Environmental factors affecting the occurrence of periglacial landforms in Finnish Lapland: a numerical approach

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Academic dissertation

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Contents

Abstract ......................................................................................................................... VII
Acknowledgements .......................................................................................................... VIII
List of Figures ................................................................................................................... IX
List of Tables .................................................................................................................... XII
List of Appendices ........................................................................................................... XIII
Abbreviations .................................................................................................................. XIII
Symbols ............................................................................................................................ XIV

1 INTRODUCTION ............................................................................................................ 1
2 PERIGLACIAL PHENOMENA .......................................................................................... 5
   2.1 Classification of periglacial landforms ..................................................................... 6
   2.2 Description of periglacial landforms ..................................................................... 9
      2.2.1 Permafrost landforms ................................................................................. 9
      2.2.2 Thermokarst features ............................................................................... 10
      2.2.3 Patterned ground ....................................................................................... 10
      2.2.4 Solifluction and other slope phenomena .................................................. 16
      2.2.5 Periglacial weathering features ................................................................ 19
      2.2.6 Nival phenomena ..................................................................................... 20
      2.2.7 Aeolian processes and landforms ............................................................... 21
3 STUDY AREA ............................................................................................................... 23
   3.1 Location and topography .................................................................................... 23
   3.2 Bedrock and general geology ............................................................................. 23
   3.3 Weichselian glaciation, deglaciation and soil types ........................................... 23
   3.4 Geomorphology of the Bāišduattar – Áilegas .................................................... 25
   3.5 Previous periglacial research in the study region ............................................... 29
   3.6 Past and present climate ................................................................................... 30
   3.7 Hydrology ........................................................................................................... 32
   3.8 Vegetation ............................................................................................................ 32
4 MATERIALS AND METHODS .................................................................................... 35
   4.1 Modelling data ................................................................................................... 35
      4.1.1 Resolution .................................................................................................. 35
      4.1.2 Periglacial landforms ................................................................................. 35
      4.1.3 Predictor variables ..................................................................................... 37
      4.1.4 Predictor variable selection and data split .................................................. 44
   4.2 Statistical modelling ............................................................................................ 44
      4.2.1 Statistical formulation ............................................................................... 44
      4.2.2 Model calibration ...................................................................................... 46
      4.2.3 Model evaluation ....................................................................................... 46
5 RESULTS ..................................................................................................................... 49
   5.1 Predictor variables .............................................................................................. 49
   5.2 Periglacial landforms in Bāišduattar – Áilegas .................................................... 49
      5.2.1 Palsas .......................................................................................................... 51
      5.2.2 Convex non-sorted circles ....................................................................... 53
      5.2.3 Stony earth circles .................................................................................... 53
      5.2.4 Earth hummocks ....................................................................................... 56
      5.2.5 Peat pounus ............................................................................................... 59
      5.2.6 Stone pits .................................................................................................... 60
      5.2.7 Sorted nets .................................................................................................. 61
      5.2.8 Sorted stripes ............................................................................................. 62
      5.2.9 Non-sorted solifluction terraces ............................................................... 64
      5.2.10 Sorted solifluction sheets ....................................................................... 64
      5.2.11 Sorted solifluction streams .................................................................... 66
      5.2.12 Deflations ................................................................................................. 66
ABSTRACT

The conclusions about the determinants of earth surface processes and landform patterns are often derived from traditional field survey methods. Recent developments in the spatial and numerical analysing techniques have improved the possibility to study different aspects of geomorphological phenomena in extensive regions. The objective of this research was to map and quantitatively analyse the occurrence of cryogenic phenomena in subarctic Finland in the zone of discontinuous permafrost. More precisely, utilising a grid-based approach the distribution and abundance of periglacial landforms were modelled to identify important landscape scale environmental factors and potential methodological limitations.

The study was performed using a comprehensive empirical data set of periglacial landforms from an area of 600 km² at a 25-ha resolution. The utilised statistical methods were generalized linear modelling (GLM) and hierarchical partitioning (HP). GLMs were used to produce distribution and abundance models and HP to reveal independently the most likely causal variables. The GLM models were assessed utilising statistical evaluation measures, prediction maps, field observations and the results of HP analyses.

A total of 40 different landform types and subtypes were identified. At lower altitudes with gentle slope angles occurred earth hummock, stone pit, peat pounu and palsa continuums and at higher altitudes with steeper slopes sorted stripe, solifluction stream and solifluction sheet sequences were prevalent. At present, the environmental conditions promote the formation of different cryoturbation and peat accumulation based non-sorted features, whereas most of the sorted landforms were probably formed before the climatic optimum over 8000 years ago.

