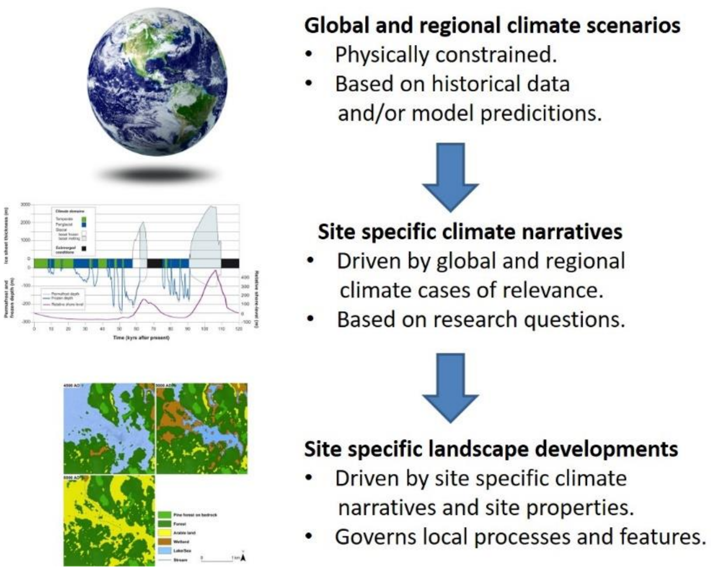

Figure 1. The general strategy to extract information from global and regional climate models, adapt the information to a specific site and finally, feed the landscape development modelling with long term processes.

Global climate varies on a wide range of timescales, with those variations determined by many mechanisms and processes, see e.g. Goodess et al. (1992). Uncertainties in how these mechanisms and processes affect climate and hence impact on a specific landscape are large and not possible to assess in the long term.

It is now possible to develop a set of climate scenarios for a specific site that can be used to explore the range of different long-term changes in historical and potential future climate (e.g. Näslund et al. 2013). This approach allows the development of a set of calculations consistent with those climate scenarios that can be used to assess the range of time-dependent landscape impacts possible. The overall conceptual strategy is to use global climate models to feed regional modelling of climate-related processes and finally to assess the implications of these on a local landscape (Fig. 1).

At a coastal site, large-scale climate variations affect the shoreline displacement as well as the development and in-growth (sediment infilling and vegetation in-growth) of lakes. Present shoreline displacement due to isostatic rebound is in many places large enough to be observed by inhabitants during a life time. In central Sweden, the shoreline displacement is around 6 mm y^{-1} (Påsse 2001), constantly adding new land along the shores. Therefore, it is obvious that shoreline displacement needs to be addressed as an important aspect of the description of landscape development for coastal sites with both isostasy (Earth's crust movement) and eustasy (sea level change) as active processes. Because past shore-level displacement is measurable (Yokoyama et al. 2000; Hedenström and Risberg 2003), over a short time frame it can be extrapolated into the future (Brydsten and Strömgren 2010), and for longer time frames it can be modelled (Whitehouse et al. 2006; Näslund et al. 2013). Shoreline displacement affects the landscape geometry which determines the distribution of land and formation of lakes (e.g. Brydsten and Strömgren 2010). It should also be noted that other processes than those associated with global climate cycles may cause shoreline displacement. In Japan, co-seismic uplift driven by plate tectonic factors dominates the long-term changes (Matsu'ura 2015), and is a good example of such an alternative process. For coastal areas, land uplift and sea-level changes are thus likely dominating factors for landscape evolution, at least over the next few thousands to tens of thousands of years.

By extrapolating back the ongoing shoreline displacement for a site, the highest coastline can be recovered. This constitutes the most inland shoreline that occurred during early stages of deglaciation. For inland landscapes located above the past and assumed future highest coastline, shoreline displacement at the coast has less or no importance for landscape development (though the local sea-level may exert an influence as the base level to which river profiles grade).

Examples of changes relevant for an inland landscape are erosion and sedimentation due to fluvial processes in river systems, as well as the infilling and ingrowth of lakes, glacial erosion and the formation of valleys (Anderson and Anderson 2010). During longer periods of stable climate-related conditions, landscape change is dominated by internal succession processes. In the Krycklan catchment (Laudon et al. 2013), situated on the highest coastline at 260 meters above sea level in northern Sweden, ongoing research is exploring elemental behaviour in the landscape. One example is work done by Lidman et al. (2013) that presents results on elemental distribution and transport processes affecting the concentration patterns seen in a boreal mire system. Other examples are Laudon et al. (2012) and Oni et al. (2015) that investigate the landscape dynamics of carbon due to water-flow processes and perform projections into the future. For landscapes that experience periods with relatively stable climate, ecosystem succession will most likely adapt to local processes and events affecting both abiotic and biotic properties in the landscape. Lake succession is an example of this type of ecosystem development that will change the landscape pattern (Brydsten 2004). Sedimentation and vegetation in-growth in lakes are dependent on geometrical factors, initial soil and sediment properties, the shoreline displacement (if coastal) and climate. In-growth by vegetation will probably follow the general pattern for a specific region and can be estimated from sediment and/or peat paleo data, e.g., Fredriksson (2004). A general rule for terrestrial vegetation is that the future distribution of vegetation should be assigned to the future landscape in accordance with the present pattern relating vegetation to its underlying soil or soils for each climate variant (Lindborg 2010).

A concept used to evaluate landscape change or to assess implications for the landscape due to climate-driven processes is to quantify present elemental pools and fluxes (e.g. Anderson 2007; Velbel and Price 2007; Parmentier et al. 2017). Material is constantly moving at different rates and at all temporal and spatial scales. The mobility rate is mainly determined by elemental or material properties, and gravity is a major force. Air and water function as mediators of transport of particles and dissolved material. The general idea is often to use the landscape fractionation of elemental pools and associate the distribution pattern with transport processes. Mostly this is done for single elements, such as carbon, that can trigger feedback mechanisms affecting processes related to climate change (Lundin et al. 2016), or elements of interest for their role in specific ecosystem functions (Shaver and Chapin 1991), or as tracers for events (Bindler et al. 2017). Several factors affected by climate change may influence the chemistry in the landscape. Land uplift, formation of vegetation cover, formation of catchments, lakes and wetlands, hydrology, atmospheric deposition and land use are examples of landscape properties that, when changing, will have effects on the landscape biogeochemistry (Schlesinger and Bernhardt 2013).

By quantification of element pools and fluxes, the landscape mass-balance can be used to investigate process rates associated with specific elements or element groups. Global databases on elemental pools are available, see e.g. Hugelius et al. (2014), but for specific landscapes the data can be sparse and also may not be associated with general site understanding on ecosystem behaviour. Such conceptual site understanding is crucial when interpreting results from single element or property data. Also, the historical element behaviour (pools in defined environmental components) can be compared with present (fluxes) to understand changes in process rates in time. To gain understanding on global mass-balances, ecosystems and the linkages between ecosystems, many studies have been performed.

Already before the landscape concept (Risser et al. 1984) was established, the abiotic and biotic properties and elemental fluxes between pools were assessed on global as well as local scales, see e.g. Lotka (1925) and Lindeman (1942). The use of biogeochemistry to inform ecosystem models is a large scientific discipline in itself and Odum (1960) is a good example of early work on modelling element fluxes in an ecosystem. However, the use of a large number of element pools and fluxes to conceptually and quantifiably identify the long-term processes affecting material transport in a landscape has seldom been attempted. One exception is work done by Tröjbom and Grolander (2010) who describe chemical mass-balances for a landscape in Sweden and discuss implications on chemical properties in the future related to site-specific landscape development.

1.3 Gaps of knowledge and research questions

Limited research has been performed to describe the link between long-term climate change and long-term catchment-scale landscape development, and only a few publications are available on this topic. However, in the Baltic area, Ikonen et al. (2008) and Pohjola et al. (2014) describes landscape modelling methods and results for an area on the west coast of Finland, for up to 10 000 years into the future and Grudzinska et al. (2012) produced historical landscape maps in a project to reconstruct the palaeogeography of two Estonian peninsulas. Recent studies on landscape development in the UK emphasise fluvial erosion over the projected long interglacial to come due to anthropogenic influences on atmospheric CO_2 levels (Thorne & Towler 2017), and in van Balen et al. (2010) they use a landscape development model to examine responses to climate change in Rhine–Meuse, a large fluvial system in central Europe. They conclude that correlations of morphological features in the fluvial record to specific short term palaeo-climatic events could be risky without consideration of catchment size. Also, in France, long-term geomorphological studies have been emphasised in modelling of landscape evolution because the area of interest is situated beyond the margins of a future ice sheet, see Thorne et al. (2011) appendix E and references therein. Another example of a site that has been examined in terms of landscape evolution processes is the Yucca Mountain area in Nevada, USA. The role of erosion and fluvial processes is a key feature in the landscape evolution of the area, see e.g. Stuckless & Levich (2007) and Stuckless (2012) for a compilation of papers describing site conditions and discussions on site evolution.

The uncertainties involved in producing landscape development models are very large, and together with the multi-discipline characteristics of the information needed, the task is difficult to handle. Also, few societal questions have this long-term focus and instead tend to use a 100-year perspective as an upper limit. As stated earlier, nuclear waste management organisations are the only actors with research questions that require site-specific landscape development research applicable to these long time scales. The questions raised in previous work by radioactive waste assessment groups have been focused on the types of "biospheres" that will emerge or evolve over time (BIOMASS 2003). Generic reference future "biospheres" have been given as examples, and methods described (BIOCLIM 2004). However, no or little site-specific understanding was used and the landscape evolution due to climatic forcing was not fully analysed for specific sites. Even though recent (IAEA 2016) and ongoing work (the MODARIA I and II IAEA programmes) has addressed these gaps more fully (Lindborg et al. 2017), there are still many questions that need to be addressed. These are described below.

Depending on latitude, altitude and degree of continentality, the local-scale impact of global long-term climate change (natural glacial-interglacial cycles as well as human-induced climate change) will be very different. Therefore, we need a method that can use general and global understanding on past, present and future climate to understand regional impacts. We further need to downscale this global understanding to a site and extract the changing climate-related processes that will act upon that site. Finally, we must apply these changing processes on the landscape and evaluate the impact on the ecosystems, abiotic and biotic functional units, that are the building blocks of the landscape.

Having the above general strategy, several predictions arise that can be tested. From the outset, it is of importance to acknowledge that no predictions of the future are testable. What we must aim for is to test our ability to understand and mimic present-day conditions as well as the past by comparison with data.

If so, this can be used as an argument to justify our projection of possible site-specific futures. We must also test the assumption that only a handful of processes and properties govern landscape development, and that these are not just understood, but also robustly quantifiable in time using available data. It can be argued that temperature over time is the only global parameter needed, apart from an extensive site-specific database, to be able to produce a site narrative describing landscape evolution. This implies that all supporting modelling relies on temperature estimates to characterize climate-related processes and properties needed to drive the landscape development model. In the safety assessments performed for the Forsmark site in Sweden, such a global temperature curve is used to drive ice-sheet development, permafrost models, isostatic changes due to ice loading, and eustacy (SKB 2010; SKB 2014). All these models are based on processes that are governed by temperature, and all are used in the landscape development modelling.

Having stated the above, I once again emphasize that landscape modelling of future site characteristics should be used to provide relevant examples that build upon the best available understanding of global and regional climate, together with site-specific understanding of the past and a high confidence in our understanding of present-day site processes. Any application of a landscape model that projects a set of future characteristics of a site provides only one of several possible futures to be used in deterministic or probabilistic calculations. A recent example of the latter is a study done by Pohjola et al. (2016) who assess a lake succession in Finland for 10,000 years derived from landscape modelling with applied probabilistic techniques. The main argument for developing landscape narratives is to narrow down uncertainties using physically constrained examples as a base. That is, examples of relevance for the specific long-term assessment questions.

In this thesis, I present a set of papers (I-VI). These papers are the result of a need to better understand landscape succession and ecosystem behaviour during different climate conditions. They each address specific research questions that together build up and strengthen the overall hypothesis or statement; a landscape, with its ecosystems, can be described in time for different climates well enough to support site-specific assessments applicable to that landscape in time. You may argue that this is not a falsifiable hypothesis, and that is true, but the tests should be on the supporting data and models that describe present-day conditions and their responses to historical information. Then the confidence in narratives describing the future can be argued for, and associated uncertainties identified and quantified. Therefore, the main objectives for this thesis are the following:

1. to show how global climate information can be used as input to landscape modelling,
2. to assess the importance of site-specific data,
3. to investigate, analyse and synthesise a landscape with periglacial climate conditions and describe elemental pools and fluxes, and climate-related processes and features,
4. to assess conceptual differences in temperate versus periglacial ecosystems.

The study components within this thesis were divided into following papers:

Paper I:	This is a method paper that links climate science to landscape modelling and shows an example of climate-driven landscape modelling. Supports objective 1.
Paper II:	Here we hypothesise that major driving forces on long-term landscape development are few and can be characterized quantitatively. Supports objectives 1 and 2.
Paper III:	The overarching objective of this work was to describe the periglacial conditions on a landscape scale using multidisciplinary data. This to better understand and constrain the uncertainties associated with periglacial environments. Supporting objectives 2 and 3.
Paper IV:	In this paper, we assess the processes in a periglacial catchment using the sediment record. We ask if aeolian processes are of major importance close to an ice sheet and if the linkages between the terrestrial and the limnic systems are weak, due to very limited water flows between the terrestrial and limnic systems. Supporting objectives 3 and 4.
Paper V:	Here we work with carbon in permafrost soils and lake sediments to find evidence for their role as carbon sinks in the landscape. We also wanted to have more support for the hypothesis that linkages between terrestrial and aquatic systems are weak in West Greenland. We further asked if the aquatic primary production was sufficient to support the aquatic carbon balance. Supporting objectives 3 and 4.
Paper VI:	The paper describes the distribution of elements in a periglacial landscape and evaluates what this information can tell us. In this paper, we report mass-balances for 42 elements in total. Major pools and fluxes in the landscape are determined to help characterize transport processes. We argue that the pattern of elements associated with major pools in the landscape will give not only the present-day conditions, but also information on the site history. Supporting objectives 3 and 4.