Topographical, soil property and vegetation variables were the primary correlates for the occurrence and cover of active periglacial landforms on the landscape scale. From the pure topographical factors, mean slope angle and mean altitude were commonly in the final models. Peat cover was the most important soil type variable because of its varying thermal properties and moisture holding capacity. Topographical wetness index was a crucial surrogate of environmental factor exhibiting the general soil moisture distribution. From vegetation variables, the shrub cover affected the distribution of several periglacial landforms.

In the model evaluation, most of the GLMs were shown to be rather robust although the explanation power, prediction ability as well as the selected explanatory variables varied between the models. The most robust distribution models were constructed with palsa, earth hummock, peat pounu, sorted solifluction sheet and sorted solifluction stream data. Earth hummock and peat pounu models obtained the best prediction and explanation ability in the abundance modelling, respectively.

The great potential of the combination of a spatial grid system, terrain data and novel statistical techniques to map the occurrence of periglacial landforms was demonstrated in this study. GLM proved to be a useful modelling framework for testing the shapes of the response functions and significances of the variables describing environmental gradients and the HP method helped to make better deductions of the important factors of earth surface processes. Hence, the numerical approach presented in this study can be a useful addition to the current range of techniques available to researchers to map and monitor different geographical phenomena. However, the data related limitations and method-based weaknesses may bias the modelling results and the model outcomes should not be interpreted uncritically.

Keywords: periglacial geomorphology, patterned ground, solifluction, numerical analyses, generalized linear modelling, logistic regression, hierarchical partitioning, GIS, subarctic, Lapland, Finland

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List of Figures

Figure 1. Simplified conceptual model of the relationships between environmental factors, periglacial processes and landforms commonly found from subarctic regions. ........................................ 2
Figure 2. Complex palsa mire in Biesjaaggi mire. ........................................................................... 10
Figure 3. An example of thawing palsa in Biesjaaggi mire.......................................................... 11
Figure 4. Small vegetated thermokarst pond in Biesjaaggi mire ................................................. 11
Figure 5. Patterned ground, sorted polygon, in a temporary ponding depression........................ 12
Figure 6. Convex non-sorted circles from the valley northeast of Guivi fell ................................ 13
Figure 7. Sorted circle, debris island, in a blocky soil material in Čeavresjohkka valley ............. 13
Figure 8. Boulder depression above the treeline in the valley southwest of Guivi fell ............... 14
Figure 9. Non-sorted steps on a valley slope northwest of Suophášoaivi fell .............................. 15
Figure 10. Non-sorted stripes on a fell slope southeast of Ulhe-Áhkováráš fell ......................... 15
Figure 11. Sorted solifluction sheets on the eastern and southeastern slopes of Suobbatoaivi fell ................................................................................................................. 16
Figure 12. Ploughing block with downslope ridge west of Guivi fell ............................................. 17
Figure 13. Large block preventing the soil creep on the slope of Guivi fell ................................... 18
Figure 14. Talus features under rock faces in the Geavvu canyon .............................................. 19
Figure 15. Tor on summit close to Suobbatoaivi fell ................................................................. 20
Figure 16. Large longitudinal nivation hollow-like snow accumulation site north of Čeavresgielas fell ........................................................................................................... 21
Figure 17. Deflation depression formed in a sand dune on the eastern slope of Geatgielas fell ......................................................................................................................... 22
Figure 18. Location of the study area in northern Fennoscandia .................................................. 24
Figure 19. Generalised map of the study area .............................................................................. 26
Figure 20. Three-dimensional terrain view of the study area ...................................................... 27
Figure 21. Lateral glacial melt-water channels on the northwestern slope of Gaskkamušaláš fell ......................................................................................................................... 28
Figure 22. Luopmošjáguotkku esker between the Stuorrajávri and Nuorttatjávri lakes in the southern part of the study area ............................................................................. 28
Figure 23. Áhkkojohka river valley after the spring flood .............................................................. 33
Figure 24. Only partly recovered open mountain birch forest damaged by larvae of the moth Epirrita autumnata in the southeastern part of the study area ......................... 34
Figure 25. The main steps of the compilation of response, i.e. periglacial data ......................... 35
Figure 26. Examples of active and inactive periglacial features .................................................... 37
Figure 27. The main interactions between environmental factors affecting periglacial phenomena ...................................................................................................................... 38
Figure 28. Examples of the compiled environmental predictors at 20 m resolution .................. 40
Figure 29. Examples of the compiled environmental predictors at 25-ha resolution ................. 41
Figure 30. Generalised geomorphological map of the periglacial phenomena observed in the study area ............................................................................................................. 53
Figure 31. Number of different periglacial landform types in the study area at 25-ha resolution .. 54
Figure 32. String-form palsa in Luopmošjohjeaggi mire ............................................................... 56
Figure 33. Dome-shaped palsas in Vanadanjegaggi mire ............................................................ 56
Figure 34. Mean altitude and mean slope angle of the present and absent palsa, convex non-sorted circle and stony earth circle squares ......................................................... 57
Figure 35. Convex non-sorted circles on a gentle slope west of Ráššoaivi fell ............................ 58
Figure 36. Convex non-sorted circle with small partly vegetated non-sorted polygons on the surface .................................................................................................................. 58
Figure 78. Observed and predicted distribution of peat pounus in the whole modelling area. ............................. 82
Figure 79. Results of the hierarchical partitioning analyses for peat pounu distribution. ................................. 82
Figure 80. Results of the univariate analyses for peat pounu distribution. .................................................... 83
Figure 81. Relationship between peat pounu abundance and mean slope angle. .......................................... 83
Figure 82. Results of the hierarchical partitioning analyses for peat pounu abundance. ................................. 83
Figure 83. Results of the univariate analyses for stone pit distribution. ......................................................... 84
Figure 84. Relationship between stone pits and glacigenic deposit cover and mean slope angle. ..................... 84
Figure 85. Observed and predicted distribution of stone pits in the whole modelling area. ............................. 85
Figure 86. Results of the hierarchical partitioning analyses for stone pits distribution. ................................ 86
Figure 87. Results of the univariate analyses for sorted net distribution. ....................................................... 86
Figure 88. Relationship between sorted nets and peat cover. ........................................................................... 87
Figure 89. Observed and predicted distribution of sorted nets in the whole modelling area. ........................... 87
Figure 90. Results of the hierarchical partitioning analyses for sorted net distribution. ............................... 88
Figure 91. Results of the univariate analyses for sorted stripe distribution. ................................................... 88
Figure 92. Relationship between sorted stripes and mean altitude and mean slope angle. .............................. 89
Figure 93. Observed and predicted distribution of sorted stripes in the whole modelling area. ........................ 89
Figure 94. Results of the hierarchical partitioning analyses for sorted stripe distribution. ............................. 90
Figure 95. Results of the univariate analyses for non-sorted solifluction terrace distribution. ...................... 90
Figure 96. Observed and predicted distribution of non-sorted solifluction terraces in the whole modelling area. .................................................................................................................. 91
Figure 97. Results of the hierarchical partitioning analyses for non-sorted solifluction terrace distribution. .......................................................................................................................... 92
Figure 98. Results of the univariate analyses for sorted solifluction sheet distribution. ................................. 92
Figure 99. Relationship between sorted solifluction sheets and environmental variables. .............................. 92
Figure 100. Observed and predicted distribution of sorted solifluction sheet in the whole modelling area. .... 93
Figure 101. Results of the hierarchical partitioning analyses for sorted solifluction sheet distribution. ......... 94
Figure 102. Results of the univariate analyses for sorted solifluction sheet abundance. ............................... 94
Figure 103. Results of the hierarchical partitioning analyses for sorted solifluction sheet abundance. .......... 94
Figure 104. Results of the univariate analyses for sorted solifluction stream distribution. ........................... 95
Figure 105. Relationship between the sorted solifluction stream occurrence and mean altitude and mean slope angle. ......................................................................................................... 95
Figure 106. Observed and predicted distribution of sorted solifluction streams in the whole modelling area. .......................................................................................................................... 96
Figure 107. Results of the hierarchical partitioning analyses for sorted solifluction streams distribution. .......... 97
Figure 108. Results of the univariate analyses for deflation distribution. ..................................................... 97
Figure 109. Relationship between deflations and sandy soils and altitude. .................................................... 98
Figure 110. Observed and predicted distribution of deflations in the whole modelling area. .......................... 98
Figure 111. Results of the hierarchical partitioning analyses for deflation distribution. .............................. 99
Figure 112. Summary of the environmental factors of the final distribution models. ................................... 100
Figure 113. Summary of the environmental factors of the final abundance models. ................................. 100
Figure 114. Schematic cross-section summarising the study results. .......................................................... 102
Figure 115. Potentially important environmental factors affecting periglacial feature distribution in northernmost Finnish Lapland at a landscape scale. ......................................... 127
Figure 116. Potentially important environmental factors affecting periglacial feature abundance in northernmost Finnish Lapland at a landscape scale. ........................................ 128
List of Tables