2 Methods and data

2.1 The Forsmark site, Sweden

2.1.1 Site description

The Forsmark site is situated at the shoreline of the Baltic Sea in northern Uppland, Sweden, approximately 150 km north of Stockholm (lat 60.389900, long 18.198100). The area (approx. 100 km^2) constitutes of several catchments and sea basins to the north. The landscape represents a typical coastal site for the region (Fig. 2). Post-glacial land uplift, in combination with a flat topography, implies fast shoreline displacement that has resulted in a very young terrestrial system. The area consists of several new-born and, in this context, short-lived (estimated to 100–3000 years) shallow lakes and wetlands. The lakes themselves are also of a specific type that is found only in the region. Shallow and with sediments rich in calcium.

Figure 2. To the left: Picture of the Forsmark landscape heading north. In the background, a sparse archipelago can be seen that closer to the shores develops into bays, shallow lakes and wetlands. To the right: Geographic location of field site in Europe and Sweden. Figure modified from paper II.

Mean annual air temperature (MAAT) is +5˚ C, 1961-1990, for the region (Larsson-McCann et al. 2000) and local measurements between 2003-2015 show a MAAT of +6.8˚ C. The site location close to the shoreline of the Baltic Sea is probably the main cause of this local temperature difference. The vegetation period lasts approximately from May to September. The locally measured precipitation for the period 2003 to 2010 is 590 mm, with approximately 30% of the precipitation falling as snow. The average runoff from the largest sub-catchment in the area is 188 mm y^{-1}, resulting in an annual evapotranspiration of approximately 410 mm y^{-1} (Johansson 2016). A comprehensive description of present conditions at the Forsmark site can be found in Lindborg (2008) and a synthesis of landscape characteristics in Lindborg (2010).

The deglaciation at Forsmark took place during the Preboreal climatic stage, c. 8,800 BC (Strömberg 1989; Persson 1992; Fredén 2002). Forsmark is located below the highest coastline, and, during the latest deglaciation, the area was covered by 150-180 m of water (Söderbäck 2008). The closest land area at that time was situated c. 100 km to the west of Forsmark. Reconstructed MAAT for the last glacial cycle shows a fluctuation between +10˚ C and -10˚ C at the site between interglacial and glacial periods (SKB 2010), but these numbers are associated with uncertainties of several degrees. The shoreline displacement has strongly affected landscape development (Paper II). During the first stages of the Baltic Sea following the last deglaciation, the vertical shoreline displacement was in the order of 350 mm y^{-1} and the process still causes a continuous and relatively predictable change (presently 6 mm y^{-1}) in the landscape. The first parts of the Forsmark area emerged from the sea around 500 BC as islands in an archipelago. Thus, the post-glacial development of the landscape has, until present time, been determined mainly by the Baltic basin development, the associated shoreline displacement (Påsse 2001) and natural ecosystem succession with more recent interruptions caused by human land use.

2.1.2 Site investigations and data types

During 2002–2008, an extensive site investigation and characterisation of the biosphere was performed at the Forsmark site by Swedish nuclear fuel and waste management Co (SKB) (Lindborg 2008; 2010). The characterisation aimed at building a biotic and abiotic site-specific database to be used in conceptual ecosystem modelling and elemental (radionuclide) transport modelling in safety assessments (Löfgren and Lindborg 2003; Lindborg et al. 2006; Kautsky et al.

2013). The work presented in Paper I and Paper II used this information, but no further field work was performed in support of this thesis. The characterization of the Forsmark site was primarily made by identifying and describing important properties of different parts of the surface system, properties concerning e.g. hydrology and climate, Quaternary deposits and soils, biogeochemistry, terrestrial and aquatic ecosystem functions, and processes describing landscape development, but also current and historical land use. In Lindborg (2008) available data were presented together with a data evaluation, modelling methods, and resulting models for each of the different disciplines. Results from the modelling of the surface system were also integrated with results from modelling of the deep bedrock system. A further analysis of the Forsmark landscape characteristics, describing present and possible future conditions, was also made and published in Lindborg (2010).

2.2 Two Boat Lake, Greenland

2.2.1 Site description

The Two Boat Lake (TBL) catchment is situated close to the Greenland ice sheet and approximately 30 km from the settlement of Kangerlussuaq, West Greenland (lat 67.125940, long -50.180370; Fig. 3).

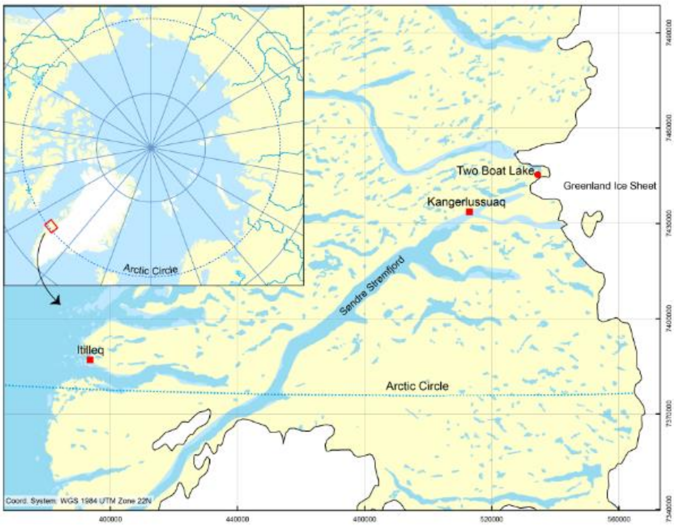

Figure 3. Location of the Two Boat Lake catchment close to the settlement of Kangerlussuaq. An inserted Circum-polar map shows the area location in West Greenland. Figure from paper III.

The catchment area is 1.56 km^2, of which the lake occupies 0.37 km^2. Although close to the ice margin, it is not part of the meltwater-driven surface water system (Fig. 4), and surface-water runoff to the lake is generated by precipitation only. A digital elevation model describing both the topography of the terrestrial part of the catchment and the bathymetry of the lake has been developed and published in Petrone et al. (2016).

The Kangerlussuaq region is characterized by a hilly tundra landscape with numerous lakes and is the most extensive ice-free part of Greenland. Continuous permafrost, interrupted by through taliks under larger lakes, covers the area. Permafrost is perennially frozen ground that develops downwards from the surface and is defined as ground that remains at or below 0°C for at least two consecutive years. The total depth of permafrost depends on heat exchange processes between the atmosphere and soil/bedrock (French 2007). An active layer that thaws each summer of 0.15–5 m, depending on soil type and vegetation cover, overlies the permafrost in the area from the settlement of Kangerlussuaq up to the ice-sheet margin (van Tatenhove and Olesen 1994). Measurements during the site investigations in the TBL catchment indicate an active layer depth of around 0.4–2.0 m (Petrone et al. 2016). Permafrost depths in the range 300–400 m have been observed from temperature measurements in deep bedrock boreholes 5–6 km from TBL and a borehole that is situated 20 m from the TBL shoreline and inclined to penetrate under the lake shows that TBL is underlain by a through talik. This confirms permafrost modelling that suggests a continuous permafrost depth of 350–400 m in the area, with through taliks beneath larger lakes (Harper et al. 2011; Harper et al. 2016; Claesson Liljedahl et al. 2016).

Figure 4. Photograph of Two Boat Lake and surrounding catchment looking south west. To the left the Greenland ice sheet and the upper part of Russel Glacier can be seen. The road from Kangerlussuaq to the ice cap is also visible on the left side of the lake. (photo: T. Lindborg)

About 10,000 years ago, the ice sheet covered western Greenland all the way to the present-day coastline about 120 km west of Kangerlussuaq (Fig. 3). By about 6000 years ago, the ice front had receded to its present position, and over the following 2000 years it receded even further to the east. During this glacial minimum at the Holocene thermal optimum, the margin was likely located at least 10 km further inland as compared with its present position. From this minimum, some 4000 years ago, the ice has readvanced (Funder 1989; van Tatenhove et al.1996). The Kangerlussuaq area deglaciation history is also further discussed and illustrated in Claesson Liljedahl et al. (2016).

2.2.2 Site investigations and data types

During 2010–2016, the TBL site was studied as part of the Greenland Analogue Surface Project (GRASP), a joint project between Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm University and the Swedish University of Agricultural Sciences and funded by SKB. The GRASP project was aimed at describing the hydrology and biogeochemistry of a periglacial catchment and resulted in a large amount of information on water mass-balance, meteorological time series, topography, lake bathymetry, and soil and active layer depths, properties and maps of vegetation, sediments and soils, soil temperature, and chemical and biotic properties of the limnic and terrestrial ecosystems within the catchment. The investigations presented in this thesis comprise the biogeochemical part of the GRASP project (paper III) and the information is also available for public use via the PANGAEA data base (Lindborg et al. 2016; Table 1). Hydrological data (Johansson et al. 2015b) and data on soil, sediment and active layer depth modelling (Petrone et al. 2016) were used to calculate flux rates and volumes of elemental pools.

The general sampling strategy was to get a broad picture of element distribution and not to focus on any specific target element. The aim was to provide understanding of the general fluxes of dissolved and particulate matter in the system. Sample analyses were made for concentrations of carbon, nitrogen and phosphorus, together with associated species and isotopic composition, as well as total concentrations of a long list of major and trace elements and isotopes, which together with the hydrological model helped us to understand and calculate fluxes in the landscape. Age determinations of soils and sediment layers, together with estimates of biomass and primary production in both the terrestrial and aquatic systems, made it possible to calculate accumulation of various elements in different landscape and ecosystem units.

Table 1. Parameter overview with analytical methods used for the Two Boat Lake chemical dataset. All data are available in the PANGAEA data base. PANGAEA: doi:10.1594/PANGAEA.860961. Lindborg et al. (2016). Table from paper III.

Parameter	Sample type	Laboratory - Analytical method	
Organic content	Solid	EMG, UmU - LOI	SLU, Uppsala - LOI, ALS - LOI
Tot-C	Solid	SLU, Umeå - EA-IRMS	SLU, Uppsala - EA, ALS - EA
TOC, DOC	Water	DEEP, SU - NPOC	ALS Scandinavia - NPOC/TC-IC
TIC, DIC	Water	DEEP, SU - IR after acidification	ALS Scandinavia - IR after acidification
^{13}C	Solid	SLU, Umeå - EA-IRMS	ISO-Analytical - EA-IRMS
	Water	IGV, SU - IRMS	
Tot-N	Solid	SLU, Umeå - EA-IRMS	SLU, Uppsala - EA, ALS - EA
	Water	DEEP, SU - SFA	ALS Scandinavia - CFA
NH_4^+, NO_2^-, NO_3^-	Solid	ALS Scandinavia - IC	
	Water	DEEP, SU - SFA	ALS Scandinavia - CFA
^{15}N	Solid	SLU, Umeå - EA-IRMS	ISO-Analytical - EA-IRMS
Tot-P	Water	DEEP, SU - SFA	
	Filters	DEEP, SU - combustion-SFA	
PO_4^{3-}	Solid	ALS Scandinavia - CFA	
	Water	DEEP, SU - SFA	
Chlorophyll-a	Filters	DEEP, SU - Spectrometry	
Major+trace elements	Solid	EMG, UmU - WD-XRF	ALS Scandinavia - ICP-SFMS
	Water	ALS Scandinavia- ICP-SFMS	
Si	Water	DEEP, SU - SFA	
Br^-, Cl^-, F^-	Solid	ALS Scandinavia - IC (F only)	
	Water	ALS Scandinavia -IC	
SO_4^{2-}	Solid	ALS Scandinavia - IC	
	Water	ALS Scandinavia - IC	
^{34}S	Water	IGV, SU - EA-IRMS	
^{2}H	Water	SLU, Umeå - Liquid water isotope analyzer	
^{18}O	Water	SLU, Umeå - Liquid water isotope analyzer	
^{234}U:^{235}U	Water	FOI - ICP-SFMS	
^{14}C	Solid	C-14 dating laboratory, LU - AMS	
^{210}Pb, ^{137}Cs, ^{226}Ra etc.	Solid	Flett Research - Alpha spectr. (^{210}Pb only)	Nutech, DTU - Gamma spectroscopy
EMG - Dept. of Ecology and Environmental Science		**LOI** - Loss on ignition	**SFA** - Segmented flow analysis
SLU - Swedish University of Agricultural Sciences		**EA** - Elemental analysis	**CFA** - Continuous flow analysis
DEEP - Dept. of Ecology, Environment and Plant Sc.		**IRMS** - Isotope-ratio mass spectroscopy	**IC** - Liquid ion chromatography
IGV - Dept. of Geological Sciences		**NPOC** - Non-purgable organic carbon	**XRF** - X-ray fluorescence spectroscopy
FOI - Swedish defense research agency		**TC-IC** - Total carbon - Inorganic carbon	**ALS** - ALS Scandinavia AB
ICP-SFMS - Induct. coupl. plasma-sector field mass sp.		**IR** - IR detector	**AMS** - Accelerated mass spectroscopy

2.3 General approach and method

The general approach used in the work reported in this thesis is summarised in the following and is further developed in the papers herein. To be able to test the hypothesis stated and to support the assumptions made, several methods were used. In Paper l, we review present understanding on climate modelling and downscaling methods to local scales. Note that the overarching aim of this thesis is to follow the climate and landscape evolution for up to a glacial cycle. Further, the aim is to conceptually describe differences in ecosystem behaviour for different environmental conditions and climatic assumptions at a site-specific level. I argue that the global scale is not only relevant, but necessary to support regional and/or local climate narratives (Paper I).

I emphasise that these narratives (based on palaeorecords or models) are not forecasts, but should be looked upon as relevant examples of possible futures given specific assumptions on climate forcing. This argument has also been employed by SKB in relation to the handling and use of climate scenarios in long-term safety assessments (SKB 2010; SKB 2014). Having site-specific climate narratives, we use the local site understanding (Lindborg 2008; 2010) at the Forsmark site to quantify the major processes affecting the landscape in order to construct a landscape development model (Paper ll). These processes are either directly related to climate (Näslund et al. 2013) or derived from local properties and features. The availability of this landscape development model made it possible to conceptually describe those ecosystems that constitute the landscape in time. The landscape model showed that, during a temperate interglacial, sea bays turn into lakes. Lakes become slowly filled with sediment and in-growth of vegetation and turn into wetlands. Wetlands turn into forests or areas usable for agriculture. After having created a landscape development model that can mimic an interglacial period for the Forsmark site, we acknowledged the need to further broaden our understanding of the periglacial climate conditions represented within our landscape and ecosystem models. In Paper III, together with work presented in Johansson et al. (2015a; 2015b) and Petrone et al. (2016) we present the site investigation methods and data requirements to model ecosystems in an inland periglacial landscape (the Two Boat Lake catchment in West Greenland). This site could be described as a present-day climate analogue for a future colder Forsmark. In short, the site investigation included the chemical, hydrological, and physical and geometrical properties needed to describe biotic and abiotic ecosystem functions, pools and fluxes within a catchment and in time. In Fig. 5 examples of catchment maps are shown. These are the result of analyses of aerial photographs and initial site investigations (Clarhäll 2011; Petrone et al. 2016). The maps together with topography and lake bathymetry data were used to establish installations and a sampling strategy to be representative for the landscape, i.e. to determine type areas and a stratified sampling programme.

An important part of site understanding is to be able to describe the site history. This helps to relate features in the landscape with events and to adjust process rates needed in the landscape development modelling. In Paper IV we describe how we investigated the TBL lake sediment chemistry and used sediment dating as support to a discussion of landscape processes affecting elemental transport and accumulation in the area. Literature and work on regional history is often available. When arguing for the representativeness of a site, such local data are needed.

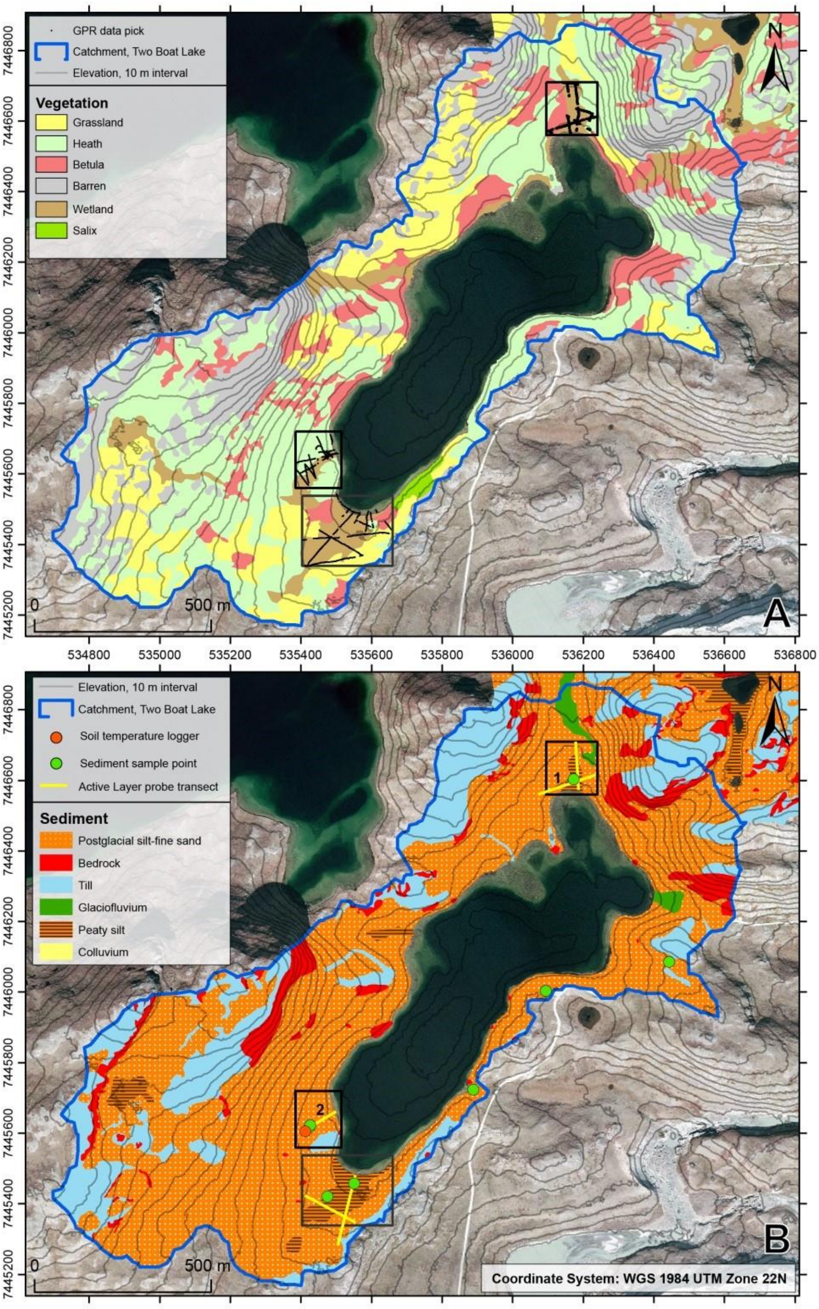

Figure 5. (A) Vegetation map for Two Boat Lake with sites for ground-penetrating radar measurements (black lines). (B) Terrestrial soils and deposits in the catchment. Focus areas for active layer investigations are shown as black rectangles. Figure from Petrone et al. (2016).

Lake sediments can be regarded as the net result of landscape processes and processes acting on the landscape (see e.g. Dearing 1991; Boyle et al. 2004; Renberg 2014). Lake sediment information is, therefore, a good starting point when building a conceptual model of a catchment/landscape. The next step in the general method used in this thesis was to construct ecosystem models for TBL. The ecosystem models were defined from mapping of the terrestrial and aquatic system, and by conceptually defining functional units within them. The terrestrial and aquatic system was finally merged into a landscape mass-balance model describing carbon pools and fluxes (paper V). The landscape carbon model is, apart from illustrating local carbon behaviour, a good support in discussions on global carbon feedback mechanisms and regional consequences of climate change. However, ideally such a local model needs replicate sites to be adequately supported as an input to regional data and global climate models. The final step in our method was to use a broad range of elements present at TBL (paper VI) to characterize transport processes of relevance when comparing temperate with periglacial climate states. Earlier work had shown that conceptual differences in how to interpret behaviour in functional biotic and abiotic units in ecosystems that experience different climate conditions must be considered when modelling climate transitions and/or climate states for specific sites (Lindborg 2010). In Fig. 6, a flow chart illustrates the general methodology used in this thesis with each box representing a standalone paper.

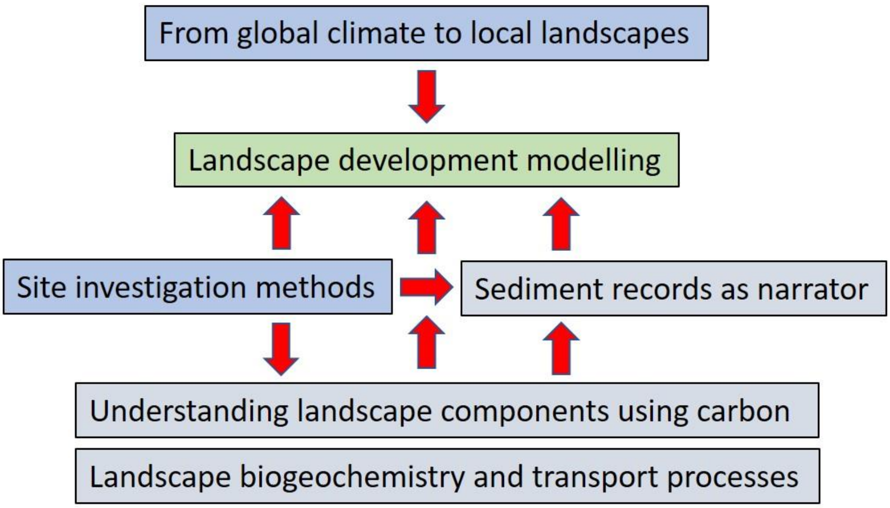

Figure 6. Flow chart illustrating the method described for going from global climate models to site-specific properties. The individual papers attached to this thesis are linked to each other to show their part in the overall methodology. Note that two sites are used in individual papers and that this figure therefore only illustrate the concept. Blue boxes = method and data papers, green = distributed modelling, grey = site data synthesis

3 Summary of main results

3.1 From global climate to local landscapes (Paper I)

Influence of climate on landscape characteristics in safety assessments of repositories for radioactive wastes. Becker, J.K., Lindborg T. & Thorne M.C. (2014). Journal of Environmental Radioactivity, vol. 138, pp. 192–204.

Paper I presents research performed and results obtained within the framework of an IAEA programme. The work was to identify the present state of the art in long-term climate modelling and the downscaling strategies available to describe site-specific characteristics over time. In safety assessments of repositories for radioactive wastes, large temporal scales must be considered (100 – 1000 000 years).

A range of different types of processes and features are required to build relevant narratives of possible developments of present environmental conditions. For a site of interest, changes may be governed by both regional and local considerations, e.g. isostasy, wave field characteristics, alteration of river base levels, river drainage network reorganisation, or the progression of an ice sheet or valley glacier across the site. The regional climate is in turn governed by the global climate.

In Paper I, a commentary is presented on the types of climate models that can be used to develop projections of climate change for use in post-closure radiological impact assessments of geological repositories for radioactive wastes. These models include both Atmosphere-Ocean General Circulation Models (AOGCMs) and Earth Models of Intermediate Complexity (EMIC). The relevant outputs available from these models are identified and consideration is given as to how these outputs may be used to inform projections of landscape development (Fig. 7).

Issues of spatial and temporal downscaling of climate model outputs to meet the requirements of local-scale landscape development modelling are also addressed. An example is given of how climate change and landscape development may influence the Forsmark site in Sweden, under the assumptions made for the future climate scenario used.

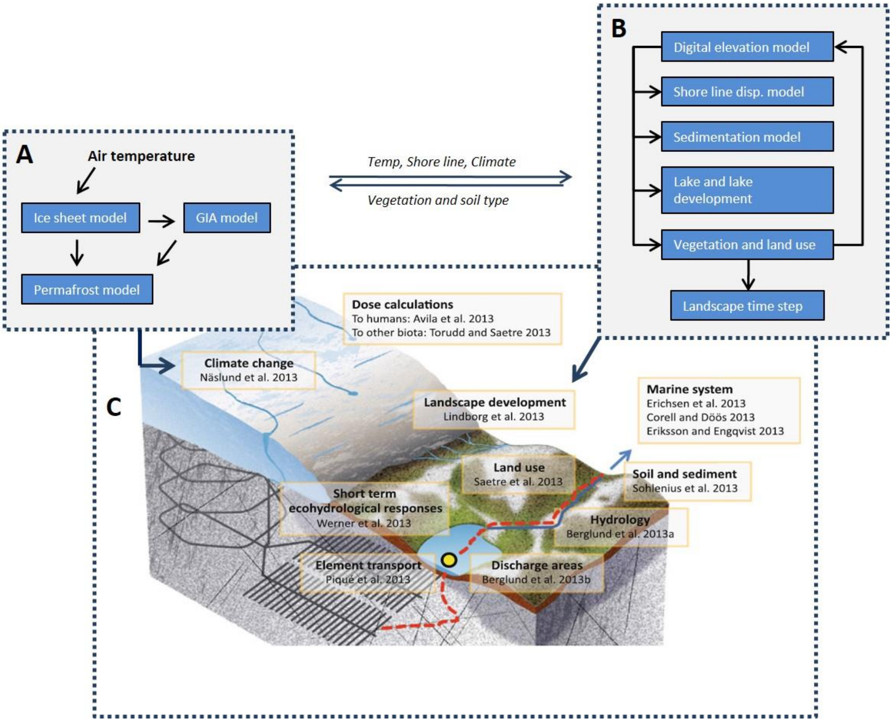

Figure 7. Modelling of an environmental system is illustrated for periglacial conditions (C). The various aspects of the system are indicated and references are given to where the work is further described as separate papers in Kautsky et al. (2013). Lindborg et al. (2013) refer to Paper II in this thesis. Climate and landscape modelling linkages to the conceptual system are shown with dark blue arrows. The red dotted line illustrates a hypothetical radionuclide pathway. Insert A is a simplified example of the coupled modelling described (modified after Näslund et al. 2013). Insert B is a simplified flow chart of the landscape development model presented in Paper II. Figure from paper I.

Where future situations are analogous to those occurred in the past, palaeoclimatological data can be used in defining the climate conditions to be assessed. However, data from analogue sites should be used with care and are not, in general, preferable to empirical information (including palaeodata) from the site of interest. Analogue sites will probably not represent future properties at the site of interest sufficiently well for data relating to them to be adopted directly, and differences in site-specific characteristics may make analogue information misleading. We argue that a better approach is to use the conceptual understanding of the analogue system and to adapt this concept when modelling future climatic conditions at the site of interest.

3.2 Landscape development modelling (Paper II)

Landscape development during a glacial cycle: modelling ecosystems from the past into the future. Lindborg, T., Brydsten, L., Sohlenius, G., Strömgren, M., Andersson, E. & Löfgren, A. (2013). AMBIO, vol. 42, pp. 402–413.

The landscape development model for the Forsmark site presented in Paper II is an extended example of how to use climate and landscape modelling output (in this case temperature and shoreline displacement) from the methodology described in Paper I in the construction of a site-specific narrative.