Table 1. Characteristic geomorphic processes in periglacial environments and examples of the resulting landforms. ............................................................... 5
Table 2. Washburn’s classification system of periglacial phenomena. ............................................................... 7
Table 3. Åkerman’s classification system of periglacial phenomena. ............................................................... 7
Table 4. Ballantyne and Harris’ classification system of periglacial phenomena. ...................................................... 8
Table 5. French’s classification system of periglacial phenomena. ............................................................... 9
Table 6. Summary of the climate parameters measured at the Kevo Meteorological Station. ............................................................... 31
Table 7. Pure topographical variables and their description. ............................................................... 39
Table 8. Surrogates for soil moisture and their description. ............................................................... 42
Table 9. Temperature and solar radiation variables and their description. ............................................................... 42
Table 10. Variables, coefficients, standard errors, t- and p-values of the final model for minimum air temperature. ............................................................... 42
Table 11. Soil type variables and their description. ............................................................... 43
Table 12. Vegetation variables and their description. ............................................................... 43
Table 13. Spatial variables and their description. ............................................................... 44
Table 14. Correlation matrix of the environmental predictors used in the statistical analyses. ............................................................... 50
Table 15. Periglacial landforms and their prevalence in the Báisduattar – Ålegas area at the 25-ha modelling resolution. ............................................................... 55
Table 16. Topographical characteristics of the active landform occurrences in relation to absent sites. ............................................................... 57
Table 17. Variables, coefficients, standard errors, z- and p-values of the final model for palsa distribution. ............................................................... 68
Table 18. Deviance information and degrees of freedom of the final distribution and abundance models. ............................................................... 69
Table 19. Variables, coefficients, standard errors, t- and p-values of the final model for palsa abundance. ............................................................... 71
Table 20. Variables, coefficients, standard errors, z- and p-values of the final model for convex non-sorted circle distribution. ............................................................... 72
Table 21. Variables, coefficients, standard errors, t- and p-values of the final model for convex non-sorted circle abundance. ............................................................... 74
Table 22. Variables, coefficients, standard errors, z- and p-values of the final model for stony earth circle distribution. ............................................................... 76
Table 23. Variables, coefficients, standard errors, z- and p-values of the final model for earth hummock distribution. ............................................................... 78
Table 24. Variables, coefficients, standard errors, t- and p-values of the final model for earth hummock abundance. ............................................................... 80
Table 25. Variables, coefficients, standard errors, z- and p-values of the final model for peat pounu distribution. ............................................................... 81
Table 26. Variables, coefficients, standard errors, t- and p-values of the final model for peat pounu abundance. ............................................................... 83
Table 27. Variables, coefficients, standard errors, z- and p-values of the final model for stone pit distribution. ............................................................... 85
Table 28. Variables, coefficients, standard errors, z- and p-values of the final model for sorted net distribution. ............................................................... 86
Table 29. Variables, coefficients, standard errors, z- and p-values of the final model
for sorted stripe distribution...............................................................88
Table 30. Variables, coefficients, standard errors, z- and p-values of the final model for non-sorted solifluction terrace distribution. .........................................................90
Table 31. Variables, coefficients, standard errors, z- and p-values of the final model for sorted solifluction sheet distribution.................................................................92
Table 32. Variables, coefficients, standard errors, t- and p-values of the final model for sorted solifluction sheet abundance.................................................................94
Table 33. Variables, coefficients, standard errors, z- and p-values of the final model for sorted solifluction stream distribution.................................................................96
Table 34. Variables, coefficients, standard errors, z- and p-values of the final model for deflation distribution.................................................................97
Table 35. Summary of the model performances of the distribution models. .................................................................99
Table 36. Summary of the model performances of the abundance models. .................................................................99

List of Appendices

Appendix 1. Distribution of palsas in the study area.................................................................151
Appendix 2. Distribution of convex non-sorted circles in the study area.........................................................152
Appendix 3. Distribution of stony earth circles in the study area.................................................................153
Appendix 4. Distribution of earth hummocks in the study area.................................................................154
Appendix 5. Distribution of peat pounus in the study area.................................................................155
Appendix 6. Distribution of stone pits in the study area.................................................................156
Appendix 7. Distribution of sorted nets in the study area.................................................................157
Appendix 8. Distribution of sorted stripes in the study area.................................................................158
Appendix 9. Distribution of non-sorted solifluction terraces in the study area.................................................................159
Appendix 10. Distribution of sorted solifluction sheets in the study area.................................................................160
Appendix 11. Distribution of sorted solifluction streams in the study area.................................................................161
Appendix 12. Distribution of deflations in the study area.................................................................162