During earlier studies in Sweden, we showed the possibility of giving a rather detailed description of site characteristics and the historical development of a site (Bradshaw et al. 2006; Lindborg et al. 2006; Lindborg 2008). Our understanding from those studies was that the successional patterns at landscape scale, would repeat themselves both in time and space. Therefore, our hypothesis was that the major driving forces for long-term landscape development are few and can be quantitatively characterized. Moreover, we considered that the drivers and resulting changes could be identified by the understanding of the historical development of a specific site. For a coastal site in Sweden, these drivers are climate variation, shoreline displacement, and mass fluxes of matter via water or primary production (e.g., lake infilling or peat formation). By applying the above processes on the landscape geometry (topography and bathymetry), we can model the development of ecosystems at the landscape level, taking into account future land emergence or submergence. The rationale behind the hypothesis and resulting work presented in Paper II relies mainly on previous studies (e.g., Påsse 2001; Söderbäck 2008; Brandefelt and Otto-Bliesner 2009; Brydsten et al. 2009; Brydsten and Strömgren 2010; Kjellström et al. 2010; Brandefelt et al. 2011).

The overall modelling strategy was to set up a chain of models that mimic the major processes involved in landscape development. In Fig. 8, the model chain is shown starting with a Digital Elevation Model (DEM) for the entire Baltic Sea, and for time steps that, in total, represent present interglacial. The DEM is then input to the wave modelling that drives the sediment distribution. The models of the whole Baltic Sea are then used to drive a local model setup of a DEM and wave model that have the resulting sediment model as output.

For each time-step, a map is produced with soil/sediment associated vegetation at land surfaces. Shoreline displacement and sedimentation/lake infilling were found to be the most important processes driving landscape development at Forsmark. The results show how the landscape develops during a glacial cycle with emphasis on the present interglacial period.

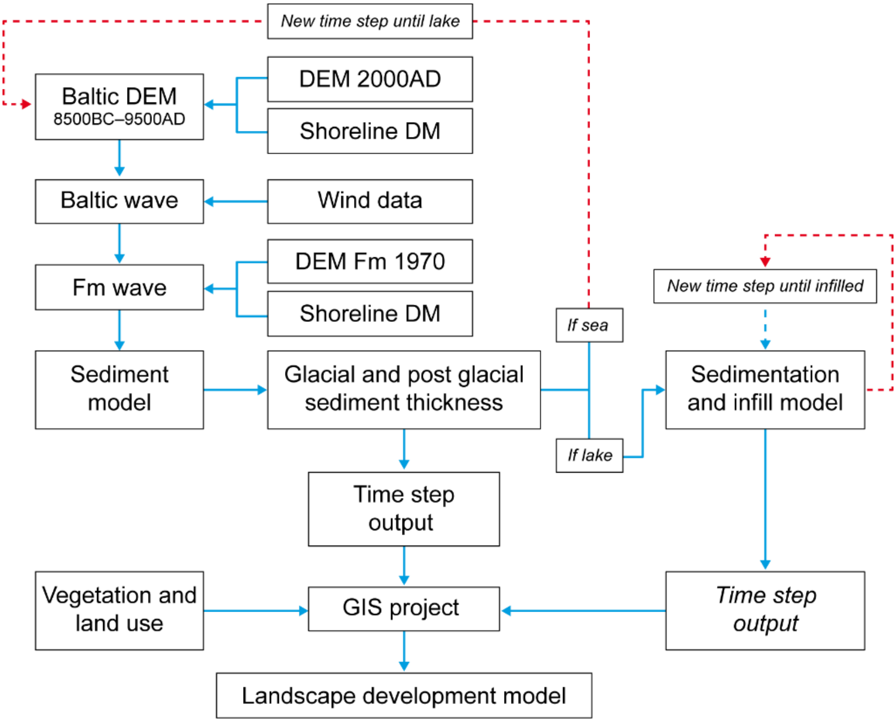

Figure 8. Illustration describing the workflow and sub-models used to construct a landscape development model. Fm = Forsmark, DEM = Digital elevation model. Red dotted arrows indicate possible model step iterations. Figure from paper II.

The period just after an earlier glaciation, was characterized by sea. Land was submerged to a depth of approximately 150–180 m (depending on location in the model) due to the load of the previous ice sheet. The first land in the model area emerged from the sea at 500 AD, and lakes and wetlands started to form. After 20,000 years (at 10,000 AD), the total model area is above sea level and only a narrow bay can be seen in the northeastern part of the Forsmark landscape (Fig. 9).

Validation of a model that describes the future is not possible. However, the input models and the handling of the processes therein can be validated against existing process rates. It is also possible to compare the output of the modelled landscape with site features of today. The landscape development model was therefore validated in two steps: (i) the input processes were validated for each input model or dataset, (ii) the final model was run using initiation data from 9,500 BC (a bit earlier then 8,800 BC that is the calculated period for the last glaciation of Forsmark) up until the present-day landscape (2000 AD). The model was then compared with present-day site characteristics. This second validation step is only qualitative and visually evaluates the model's ability to mimic process rates at a landscape level. In Paper II, the model output for 2000 AD is merged with a map of Forsmark showing present conditions at the site.

Even though the model in many ways uses the present conditions for process calibrations, the comparison is still useful to show that the model handles the major processes that describe landscape development in a correct manner. The shoreline displacement rate is one example of a process that builds upon understanding of historical conditions.

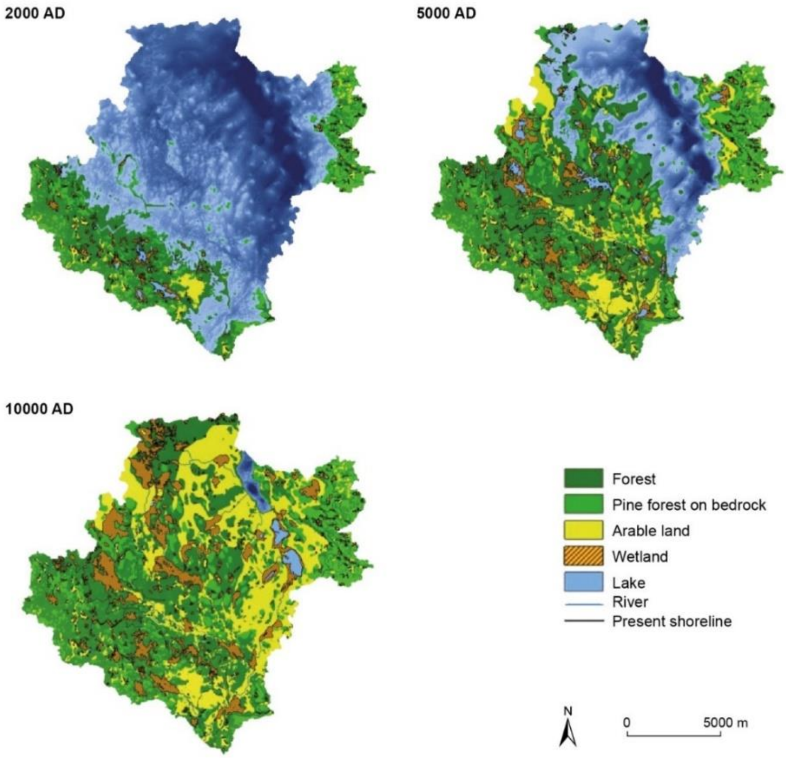

Figure 9. Distribution of ecosystems at Forsmark at 2000 AD, 5000 AD and 10,000 AD according to the landscape development model (Paper II). The distribution of arable land illustrates the assumption in which the present-day use of soil types for agriculture persists into the future.

Therefore, the validation of the landscape development model shown in Paper II is not to be taken for a validation of its capability to model the future, but rather of its ability to mimic the historical landscape development at Forsmark. However, if the processes do not change dramatically, we should have a good tool for also modelling a future of relevance for assessment studies. It is also important to note that the aim of the modelling exercise was to capture landscape characteristics and not the exact location of landscape features. The aim was to be able to tell a story about Forsmark and the resulting landscape pattern that could emerge in time due to the impact of major driving forces on the present-day Forsmark landscape.

3.3 Site understanding and analogues (Paper III)

Biogeochemical data from terrestrial and aquatic ecosystems in a periglacial catchment, West Greenland. Lindborg, T., Rydberg, J., Tröjbom, M., Berglund, S., Johansson, E., Löfgren, A., Saetre, P., Nordén, S., Sohlenius, G., Andersson, E., Petrone, J., Borgiel, M., Kautsky, U. & Laudon, H. (2016). Earth System Science Data, vol. 8, pp. 439–459.

To produce site-specific narratives as described in Paper II and associate processes that govern transport of elements in the landscape, good site characterisation is needed (see also section 2). This is not only necessary for characterising the environmental conditions and processes that prevail today, but also for considering how future climates may alter process rates and introduce new features. One way to enhance site understanding is to consider also analogue sites with conditions relevant to potential future climate conditions at the site of interest. In the context of this thesis, the Forsmark site and the work presented in Paper II needed an analogue for periglacial conditions with permafrost. A site with general conditions that could be related to both present and future Forsmark was, therefore, identified in West Greenland. Site properties like geology, deposits and catchment-lake geometries were favourable for use of this site as an analogue to Forsmark. The close location to the Greenland ice sheet allowed proglacial processes to be investigated and the topographical isolation from the ice sheet meltwater system gave an undisturbed local hydrology not influenced by purely glacial events or processes. In Paper III we describe the investigation strategy, methods used and resulting data for the TBL site in West Greenland.

The general investigation design for the TBL site was based on a conceptual model describing the different functional units in the catchment (Fig. 10), such as lake water, sediments, biota, active layer soils and permafrost. The conceptual model was, in turn, based on maps describing topography, vegetation and soils.

A survey on lake bathymetry was also part of the basic site understanding used as input to design the biogeochemical sampling programme. As an overarching goal for the investigation, it was required that the data obtained should make it possible to build ecosystem models for the catchment. These models had to be able to capture major pools and fluxes in the landscape, and to identify features related to the periglacial climate conditions prevailing at the site.

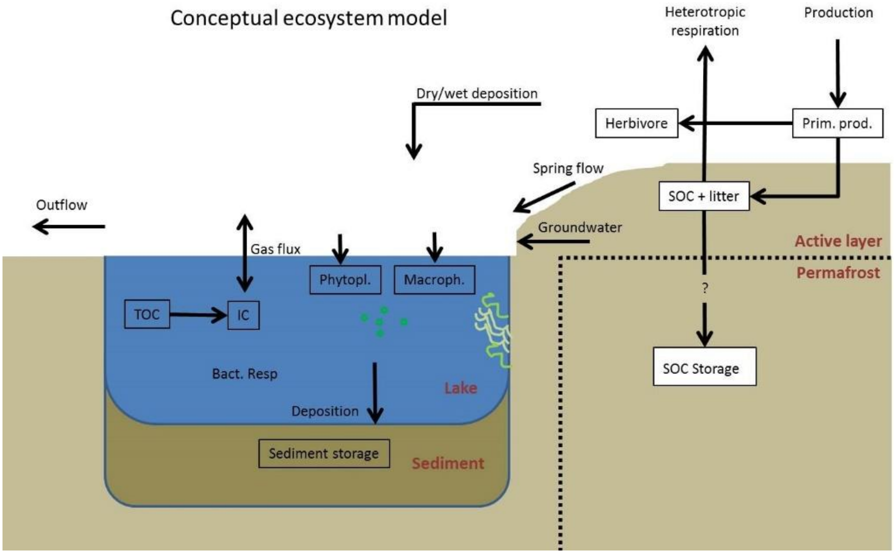

Figure 10. Example of conceptual illustration used in the planning of site characterisation at the TBL catchment.

Figure 11. Installations for soil water sampling at Two Boat Lake. To the left: Lysimeter flasks filled with soil porewater after 12 hours of pore water suction from 4 depths (10-50 cm). To the right: Lysimeter and TDR (Time Domain Reflectrometry) installations in one of the pits at a soil transect. The lysimeter tubes can be seen entering the back end of the lysimeter that is placed into the pit wall in upstream direction.

By collecting biogeochemical data for all identified ecosystem units in the conceptual model and then combining them with the existing hydrological model (Johansson et al. 2015a) and geometrical information (Petrone et al. 2016), the intent was to develop models describing the fluxes and accumulation of various elements at a catchment scale.

During the site investigation, we analysed concentrations of carbon, nitrogen and phosphorus, as well as total concentrations of major and trace elements and stable isotopes, (see section 2.2.2), which together with the hydrological model helped us to understand the fluxes of material in the landscape (Fig. 11). Age determinations of different soil and sediment layers, together with estimates of biomass and primary production in both the terrestrial and aquatic systems, made it possible to estimate the accumulation of various elements in different landscape units. The resulting database from this site characterisation was subsequently used in various calculations and modelling exercises presented in Papers IV, V and VI.

3.4 Sediment records as narrator (Paper IV)

The importance of eolian input on lake sediment geochemical composition in the dry proglacial landscape of western Greenland. Rydberg, J., Lindborg, T., Solenius, G., Reuss, N., Olsen, J. & Laudon, H. (2016). Arctic, Antarctic and Alpine Research, vol. 48, pp. 93–109.

Several processes affect the sediment accumulation in a lake. When analysing the chemistry in a sediment core, historical climate-phases and events can be identified. Also, processes that govern the accumulation of sediment are detectable and their rates can be measured. A relevant starting point when describing present conditions for a catchment or landscape is to understand historical processes. Therefore, in Paper IV we analysed the geochemical composition of the lake sediments of the TBL-regional area (5 lakes) in order to determine if and how variations in processes, mainly eolian (eolian is here defined as local originated short-range transport compared to long range atmospheric deposition), have influenced the geochemical composition of the sediment (Fig. 12). That is, we examined how the sediment geochemistry varies depending on distance from the Greenland ice sheet and in time.

The surface sediments of lakes located within 1–2 km of the front of the ice margin, have higher Zr:Rb, Zr:K, and Zr:Ti ratios as compared with the surface sediments of lakes located 37–48 km from the front of the ice sheet (paper IV). This strengthens the interpretation from the Two Boat Lake (close to the source area) record that enrichment in Zr is caused by increased eolian activity (wind-transported material). To explore the Two Boat Lake sediment data, we used a principal components (PC) analysis to identify changes in the geochemical composition through the sediment profile.

Figure 12. Photograph of sediment core taken in Two Boat Lake. Distinct colour-bands can be seen that correspond to internal lake processes and shifts in sedimentation type and amount over time.