Abbreviations

AML ARC Macro Language
a.s.l. above sea level
AUC Area Under the Curve
BP before present
CTA Classification Tree Analysis
DEM Digital Elevation Model
d.f. Degrees of freedom
GIS Geographical Information System
GLM Generalized Linear Model
GPS Global Positioning System
HP Hierarchical Partitioning
LP Linear Predictor
LS Least Square
MAAT Mean Annual Air Temperature
MARS Multiple Adaptive Regression Splines
max maximum
min  minimum
n.s.  not significant
PCC  Percentage of Correct Classification
Q–Q  Quantile–Quantile
RMSE  Root-Mean-Square Error
RMSPE  Root-Mean-Square Prediction Error
ROC  Receiver Operating Characteristic
RS  Remote Sensing
SE  Standard Error
ssp.  subspecies
std  standard deviation

Symbols

$\alpha$  slope angle / constant
$A_s$  upslope contributing area
$\beta$  regression coefficient
$E$  Elevation–relief ratio
ei  distance difference between test points
exp  exponential
$I$  independent contribution
$J$  cojoint contribution
$\kappa$  Cohen's Kappa statistic
$L\%$  percentage of lakes
ln  natural logarithm
log  logarithm
$\mu$  expected value
$n$  number of observations
$\omega$  topographical wetness index
$P_1$  probability
$p$  statistical significance
$R_s$  Spearman's rank correlation coefficient
$t$  test value
$|x|$  absolute value
$\lambda$  Finnish National Grid Coordinate (east)
$x_1$  predictor variable
$y$  Finnish National Grid Coordinate (north)
$y^\lambda$  Box-Cox transformation
$z$  test value
$Z$  elevation
*  $p < 0.05$
**  $p < 0.01$
***  $p < 0.001$
Determination of the environmental factors controlling earth surface processes and landform patterns is one of the central themes in physical geography (e.g. Goudie 1995; Allen 1997). Geomorphological processes are often studied utilising traditional field survey methods (e.g. Verstappen 1983; Summerfield 1991). However, the identification of the main drivers of the geomorphological processes is often challenging, particularly if complex systems and extensive areas are under investigation. Novel spatial analysis and modelling methods in combination with thoughtful geomorphological understanding could provide new insights into the process-environment relationships (e.g. Atkinson et al. 1998; Bledsoe & Watson 2001; Lewkowicz & Ednie 2004; Luoto & Hjort 2005, in press; Ayalew & Yamagishi 2005; cf. Wilcock & Iverson 2003).

Human activity in the polar and alpine regions has increased constantly (Harris 1986; Davis 2001). Moreover, the increasing atmospheric concentrations of greenhouse gases could lead to significant changes in regional and seasonal climatic patterns. Because of the major influence of climate on the activity of periglacial processes from the continental to local scale, climate change could strongly influence the geomorphological processes in subarctic areas, particularly in the zone of discontinuous permafrost (Anisimov & Fitzharris 2001; Nelson et al. 2001; Nelson 2003). Observations and experiments also indicate climate-induced changes in periglacial processes (e.g. Christensen et al. 2004; Lewkowicz & Harris 2005). Consequently, the need for detailed distributional information of the geomorphological phenomena governing the cold environments has recently increased considerably.

Despite that periglacial processes and landforms have been intensively studied for over a century (French 2003), gaps in our knowledge exist (e.g. Clark 1988; Ballantyne & Harris 1994). The developments in the field of geographical information system (GIS) science, remote sensing (RS) and statistical techniques have improved the possibility to survey extensive regions and study different aspects of earth surface processes in the cold regions (e.g. Walsh et al. 1998; Etzelmüller et al. 2001; Gruber & Hoelzle 2001; Luoto & Seppälä 2002a; Grosse et al. 2005; Gurney & Bartsch 2005).