So-called PC-scores were then used for each component to evaluate elemental behaviour. This method, as compared with interpreting individual elements, has the advantage that the sediment is viewed as one unit where the covariation in different sediment variables is used to describe the patterns in principal components (Rydberg and Martinez Cortizas 2014).

The sediment sequence from Two Boat Lake could be visually divided into two main stratigraphic units (Fig. 13). The deeper unit, (unit I), 96–40 cm sediment depth or ca 3170–1420 calendar years Before Present (BP, i.e., calibrated years before A.D. 1950) consisted of light, gray-brown material, whereas the upper unit (unit III), 36–0 cm sediment depth or from ca 1300 calendar years BP to present, consisted of a much darker, red-brown material. The two units were separated by a ca 4 cm section of greyish material that was overlain by a thin, distinct, clay layer designated as unit II. In total, the core represented a more than 3000-year long sedimentation record, as determined by ^{14}C dating.

Negative PC-1 scores for unit III show that the concentration of elements related to organic material were higher in unit III as compared to unit I. However, the higher sediment accumulation rate in unit I translates to a higher accumulation of organic material in unit I as compared with unit III (Fig. 13). This implies that the driving factor behind the change to more organic sediments at ~1300 cal. yr B.P. was a decrease of minerogenic input to the sediment rather than an increase in the input of organic material.

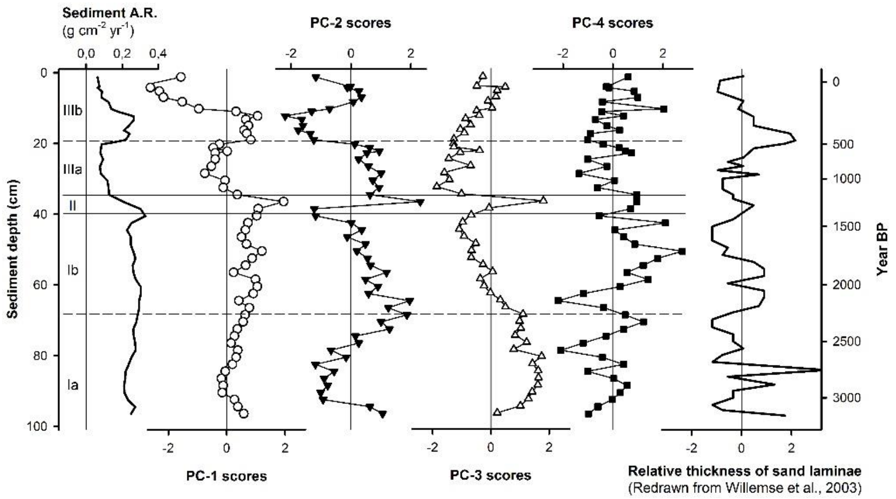

Figure 13. Sediment profiles from Two Boat Lake plotted against depth (left-hand scale) and age (right-hand scale). Horizontal solid lines separate the three stratigraphic sediment units, whereas the thin dashed lines separate subunits. From left to right: bulk density; PC-1, representing shifts between the organic and inorganic fractions of the sediment (higher scores imply less organic matter); PC-2, representing shifts between coarser and finer grain sizes (higher scores = finer grain sizes); PC-3, representing shifts in oxygen availability; PC-4, representing more or less V and Ni. The plot to the far right represents the temporal variations in sand lamina thickness in Sandflugtdalen which can be used as a proxy for eolian activity (redrawn from Willemse et al. 2003). Figure from (Paper IV).

Several processes might lead to a reduced accumulation of mineral material in lake sediment: decreased eolian input, decreased soil erosion, altered lake-water levels or the disappearance of an inflowing stream. Decreased eolian activity in the past is less likely for Two Boat Lake, because none of the records of regional eolian activity shows any decrease that fits the temporal trend in Two Boat Lake (Eisner et al. 1995; Willemse et al. 2003). Soil erosion is primarily controlled by runoff and vegetation cover (Håkanson and Jansson, 1983; Koinig et al. 2003), and neither of these are realistic explanations of the decreased accumulation of mineral material in Two Boat Lake. First, there is no indication of decreased precipitation at approximately 1300 calendar years B.P. in the precipitation reconstructions for the area made by McGowan et al. (2003).

Second, the macrofossil record from Lake SS16 (located approx. 26 km southeast of Two Boat Lake) suggests a reduction rather than an increase in vegetation cover subsequent to 1500 to 1800 calendar years B.P. (Heggen et al. 2010).

Our study shows that eolian input is higher in lakes close to the inland ice sheet, mainly due to a greater availability of material that can readily be transported by wind. We also argue that input of eolian material influences lake-water chemistry due to the fresh, un-weathered material affecting pH and alkalinity as compared with conditions in areas receiving less or no inputs of eolian material. We conclude that eolian transport needs to be considered when calculating mass balances for lake-catchment ecosystems in dry periglacial landscapes close to an ice sheet.

3.5 Understanding landscape components using carbon (Paper V)

Terrestrial and Aquatic Pools and Fluxes in a Periglacial Landscape: Carbon Budget Analysis for a Catchment in West Greenland. Lindborg, T., Rydberg, J., Andersson, E., Löfgren, A., Johansson, E., Saetre, P., Sohlenius, G., Berglund, S., Kautsky, U. & Laudon, H. (submitted).

When discussing long-term changes at ecosystem or landscape level, understanding of site-specific properties and functions (biotic and abiotic) is needed. In Paper III we presented a strategy and method to investigate a site (the TBL-site in West Greenland) and, as a part of that work, published the resulting data (Lindborg et al. 2016). In Paper IV we used the sediment record to better understand the historical development of the landscape, and processes related to lake sedimentation. In this work (Paper V), we constructed an ecosystem carbon mass-balance model for the TBL catchment. This was done by combining information on terrestrial and aquatic carbon pools and fluxes for the lake and its surrounding terrestrial catchment.

By describing the landscape as divided into several pools (or functional units) with fluxes connecting them, we aimed at supporting assumptions made on ecosystem functions in the catchment. The main hypothesis was that the dry and cold conditions in the region and the separation from the glacial meltwater system would result in a weak hydrological connection between terrestrial and aquatic ecosystems, implying relatively small carbon fluxes to the lake. This would result in a lake that tended to be net autotrophic with little dependence on terrestrial input. However, because of the long water residence time (c. 50 years), which is due to the neutral or only slightly positive hydrological balance, the lake was still expected to act as a carbon sink in the landscape.

The resulting carbon model (Fig. 14) describes a landscape with a small net carbon accumulation of less than 1% of the annual budget. Lake sediment accumulation adds to the long-term carbon surplus and the terrestrial carbon inflow via water is not as significant as in areas of warmer climate conditions. Instead, eolian deposition has a larger role together with a relatively high internal production in the lake. Despite high production, the lake is heterotrophic and the model lacks carbon in the aquatic mass-balance.

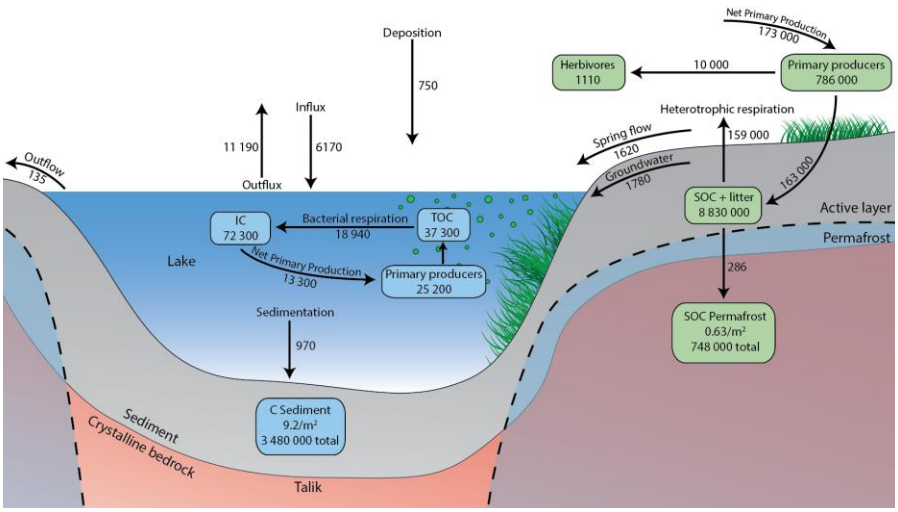

Figure 14. Conceptual illustration of the carbon landscape ecosystem model for the TBL catchment. Arrows indicate fluxes and boxes are pools. Numbers in the figure relates to kg C (pools) and kg C per year (fluxes) calculated in the modelling. Figure from Paper V.

In the permafrost, there are only small amounts of carbon stored and the two major landscape pools are found in the upper part of the active layer and the lake sediments. These pools are relatively insensitive to temperature changes due to their unfrozen state, as compared with pools in the permafrost. Therefore, we conclude that processes related to the terrestrial active layer carbon pool or influences on terrestrial primary production may be the key, together with lake accumulation processes, to the understanding of future climate influences on the carbon cycle in West Greenland.

3.6 Landscape biogeochemistry and transport processes (Paper VI)

Mass-balance of 42 elements in a periglacial lake catchment in West Greenland. Lindborg, T., Rydberg, J., Lidman, F., Tröjbom, M., Berglund, S., Johansson, E., Kautsky, U. & Laudon, H. (manuscript).

The Arctic region is at present experiencing rising temperatures (IPCC 2013), and its ecosystems have, during the last century, undergone significant changes (Anderson et al. 2017). These changes can be used as analogues to understand how climate change will affect the chemical environment when transitioning from one climate state to another. To understand the impact on transport processes and accumulation rates in sinks requires empirical data. Such data are needed to describe and understand the many factors involved in the biogeochemical cycling of elements in ecosystems and links between ecosystems in landscapes.

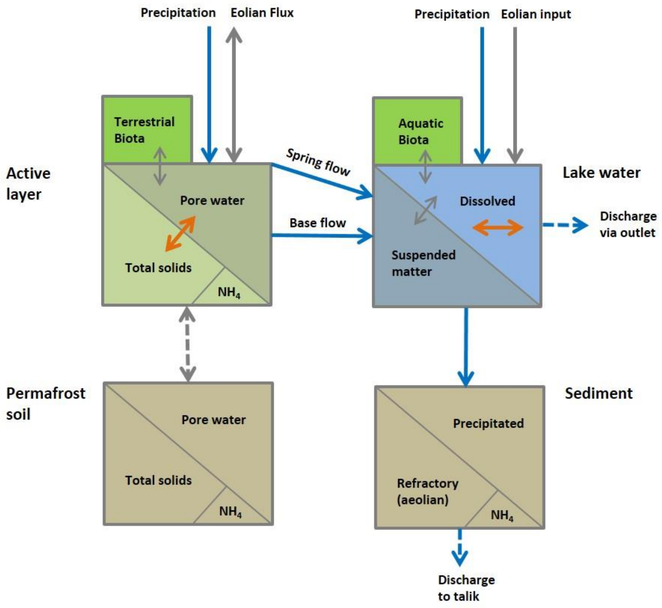

Figure 15. Conceptual model of the TBL catchment with major pools (boxes) and fluxes (arrows). Blue arrows = water driven transport. Blue dotted arrows = weak/limited transport process. Grey arrows = wind driven transport or uptake/release. Grey dotted arrow = slow element redistribution via permafrost incorporation or permafrost thaw. Orange arrows indicate storage changes.

Abiotic factors such as geology, hydrology and atmospheric deposition set limits for many elements through their control on, e.g., weathering and the transport of particulates and solutes. These abiotic factors are then modulated by biotic factors such as primary production, grazing, land use and other human activities.

In Paper VI we describe how we used the ICP-MS and XRF element concentration analysis (Table 1; Lindborg et al. 2016) from Paper III to feed a conceptual model of the Two Boat Lake catchment with data on pools and fluxes. The model is divided into pools with fluxes in a landscape representation defining biota, active layer soils, permafrost soils, lake water, and sediment (Fig. 15). The results provide comparisons of fluxes and pools for different landscape components and several patterns can be distinguished that can be related to transport processes. In Fig. 16 the results are visualized as sources and sinks in the landscape for 42 elements.

The resulting mass-balance model shows several patterns of landscape fractionation of elements. Eight groups of elements showing similar behavior were defined and associated with particular transport processes in the landscape. In the following, a short summary of the findings is presented.

The element group we call "Geogenic": Zr, Al, Ti, Si, Nb, Sc, V and Y are all minerals or related to minerals with eolian transport as main flux process. The association with weathering (Rel_ter) is slightly higher for Sc, Si, V and Y as compared with Zr and Ti.

The group "Lanthanides and actinides": Ce, Nd, La, Sm, Pr, Th and U is associated to release in the terrestrial system due to weathering. The lanthanides are noted for their similar geochemical properties. The actinides have broadly similar geochemical properties to the lanthanides, but their similarities with each other and with the lanthanides are not as close as those within the lanthanide group. The results show an accumulation in the lake sediment that cannot be explained by eolian input (AccSed_res). A possible explanation is terrestrial weathering of eolian deposits or other sources on land.

The group "Redox sensitive": Fe, Cr, Mn and Co show a flux to the lake via eolian transport as well as by weathering and water transport of terrestrial deposits. Fe and Cr show unknown sources in the lake water (Rel_lakew). This could be a result of uncertainties in concentration measurements on terrestrial inlet water to the lake due to precipitation in water samples before analysis.

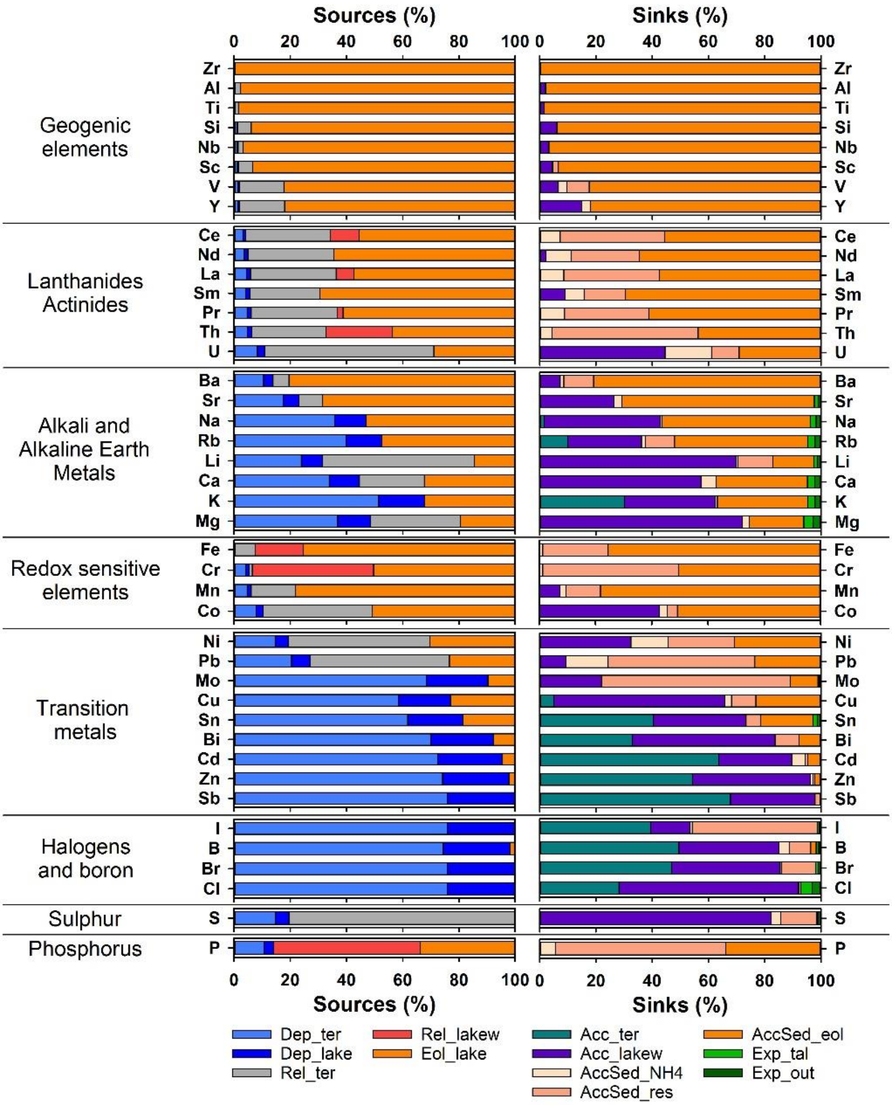

Figure 16. Comparisons of elemental fluxes in the TBL catchment. Dep_ter = waterbourne export from terrestrial to lake, Dep_lake = deposition on lake, Rel_ter = undefined release in the terrestrial system, Rel_lakew = undefined source to or in the lake, Eol_lake = eolian deposition, Acc_ter = accumulation in terrestrial system, Acc_lakew = accumulation in lake water, AccSed_NH4 = sedimentation NH4-soluble, AccSed_res = sedimentation total, AccSed_eol = sedimentation of eolian material, Exp_tal = export via talik, Exp_out = export via limnic system outlet, Figure from Paper VI.

The group “Alkali metals and alkaline earth metals” comprises Rb, K, Na, Li, Ba, Sr, Ca and Mg. Major transport processes associated with this group are atmospheric deposition, weathering in the terrestrial system and eolian deposition. There is, for these elements, a notable accumulation in the lake water and especially for Mg. Eolian deposition is larger for Ba and Sr than it is for Mg and Ca. K and Ca are here associated with long-range transport from a marine source, Li with terrestrial weathering and Rb and Na with eolian deposition. K and Rb show sorption, or biotic uptake in the terrestrial system that can be explained by K being an essential element for primary producers and Rb being a close biochemical analogue of K.

The group “Transitions metals” comprises the elements Zn, Cd, Sb, Bi, Sn, Cu, Mo and Ni. Most of the elements in this group are deposited as long-range pollutants, or, as with Ni and Pb, originate from terrestrial weathering or from the past atmospheric deposition of anthropogenic releases. The results show that substantial uptake occurs in the terrestrial system for Sb, Zn, Cd, Bi and Sn, and in the lake sediment for Cu, Sn and Bi. The lake water accumulates many of these elements.

The “Halogens and boron” group: I, Br, Cl and B exclusively arise by long-range transport from a marine source and surprisingly large quantities are accumulated in the terrestrial system. The terrestrial uptakes of Br and I are larger than for Cl which is associated with organic pools.

“Sulphur” (S) has a group to itself and is released by weathering in the terrestrial system. The fluxes can be related to pool turnover times and this suggests that much of the landscape sulphur is due to old anthropogenic inputs that are presently being released and accumulated in the lake water and lake sediment. No eolian input of sulphur is seen in the TBL catchment.

“Phosphorous” (P) is also treated as a separate group. It differs from other elements due to a large unknown source in the lake. The best explanation for the relatively high concentrations of P in lake water could be biotic loading by waterfowl droppings and terrestrial plant seeds blowing into the lake.

In Paper VI, we have provided the elemental amounts and concentrations for major pools in the TBL catchment. Numerical models of site hydrology together with extensive data on geometrical and physical properties of the catchment made it possible to calculate fluxes of material in the landscape. A good understanding of the transport between the terrestrial and the limnic system for the 42 elements included in this work has been achieved. The elemental concentrations and amounts in components of the landscape together with fluxes between those components show that the dominating processes are eolian transport together with weathering in the terrestrial system. The elemental distribution and flux pattern seen at TBL differs from distributions and fluxes reported in other studies for temperate climate conditions in three ways; the absence of the process ‘water outflux’ at TBL, differences in terrestrial accumulation of elements and the dominating eolian influx to the limnic system at TBL (a large eolian influx occurs also to the terrestrial environment, but there also a balancing export is present).

4 Discussion

The results presented in this thesis show a method for using global climate information as input to landscape modelling by the application of climate-related landscape drivers. (Papers I and II). If one aim of an assessment is to produce relevant and physically constrained narratives of specific landscapes to be used in impact evaluation, climate and paleoclimate information must be the starting point. One example where such an approach is needed, is in safety assessments of nuclear waste, where the overall context should also show consistency between scientific disciplines to enhance confidence in the results. Further, I show the importance of site-specific data and site understanding (Paper III). Without them, the task of understanding landscape or ecosystem evolution will be limited and trivial, and only a generic exercise of little relevance for calculating elemental transport for real sites. This may sound obvious, but it is important to state, since long-term assessments are still being produced relying on generic concepts.

In Paper III-VI we have investigated, analysed and synthesised a description of a landscape with periglacial climate conditions, and described pools, fluxes and climate-related processes and features. This, together with hydrological investigations (Johansson et al. 2015a) and active layer and soil/sediment mapping (Petrone et al. 2016) led to a better conceptual understanding of periglacial conditions and elemental transport in areas with permafrost.

Finally, the work at Two Boat Lake and the synthesis of data have made it possible to assess conceptual differences between temperate and periglacial ecosystems. Below follows a discussion on the above findings, and where applicable, in relation to previous work done by others.

4.1 Landscape development and climate

The landscape, as we experience it today, is a result of past events and processes. Depending on where on Earth the landscape is located, different processes have been affecting its properties and appearance. Also, the type of site-specific properties that the landscape is constituted of will play a large role in the climate response that the landscape will show. On the other hand, the landscape characteristics are a result of historical climate processes and the issue is, therefore, two-fold (Anderson and Anderson 2010). Coastal areas versus inland, low altitude versus high, latitude, flat versus hilly, submerged or terrestrial, sedimentary bedrock or crystalline, previous glaciated or not, the landscape-types are many and their global distribution is known. Also, the reasons why different landscape types have developed are also well understood and are discussed in several disciplines of natural science. Furthermore, most of the landscapes constituting Earth's surface with their ecosystems have been studied in terms of the natural sciences for a long time. As early as 1154 AD King Roger of Sicily ordered the first-known description of the land-types in the known world that, when finished, comprised 70 maps together with a book with geographical descriptions of the known world made by Muhammad al-Idrisis (Beeston 1949). We can, as a starting point, argue that the general distribution (global pattern) of landscapes on Earth is understood and that the major properties and processes controlling present-day behaviour for most of these landscapes are well described.

How do these landscapes change over time? That is a more complex issue, and is certainly not fully understood. If we define "change over time" as resulting in several possible "futures" we can assess alternative possibilities for the future landscape and provide a discussion on their probability of realisation. Even if we can never show that predictions of the future will come true, we can link the resulting landscape to the processes invoked and assess the forcing they perform on the specific landscape. After exploring processes and landscape responses, this understanding can be used to tell a story as to landscape development. With such a story, you can then go back and test different scenarios or "variants" of the future (e.g. climate-related processes) that will give you other patterns of forcing, and other landscapes variants. This demands that we can identify processes and features that are linked to scenarios, and this information is what we can find in disciplines such as paleoclimatology and climatology.

Climate models can be used at a wide range of spatial and temporal scales to inform landscape development narratives (Paper I). These are models that both describe an understanding of climate history using paleoclimate proxy data as supporting information, and models that also use present understanding on forcing factors and feedback processes to produce scenarios of future development. However, due to the high computational requirements of fully coupled general circulation models, long-term simulations can only be performed with less complex models and/or at lower spatial resolution. In Lord et al. (2017) the authors present a novel long-term climate emulator that can provide projections of climate evolution based on the output from complex general circulation models. This promising method has the potential to provide rapid simulations of the long-term evolution of climate, both past and future, and for specific sites. Climate models provide a context to follow a landscape, or site, in its development during the previous glacial cycle up until today, as well as to explore the possible impact of landscape development for different possible futures. Continental ice-sheet development is often included in long-term global climate modelling. Associated responses such as isostatic and eustatic changes can be part of such modelling, but may be handled as separate modelling tasks (Whitehouse 2009). Climate models can also define regional to local input data for other processes used in landscape development models such as temperature, precipitation and vegetation data that can be used to assess erosion. Permafrost modelling is another regional to local feature that uses input from climate models, see e.g. Hartikainen (2013). In Paper I, we describe the climate model types currently available, and their advantages and limitations in relation to various requirements at different spatial and temporal scales.

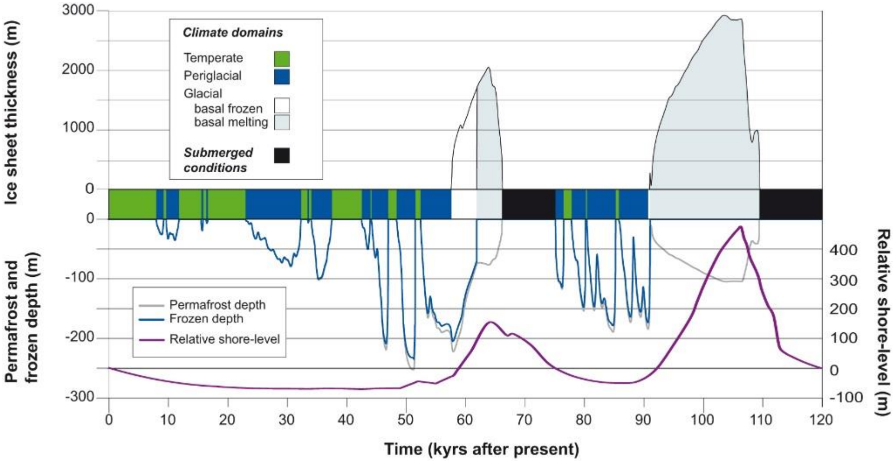

Figure 17. Example of a site-specific climate narrative for the Forsmark site based on reconstructed conditions for the last glacial cycle (the Weichselian and the Holocene) with important climate-related variables used in Paper II. In this narrative, the reconstructed historical events are repeated as a future development describing e.g. the variability in climate-related processes that is expected at this site during a future glacial cycle. From SKB 2010.

Where future situations can be expected to be analogous to those that have occurred in the past (Fig. 17), palaeoclimatological data may be used directly in defining the climate conditions to be adopted, e.g. past warmer periods during the Atlantic period in Europe as analogues for general global warming effects in Scandinavia. However, the use of analogue data sets is not without its difficulties. Few analogue data sets will closely resemble future conditions at the specific site of interest and may represent different latitudinal and topographic characteristics and site properties. Present climate analogues (Paper III) can be extremely useful because their landscapes are the result of all processes acting on a site and related to the site-specific climate of interest. The emphasis should therefore be to use analogues as conceptual blue-prints for the site of interest.

Also, analogues within the region are useful in determining process rates and succession steps for a changing landscape. An example of an analogue of the future is the gradient going from the Baltic Sea and inland at the Forsmark site (Paper II). There we can follow the succession going from sea to terrestrial area by substituting time with present-day space. Many processes and features can be identified that relate direct to the landscape development of a coastal site with shoreline displacement. Starting at the shores of the Baltic Sea with bays that further inland has been isolated to form lakes, as a direct effect of the shoreline displacement. Further inland, these lakes have turned into wetlands due to ingrowth of vegetation and sedimentation. When you pass the 10 m.a.s.l. elevation the first peatlands can be found. To substitute space with time as described above can be a very robust support to a landscape development model. This is information that guides both conceptual understanding of the site and process rates that should be applied in the landscape development model.

The landscape development modelling work presented in Paper II shows that long-term climate change with associated shoreline displacement, lake infilling/ingrowth, and sedimentation/resuspension are drivers that conceptually explain the landscape development seen at the Forsmark site today. Using the physical constraints that site-specific understanding and data provides, we have narrowed down the future landscape variants, and data characterising these futures such as to provide illustrative examples that are both relevant and realistic. This is a key task in landscape modelling and prevents arbitrary descriptions of future landscapes containing information without supporting arguments. Using the present differences in elevation at Forsmark as an analogue for time, due to shoreline displacement, we can argue that the current sea–lake–mire succession (Fig. 2) is a good representation of future development during temperate conditions and process rates similar of today for areas at the site presently submerged under the sea. However, if present-day processes change, the landscape will also change. This would be, for example, the case if sea-level rise due to human-induced global warming were to accelerate. In SKB (2014), sea transgression due to thermal expansion and loss of land-based ice sheets is discussed for the Forsmark site. A rising sea-level would then reverse the landscape development (lakes would turn into bays and land to sea). This reversed pattern is easy to understand and the information in the Forsmark landscape development model presented in Paper II can also be used to describe this variant of the future. For shorter time frames and to estimate local processes affecting a site during weather events, a more advanced strategy must be applied. This is out of the scope for a landscape development model with timeframes of glacial cycles, but is illustrative as an example of the differences in complexity in satisfying needs for short- and long-term process understanding (Fig. 18).