GIS offers an analytical framework for storing, combining, displaying and analysing large data sets on multiple spatial scales (e.g. Walsh et al. 1998; Burrough & McDonnel 2000). Correspondingly, statistical methods provide a mathematical basis for the interpretation of relationships between response and predictor variables and they enable the exploration of roles of different environmental correlates (Atkinson et al. 1998; Guisan et al. 2002; Luoto et al. 2004a). Furthermore, the numerical techniques provide an efficient approach to summarise the geomorphological knowledge and help to draw general conclusions of the studied phenomena for academic, applied and economical purposes. However, several potential data and method-based shortcomings may affect the reliability of the results when geographical data sets are used in statistical modelling (Clark & Hosking 1986: 17–19; Legendre 1993; MacNally 1996; Luoto & Heikkinen 2003).

Periglacial phenomena operate over a wide range of scales (Washburn 1979; French 1996). On a large scale, periglacial processes have been described in relation to latitudinal and longitudinal environmental gradients, i.e. climatic conditions (e.g. Lundqvist 1962; Harris S.A. 1982a). On a fine scale, local topographical, soil and vegetation factors have been used to determine the distribution and activity of phenomena (e.g. van Vliet-Lanoë 1988a; Matthews et al. 1998). The phenomena-environment interactions on a landscape scale are, however, still rather poorly explored in periglacial studies.

In this study, a quantitative description
and statistical analysis of the distribution and abundance of different active periglacial landforms on the landscape scale is provided. This work is based on a grid-based approach at the resolution of 500 x 500 m (25-ha). The general aim is to assess the applicability of the numerical modelling techniques in combination with GIS data to analyse the main determinants of periglacial phenomena. More precisely, the objectives are to (1) map the occurrence of periglacial landforms in subarctic Finland (Seppälä 1997a: 83), (2) study statistically the association between landforms and environmental factors driven from GIS data sets (Fig. 1; Etzelmüller et al. 2001: 89), based on the previous, (3) determine the most important environmental factors affecting the distribution and abundance of periglacial phenomena on the landscape scale (e.g. Barsch 1993: 154, 159–160), (4) identify the shapes of the responses, (5) evaluate the prediction abilities of the models and (6) explore the methodological advantages as well as limitations. Moreover, utilising two alternative multivariate techniques, namely generalized linear modelling (GLM) and hierarchical partitioning (HP), the aims are to gain deeper insight into the process-environment relationships and study reliability of the results when geographical data sets are used in statistical modelling. However, the determination of scale dependency of the phenomena occurrence and potential effects of climate change on the processes and landforms are beyond the scope of this study. In general, spatial scaling issues have received increasing attention in GIS science during recent decades but also in geomorphology (e.g. Luoto & Hjort in press).

The study is performed using a comprehensive empirical data set of periglacial landforms. The focus is on the active features because many of the utilised predictor vari-

Figure 1. Simplified conceptual model of the relationships between environmental factors, periglacial processes and periglacial landforms commonly found from subarctic regions, particularly northern Fennoscandia (e.g. Lundqvist 1962; Harris C. 1982; Jahn & Siedlecki 1982; Meier 1987; Seppälä 1987, 2005a; for more details see Chapter 2). The presented processes are grouped including several different subtypes of periglacial processes. For example, rapid mass movements are different kind of falls, flows, avalanches and slides and cryoturbation refer to the general lateral and vertical displacement of soil due to freeze-thaw activity (e.g. French 1988).
ables illustrate present environmental conditions and thus the current activity (cf. Nies- 
sen et al. 1992: 188). The subarctic study area of 600 km² is chosen based on the previous 
knowledge on the existence of numerous per-
iglacial landforms and variability of the envi-
ronmental conditions in the region (e.g. Piïrola 
1969, 1972; Kejonen 1979: Luoto & Seppälä 
2000; van Vliet-Lanoë & Seppälä 2002). The 
diversity of relief, soil properties and vegeta-
tion provides an excellent setting for detailed 
quantitative study of the determinants of per-
iglacial landforms and processes in subarctic 
landscapes.

Specific questions to be answered are: (1) 
What kind of periglacial phenomena exist in 
the study area? (2) Which are prevalent land-
form types in subarctic Finland? (3) What are 
the most important landscape scale environ-
mental factors of the periglacial phenomena? 
(4) How well can we predict the distributions 
and abundances of different periglacial land-
forms on the basis of GIS data? (5) Are the 
model outcomes realistic? (6) Which are criti-
cal methodological limitations? (7) What are 
the next critical steps to improve the models 
in periglacial research?
Which are periglacial phenomena? How do we define a periglacial environment? Which factors control the activity of geomorphological processes in cold environments? These and numerous similar questions have inspired geoscientists even long before the concept of periglacial was considered (e.g. Jahn 1975: 1–4; Ballantyne & Harris 1994: 4–5). The term periglacial was first introduced by von Łoziński (1909) to describe frost-weathering conditions in the Carpathian Mountains. Ever since researchers have made an effort to characterise the periglacial domain but we cannot find any generally accepted quantitative parameters to the definition of periglacial phenomena or environments.