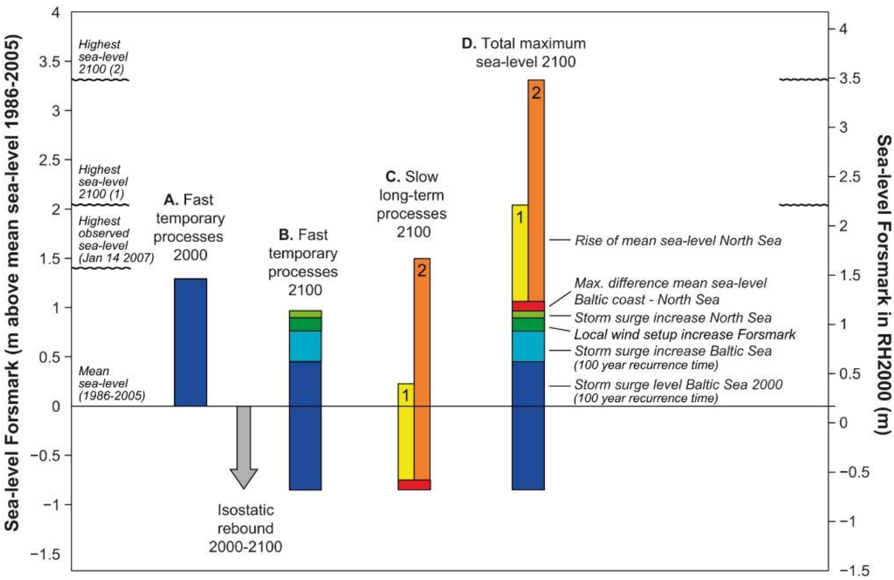

Figure 18. Resulting estimates for maximum possible sea level at Forsmark at 2100 AD from a recent safety assessment in Sweden, SR-PSU (figure from SKB 2014). A: present day maximum sea-level rise due to fast temporary processes, B: maximum sea-level rise at 2100 AD due to fast temporary processes, C: sea-level rise at 2100 AD due to slow long-term processes, i.e. rise of mean sea level. 1: IPCC (2013), 2: Sriver et al. (2012), D: total maximum sea-level rise in the year 2100 when considering both the fast-temporary processes and the slow long-term processes. The C2 value of Sriver et al. (2012) represents the upper, worst-case, value in a range of values estimated by semi-empirical models and kinematic constraints on ice-sheet melting. The isostatic rebound (0.84 m) compensates for a portion of the sea-level rise. The sea level is given in m above the present-day mean. Figure from SKB (2014) developed from previous work in Brydsten et al. (2009).

The shorter-time perspective needed to capture the maximum sea level at 2100 AD at the Forsmark site involves consideration of several processes not requiring consideration in the long-term landscape development model. In Fig. 18, the isostatic rebound together with two sea-level predictions (1 and 2) are merged with several local short-term processes to evaluate the highest possible shore-line at 2100 AD due to the simultaneous occurrence and accumulated effects of events (SKB 2014).

A landscape development model can be limited to providing the combined information on present and historical data describing one or several specific catchments with their dominant ecosystems. However, to also give examples of possible futures, the model can use climate-related processes as drivers. The landscape development model should function as a basis for the construction of more detailed models describing the transport of matter, hydrology and ecosystem characteristics. The model should take all relevant processes into account that alter the appearance, distribution and succession of the landscape and its ecosystems. There are no intrinsic limits in space and time, with the scale and resolution required determined by the assessment question being addressed.

4.2 Conceptualising ecosystems in time

A landscape in ecological terms is the spatial and temporal pattern of exchanges of matter and energy and both biotic and abiotic interactions and is not restricted to any specific scale (Wu 2013). Accepting this definition, Earth's surface can be described as a set of functional units or ecosystems divided in areas of similar pattern exhibiting common characteristics, and the landscape a space-filling arrangement of different types of ecosystems. Ecosystems like lakes, sea-basins, streams, wetlands, areas of agricultural land use, and forests of different types. These components can also be defined as a mosaic of ecosystems linked together by hydrology to form one or several catchments or sea basins. The latter is a definition that builds upon Forman and Godron (1986) but adds hydrological processes. The catchment scale therefore constitutes a landscape, with gradients and nonuniformities in its properties. When calculating pools and fluxes for a landscape, this latter definition is easier to use and is adopted in this thesis. Given the above, to describe landscape evolution, one needs to understand the ecosystems that are within the catchment as well as the catchment as a whole, by linking ecosystems with material-transport processes (as evidenced by their effects on chemical element concentrations).

Landscape geometry expressed in digital elevation models (Brydsten and Strömgren 2010; Petrone et al. 2016) is the starting point to define a landscape. Hydrologically distributed numerical models use elevation models to define the geometries of catchments, but such elevation models also define topographical gradients. This implies that they have a major impact on flow-paths and flow-rates within the catchment, which in turn influences the mass balance of the ecosystems that constitutes the catchment (Johansson et al. 2015a). The ecosystems can be defined depending on the question at issue. For long-term assessments, the right level of ambition probably is somewhat approximative and, in this work, the landscape was from the beginning divided into two broad types of ecosystems; terrestrial and aquatic (Paper III; Fig. 19). Nevertheless, if site-specific properties give information that guides you into a more detailed ecosystem pattern that can be followed through time, this will be the appropriate route to follow (Paper II).

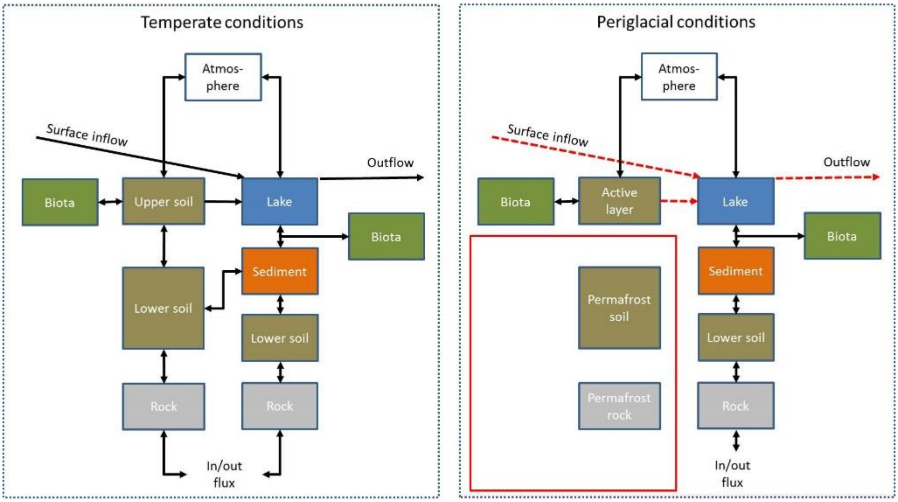

Figure 19. Conceptual illustrations of pools and fluxes of material for ecosystems in a catchment for two different climate conditions. To the left temperate climate with warm and wet conditions and to the right periglacial climate with cold and dry conditions. Boxes represent functional units within the landscape and arrows describe material flows. The red box illustrates permafrost and no-flow conditions. Red dotted line = weak or no water flow.

The ecosystems defined should build upon site understanding, i.e. enough information, but not necessary quantitative data, must be present to define the ecosystems and their functional units. This is an iterative process and the first conceptual model of a site may rely only on aerial photographs and maps. As more information is gained via site characterisation, both the site understanding and the conceptual model will develop (Thorne et al. 2011; Lindborg et al. 2017).

In Walke et al. (2015), a model comparison is made between different levels of ecosystem complexity for the future Forsmark site. A discussion is provided on the need for justification of the level of resolution chosen in landscape descriptions in a safety assessment for nuclear waste. As we suggest in Paper I, the overall context and questions required to be addressed in an assessment should be the main guide in choosing the temporal and spatial resolution. Also, the specific climate scenarios chosen as drivers for landscape modelling should address these questions. If, for example, questions that relate to deep bedrock repository integrity are in need of a landscape model with high resolution (to be able to produce distributed numerical models giving geohydrological flow-paths down to repository depth), the same landscape development model will also be available for dose calculations in the biosphere.

Therefore, the landscape development modelling and associated ecosystem evolution modelling have a common purpose and are closely linked in this type of assessment. In Fig. 19 an example of a conceptual model is shown for the Two Boat Lake site (Paper III-VI) with, to the right, a present-day periglacial conceptual description of the catchment and ecosystem functional units and, to the left, a hypothetical situation with temperate conditions as comparison. This simple conceptual model is an example of results gained from applying site-specific information on biogeochemistry (Paper III), hydrology (Johansson et al. 2015b) and soil/sediment characteristics (Petrone et al. 2016) with associated properties and transport processes presented in this thesis (Paper V and VI). One specific feature that was discovered, was the fact that almost no surface runoff occurred in the periglacial catchment. Due to the active layer not being established until after the spring flood, the snowmelt gradually filled the thawing active layer. In general, hydrological connection was limited to the spring flood and a few precipitation events during the active summer period. Also, no terrestrial connection to the deeper groundwater was possible due to extensive permafrost extending to depth.

Even though the models shown here have low complexity, with only a few compartments, the insights as to climate-related changes, and conceptual adaptation, can make big differences in the model results describing transport of elements (Paper V and VI). Using this type of conceptual modelling when constructing numerical models of elemental transport provides support for the assumptions and simplifications made when assessing long-term landscape development. Two major differences are seen in the conceptual understanding in Fig. 19. One is the effect of permafrost on hydrology and elemental mobility in the frozen volumes. The other is the change in connection between the terrestrial and aquatic systems. Both these differences are related to changes in water mass balance. This emphasises the importance of hydrological understanding when assessing the consequences for a site during environmental change, see further discussions in section 4.3. The permafrost impacts on catchment hydrology are discussed in detail in Johansson et al. (2015a) and the large-scale hydrological pattern with talik features and transport routes in a permafrost landscape is modelled and discussed in Johansson (2016). Taliks are not further discussed in this thesis even though they represent large features in the subsurface and bedrock. Changes in groundwater transport routes and release of methane in shallow short-lived lakes (thermokarst lakes) with active redistribution of material in the active layer are the main processes of interest for taliks. In a landscape development model, thermokarst areas would probably be represented as wetlands with too short a life span to usefully distinguish individual lakes. Two Boat Lake has a volume large enough to support a through talik and no thermokarst was identified in the catchment.

4.3 Landscape transport processes in a changing environment

During landscape evolution, either as aging in a period of steady state climate or under a changing climate, elemental mobility and/or accumulation will also change, e.g. Pokrovsky et al. (2012). This can be used to investigate past climate or to predict how a landscape will behave under different climate conditions. One example is tree-ring data that uses the fact that primary production is affected by climate (Mann et al. 1998). Other examples are terrestrial, aquatic and ice-core data that give information on the processes involved during deposition and, together with dating techniques, also their rates, see Porter and Zhisheng (1995) and Allen et al. (1999).

In Paper V we present a carbon mass-balance model for the Two Boat Lake catchment. When comparing pools with transport rates and sample dating, we get turn-over times for different landscape units and can also describe the effects on the landscape due to possible changes in process rates. In Fig. 20, six transport processes at Two Boat Lake are conceptually illustrated for their possible part in transport of elements in relation to temperature. Eolian transport is dependent on a cold and dry landscape with constant access to new material released from an ice sheet or development of wind scars (Paper IV). When temperatures rise, the eolian activity will probably decrease drastically due to increased vegetation coverage and, eventually, less new material produced at the retreating front of the ice sheet.

Weathering is a complex process that releases material mainly from the soils and sediments. When very cold, the weathering is high in the upper part of the soils due to little or no stabilisation effect from vegetation and frost shattering. In the lower parts of soils, the permafrost acts as an inhibitor of processes. Once the temperature rises above 0˚C MAAT and the permafrost thaws completely, the soil weathering accelerates and keeps increasing with temperature.

Water movement in the active layer will affect weathering and transport rates of solutes, i.e. nutrients, major cations, metals, and trace elements. Further discussion on this topic is given in Jessen et al. (2014) for a catchment close to the coast in Ilulissat, West Greenland, and Anderson (2007) who discusses glacial erosion processes as a main contributor to landscape fluxes of elements.

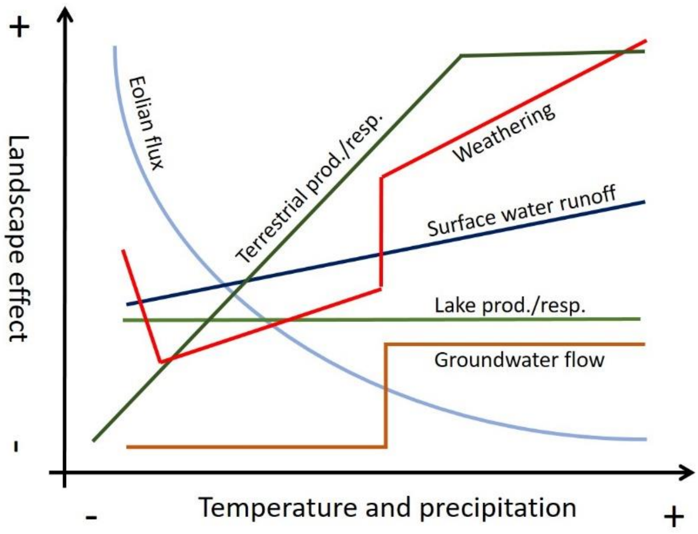

Figure 20. Conceptual illustration of possible landscape effects of changes in temperature on transport and accumulation processes.