Different, mainly climate-based, limits have been presented. According to Peltier (1950: 215) mean annual air temperature (MAAT) should be between −15°C and −1°C and precipitation should range from ca. 130 mm to 1400 mm. Wilson (1968: 723) gave values −12°C – +2°C and 50 – 1250 mm for the limits. French (1996: 20) defined a periglacial region to be all those areas where the MAAT is under +3°C. In addition to pure climatological determinants, there exist definitions based on permafrost, treeline, snowcover and frost processes (e.g. Tricart 1968: 830; Jahn 1975: 10–14; Ballantyne & Harris 1994: 28). However, because there is no agreement for the quantitative limits of periglacial environments, it is widely accepted that the term periglacial refers to the conditions and phenomena associated with cold, non-glacial regions where frost processes dominate (Karte 1979: 177; Washburn 1979: 4; Ballantyne & Harris 1994: 3; French 1996: 3; van Everdingen 2005: 54–55). Regardless of the different definitions, we can emphatically state that periglacial conditions prevail in extensive areas and even 20–35% of the Earth’s land surface could be considered as periglacial environment (French 1996: 5; Worsley 2004: 773).

The processes acting in the periglacial domain and responsible for the formation of different landforms are numerous (Fig. 1; Table 1). Many of the so-called periglacial processes can also operate in the other non-glacial environments and differ only in their frequency and/or intensity. Characteristic periglacial phenomena are related to the permafrost aggradation and degradation (e.g. French 1996: 6) but, in general, frost action is the most widespread and important periglacial process (Washburn 1979: 6).

<table>
<thead>
<tr>
<th>Processes</th>
<th>Landforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground ice development (e.g. ice intrusion and segregation)</td>
<td>Pingos</td>
</tr>
<tr>
<td>Thermal, desiccation and dilation cracking of soil</td>
<td>Non-sorted polygons</td>
</tr>
<tr>
<td>Frost and complex physico-chemical weathering processes</td>
<td>Block fields</td>
</tr>
<tr>
<td>Frost heave, frost thrusting, mass displacement and particle size sorting</td>
<td>Sorted circles</td>
</tr>
<tr>
<td>Thawing of ice-rich soil i.e. thermokarst</td>
<td>Thermokarst depressions</td>
</tr>
<tr>
<td>Snowbank related processes (nivation)</td>
<td>Cryoplanation terraces</td>
</tr>
<tr>
<td>Soil creep and gelifl uction (solifl uction)</td>
<td>Solifl uction lobes</td>
</tr>
<tr>
<td>Rapid mass movements (e.g. slushflows, debris flows and rockfalls)</td>
<td>Taluses</td>
</tr>
<tr>
<td>Fluvial processes (e.g. associated with spring floods)</td>
<td>Break-up features</td>
</tr>
<tr>
<td>Aeolian activity caused by strong winds</td>
<td>Sand dunes</td>
</tr>
<tr>
<td>Coastal processes associated with lake or sea ice</td>
<td>Ice-shove ridges</td>
</tr>
</tbody>
</table>
The environmental determinants influencing the phenomena are almost as varied as the periglacial processes themselves (e.g. Fig. 1). Washburn (1979: 10–17) listed five basic (i.e. independent) factors and three dependent determinants. In general, the most important environmental drivers are climate (temperature, precipitation and wind), topography, material (surficial soil and bedrock), moisture conditions, snow- and ice cover as well as vegetation. Washburn (1979: 15) also included time and human activity into the set of factors. Climatological conditions affect, for example, freeze-thaw cycles and general moisture distribution and therefore all periglacial processes. In addition, the wind has a significant role in the snow redistribution, which affects the soil temperatures and moisture conditions. Soil moisture is among temperature as the most important determinant of frost processes (Fig. 1; Washburn 1979: 63). Soil material affects the moisture distribution and process activity. Topography, snowcover and vegetation influence the processes through the main drivers; temperature and soil moisture. However, topography affects directly on the slope phenomena and vegetation on the slope and aeolian processes.

Subsequently, different periglacial landform classifications will be presented. In general, the classification of diverse and continuous phenomena areas where activity may vary spatially and temporally is rather difficult and artificial, but the classification of phenomena is essential to structure the study and in the compilation of response data sets. Description of different periglacial landforms is provided after the classification. Focus will be on the landform types commonly found in subarctic regions, particularly in Finland (see also Okko 1954; Aartolaiti 1980; Seppäälä 1997a). Interaction between environmental factors and periglacial phenomena are treated in Chapter 6 in more detail.