In Johansson et al. (2015a) and (2015b), we describe hydrological conditions and hydrological and meteorological data from the Two Boat Lake catchment. The understanding of local hydrology at TBL achieved in these studies is crucial when calculating elemental transport in the same landscape. The presence of permafrost also influences the hydrology (Johansson et al. 2015a). Groundwater flow in the active layer acts as a mediator for elemental transport, and the transport is directly related to the active period. Due to generally increased precipitation with warmer temperatures, surface runoff will also be a more important factor together with an increasing upstream contributing area (Wang et al. 2015). With a deeper active layer, the supra-permafrost aquifer will grow and new deeper flow paths with potential to transport elements in the deeper soil layers and bedrock will be activated. Lake primary production at TBL today is within the same range as temperate areas (Paper V) and the production is already high. Therefore, no or little change in the Two Boat Lake ecosystem production is expected due to a warming climate.

In Paper VI, we used the data from the Two Boat Lake catchment to explore the distribution and fluxes of 42 elements. By analysing the range in elemental behaviour and assessing the pattern by groups of elements with similar behaviour in the environment, we evaluate the processes affecting transport. The approach used is a relative simple budget calculation linking several sources of information at landscape level to quantify major fluxes, pools and turn-over times in the landscape.

Eolian processes dominate the elemental influxes to the TBL system for most elements and changes in eolian inputs induce changes in other process rates such as weathering, leaching, sheltering, vegetation patterns, small-scale topography and accumulation. The eolian influx affects the internal properties within the catchment related to lateral flux. Silt deposition on vegetation and organic layers below more minerogenetic layers can be found in the active layer, indicating past events or periods with increased eolian activity. Deflation patches are common at TBL and, according to Heindel et al. (2017), these features started to develop around 800 years ago when the climate turned colder and dryer during the beginning of the “little ice age”. In Paper IV we discuss the eolian activity using a lake sediment core to describe the lake loadings. We there conclude that increased eolian activity can be identified from around 500 years BP. Eolian deposition is, by these deflation patches, balanced for the catchment with erosion. However, this erosion may deposit within the catchment (e.g. the lake) or leave the catchment to deposit elsewhere. Eolian processes are, in contrast to sites with temperate climates, a major consideration in system function. The Forsmark site in Sweden has no active eolian processes and the main influx from the atmosphere comprises wind-borne elements associated with the marine system. Such long-range atmospheric transport and deposition processes at TBL can be illustrated with the halogens and boron (B) that originate from the marine environment. In the mass-balance model, this element group is well retained in the terrestrial system, which is surprising and not yet understood.

The most well-defined variations in the sediment core record (Paper IV) from Two Boat Lake were the ratio between organic and mineral material. These variations can mostly be attributed to variations in the eolian input of particulate material to Two Boat Lake, which has resulted in variations in the composition of the minerogenic fraction. Some of the eolian material originates from soil erosion within the lake’s catchment, but the main source is likely the glacier outwash plains located close to the lake (Anderson 2007). Furthermore, our study suggests that eolian input is higher in lakes close to the inland ice sheet, mainly due to a greater availability of material that can readily be transported by wind.

We also speculate that this input of eolian material has an effect on lake-water chemistry, because the fresh, un-weathered material can result in a higher pH and alkalinity as compared with lakes receiving less or no inputs of eolian material. Overall, this implies that eolian transport needs to be considered, for example, when calculating mass balances for lake-catchment ecosystems in dry proglacial landscapes.

Water transport is a dominating process in temperate Forsmark. At TBL, this process is less important, even though the water flow (both surface spring flow and active layer groundwater base flow) is a clear factor in element redistribution in the catchment. Elements associated with terrestrial weathering and low retention end up in the limnic water as well as in sediment pools. A slow ongoing accumulation in lake water is seen in the model for many elements implying that the water-balance may have been more positive in the past. Although TBL still remains relatively dilute, there are examples of saline lakes in West Greenland, and especially in the inland areas close to the ice sheet. (Anderson & Stedmon 2007; Henkemans 2016).

4.4 Uncertainties

When we argue for possibilities characterising the future, we tend to fall into a pit of detailed complexity, striving to list and answer all questions related to features, processes and events that may have impact on a site. However, if we disregard all small-scale processes and just focus on those that, by empirical evidence, have a major impact on the landscape in time, we find that these are quite few and often quantifiable. It seems that size and timeframe play a role in what can be assessed. Fewer processes act upon larger things at low resolution. The key is, therefore, to look at the future with large-scale glasses, and then apply the small scale, but only if needed, to the picture you see.

Climate models are described herein (Paper I) to set a context and to provide climate-related data for studies of landscape development. Even though this thesis does not attempt to detail the techniques involved in climate modelling, the uncertainties in the field need to be assessed to better understand implications for landscape evolution. This in turn may trigger identification of feedback mechanisms in the landscape that needs to be better implemented in climate models. For example, response times of processes related to the global carbon cycle and potentials for storage in various pools, can control the timescale and magnitude of CO_2 emissions (Lord et al. 2015). This type of processes may have implications for future climate change, e.g. the timing and length of glacial-interglacial cycles and the occurrence of climate-related features, e.g. permafrost, taliks and land-use styles.

It is common in climate modelling (Paper I) to use ensembles of climate models and simulations to study the effects of model and parametric uncertainties. This should also be the case when using climate models to assess long-term changes aiming to support studies of landscape development with climate-related data. Therefore, scenario formulation and the techniques involved in climate modelling should be undertaken together with landscape development modelling. The development of robust, well-justified climate and landscape development models to use in long-term assessments has been, and will continue to be, an important task for the future.

As stated in the introduction, no model or description of the future can be validated for systems with complex relations and yet not fully understood processes. The results presented herein are based on data from past and present conditions for specific areas. This information is used to support assumptions made or to test hypotheses. Testable predictions are only possible if we use the present day as an analogue for the future. One example of this is the test we performed in Paper II. There we had the landscape model to run for the period from deglaciation up until present day for the Forsmark site (8,800 BC to 2000 AD). The results showed that the model constructed a landscape (shoreline, sedimentation, erosion, lake ingrowth, terrestrialisation and vegetation) with only minor differences compared with Forsmark at present. It is, however, important to acknowledge that the model process rates and forcing sensitivity were tuned using information from present Forsmark. Nevertheless, the model results show that processes and properties that governs the site today are well understood and implemented.

To construct a landscape development model and relate global changes in climate over long-term periods to a site with its properties and features, site data are needed. Both the investigations at Forsmark (Lindborg 2008) and the field campaign on Two Boat Lake in West Greenland (Paper III) were performed to assess the terrestrial and aquatic environments (biotic and abiotic) in the landscape. Further the goal was to develop mass-balance calculations for all major pools and fluxes and to relate spatial distributions to transport processes. With such a broad approach, the uncertainties are many on a detailed level. The strategy we used was to first map the catchment vegetation, soil-unit, topography, hydrology and lake heterogeneity (Clarhäll 2011; Petrone et al. 2016; Paper III). Having these maps with classes of properties made it possible to define “type areas” for installations and sampling with common properties and to upscale information to the catchment scale. The sampling was then performed according to standard methodology (Paper III; IV; V; VI). For areas in the catchment where we identified a gradient in properties, we installed instruments along, or sampled along, transects.

Examples of transects that were studied related to lake sediment, benthic primary producers and areas with relatively high soil wetness in the valleys close to the lake. The sampling was adjusted according to spatial distribution (landscape patchiness) and gradients due to flow regimes, as well as differences in water depth and sedimentation processes.

In Kautsky et al. (2013) we discussed uncertainties in describing future development for a specific site in long-term assessments and exemplified a few common approaches to representing future development. One is to treat the future as having present-day conditions (or not very different conditions), see ICRP (2012). This is based on the idea that present-day condition is the only hypothetical future we fully can argue has existed. However, for long-term futures, this strategy is, as shown in this thesis, not a valid approach. The main argument should rather be that the landscape pattern of today may repeat itself due to similar conditions and site properties from time to time during climate cycles.

Another concept to handle our lack of ability to foresee the future is to use generic reference descriptions of sites. This has been done for “type biospheres” (van Dorp et al. 1998) with the aim of calculating risks to humans due to future possible failures of nuclear waste repositories. The problem with such a strategy is the total lack of coupling to a real site and the rest of the assessment science. Another argument against this approach is that you gain no confidence by introducing more uncertainty concealed in calculations that appear to be relevant at a first glance, but, when put into a real site context, lose all power of explanation and scientific support. Not even for exercises is this strategy a good choice since the exercise never can be trusted, or argued for as a representative benchmark for the assessment that is required. If no site exists, it is better to use anonymous real sites that can inform the assessment and also be used in results validation.

By applying random variation and Monte Carlo simulations on site parameters, a wide range of possible variations for a site can be assessed (Avila et al. 2013). This achievable technique should be handled with care. First, the dependences between parameters must be known and taken into account. Otherwise physical impossibilities may arise in the site description and property data output. Furthermore, site-specific process understanding and the site narrative will be hard to develop using this method. Instead, the strategy should be to derive landscape development models by using best available site knowledge and then apply uncertainties applicable to specific processes or properties in that landscape.

Land use and other human influences can have large impacts on the natural landscape. Human disturbances can range from gatherer-hunter types of impact to the construction of cities with no traces left of the previous landscape. The task to incorporate humans and land-use into the long-term landscape development is therefore a difficult task that needs careful thinking. On the other hand, the human population is often the endpoint in risk assessments. This implies that when introducing humans into the landscape-development scenarios, the assessment questions must be guiding the assumptions made as to population sizes and impacts made by the population on the landscape. In Jansson et al. (2006), a method was presented that used future landscape production capabilities to calculate population sizes and give the area´s sustainable characteristics over time. In Saetre et al. (2013), the method was further assessed in terms of human land-use and food intakes to calculate projected radiation doses in a potential future landscape.

5 Conclusions and the way forward

In this thesis, I have shown the linkage between long-term climate scenarios and landscape development modelling. The site-specific nature of a landscape is explored and the need to understand local properties to apply well-supported estimates of rates of processes has been demonstrated. My conclusions are the following:

- I have demonstrated that landscape development can be modelled into the far future for a specific site. Uncertainties in time and space are large and not quantifiable, but can be handled with climate scenarios as well as by using local process rates and assumptions. Palaeorecords show that the long-term landscape pattern will repeat itself in time as it follows climate cycles and indicate how the landscape will respond to anthropogenically induced climate changes. The historical landscape development for a site can be mimicked due to relatively few and quantifiable processes that govern the changes.
- Site understanding in terms of data, conceptual and numerical models is essential when producing landscape narratives over glacial cycles. A site is bound by basic physical constraints and those will mostly be inherited in its future development. This narrows down possible landscape futures.
- Elemental transport under different climate states is a useful tool to strengthen the conceptual understanding of specific sites and their development. However, analogue sites should preferably not be used with the purpose of transferring data to the site of interest. Instead, the conceptual understanding of ecosystem behaviour under different types of climates should be used.
- The differences between temperate and periglacial terrestrial ecosystems in terms of pools and fluxes are large. Permafrost cuts off the deeper groundwater, and eolian activity in the periglacial landscape changes transport routes beyond the catchment limits. Limnic systems do not show

the same magnitude of difference even though the elemental fluxes from terrestrial and atmospheric pools differ.

- Finally, I conclude that this thesis shows that techniques are available and results can be derived that address the research questions asked. It is possible to describe long-term landscape evolution in a way that can inform conceptual ecosystem models and calculations of transport of matter in the landscape over time.

5.1 The way forward

Several issues have been raised during the work presented herein. Some of them could not be handled due to limitations in the current work program. However, taking account of on-going research and assessment interests, the following tasks provide a way forward.

- Sample size of catchment. To have a good representation of the different possible environmental changes that may occur in the future, a robust database for several present climate conditions would be useful. Instead of one site per domain, as in this work, several representative catchments per climate type would give the conceptual understanding a better foundation. An alternative approach could be to investigate a climate gradient with multiple sites going from temperate to periglacial to compensate for sample size.
- Climate-related processes. Landscape evolution is mainly dependent on climate models. The models and modelling exercises performed should be integrated. Ensembles of stand-alone and coupled models should be used to give robust estimates of changing climates and to quantify uncertainties.
- Elemental transport processes. To fully understand chemical fractionation in the landscape and what processes are involved for all elements and in all types of subsystems, comprehensive transport modelling must be undertaken. This would include reactive transport modelling in soils and more eolian sampling together with enhanced modelling of eolian transport.
- Atmospheric fluxes. Many processes are hard to capture in a landscape. The processes associated with fluxes to, from and in the atmosphere, are some of them. There was no possibility to instrument the Two Boat Lake catchment in West Greenland with eddy flux or other type of gas exchange measuring instruments, but that would have been useful.

6 Acknowledgements

The acknowledgement is the part of a thesis that is written last, put last into the manuscript but probably read most. Thereby, by some it is argued to be the most important section in any publication. Others have insisted that the acknowledgement is even titled its own publication and should not only be formatted as text, but as a piece of art.

Anyway, my simple philosophy in the making of an acknowledgement is to just make sure that the names are there. Also, in Fig. 21 a picture illustrates roughly the kind of help I want to say thank for and would take 1000 photos to cover. Let's start.

Figure 21. Dirk van As, Johannes Petrone and Sten Berglund during the weather station installation, April 2011, Two Boat Lake catchment, Kangerlussuaq area, West Greenland (Photo: Tobias Lindborg).

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Postscript

It is midnight in the Arctic summer. A low sun makes the mountain peaks glow. In the valley, mosquitoes thrive on a group of scientists sitting on the stairs to a house. They are sipping slowly on an evening beverage while recapitulating a week in the field. Large quantities of tonic water can, for a short period, have therapeutic effects, they conclude[1] while poring themselves another one. Stories of earlier field excursions and bragging on insights gained and papers published can be heard in the dusk for a little while longer.

In the morning, the flight back to lower latitudes is scheduled. They are ready.

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