2.1 Classification of periglacial landforms

Classification of the landforms is a fairly challenging task due to the diversity of the periglacial phenomena (e.g. Ballantyne & Harris 1994: 7–8). The classification can be performed based on the processes (e.g. frost, solifluction, aeolian), landforms (e.g. patterned ground), environments (e.g. forest, mire, slope, lowland), climate (e.g. Harris S.A. 1982a) or some combination of the former. Most of the researchers have created a classification of their own to structure their work (e.g. Åkerman 1980). Consequently, there is not available any classification that includes all known landform types. This is natural, because every study area is unique and probably no region is so representative that it would include all known periglacial features.

Six different classifications will be briefly presented here. Five of them are taken from periglacial textbooks (Embleton & King 1975; Washburn 1979; Williams & Smith 1989; Ballantyne & Harris 1994; French 1996) and one is from a mapping research (Åkerman 1980). The classifications were interpretated from the sources because explicit tables describing the classifications were not available.

Embleton and King (1975) classify periglacial phenomena into six main groups: (1) frozen ground phenomena, (2) patterned ground, (3) mass movement and slope deposits, (4) the action of snow, (5) cryoplanation, tors, blockfields and blockstreams and (6) wind action. Their classification is partly process and partly landform based. Washburn’s (1979) classification is mostly based on the processes but periglacial forms such as patterned ground, involutions and palsas are grouped together (Table 2). Åkerman’s (1980) classification is also mainly based on the processes but he has more classes than the previous classifications (Table 3). Williams and Smith (1989) divided landforms into only two main groups according to the topography of the occurrence area, i.e. landforms that prevail on slopes and subsides and features on level ground. Ballantyne
and Harris (1994) use a partly process and partly landform-based classification also including the spatial and temporal aspect (Table 4). French (1996) has six classes and he uses mainly the process-based approach (Table 5).

All the presented classifications more or less differ from each other. The classification of Williams and Smith (1989) was the simplest and rather incomplete because fluvial processes were largely lacking and aeolian and coastal phenomena were absent. Washburn (1979) treated periglacial phenomena relatively completely but the classification differed slightly from the others. The classifications of Embleton and King (1975), Ballantyne and Harris (1994) and French (1996) were relatively simi-

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Table 2. Washburn's (1979) classification system of periglacial phenomena.

<table>
<thead>
<tr>
<th>Main division</th>
<th>Periglacial landforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periglacial forms</td>
<td>Patterned ground, involutions, stone pavements, string bogs, palsas and pingsos</td>
</tr>
<tr>
<td>Mass-wasting processes</td>
<td>Avalanche features, slushflow deposits, frost creep and gelifluction deposits, ploughing blocks and braking blocks, rock glaciers, talus and protalus ramparts</td>
</tr>
<tr>
<td>Nivation</td>
<td>Nivation benches and hollows and cryoplanation terraces</td>
</tr>
<tr>
<td>Slope wash</td>
<td>Grèzes litées</td>
</tr>
<tr>
<td>Fluvial action</td>
<td>Icing, break-up features, flat-floored valleys, asymmetric valleys, dry valleys and dells</td>
</tr>
<tr>
<td>Lacustrine and marine action</td>
<td>Varves, ice rafting features, lacustrine and marine ice-shove ridges</td>
</tr>
<tr>
<td>Wind action</td>
<td>Loess, dunes, niveo-colian forms, deflation and ventifacts</td>
</tr>
<tr>
<td>Thermokarst</td>
<td>Collapse pingos, thaw slumps, linear and polygon troughs, beaded drainage, thaw lakes and alases</td>
</tr>
</tbody>
</table>

Table 3. Åkerman's (1980) classification system of periglacial phenomena.

<table>
<thead>
<tr>
<th>Main division</th>
<th>Periglacial landforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weathering processes</td>
<td>Block fields and slopes, cavernous weathering and surface karst features</td>
</tr>
<tr>
<td>Ground ice features</td>
<td>Palsas, hummocks, ice-wedge polygons, “talus pingos”, “pseudo pingos”, hydrolaccolites, naledi and naledi pavements</td>
</tr>
<tr>
<td>Thermokarst processes</td>
<td>Thermokarst basins, slope of thermokarst denudations, thermokarst landslides, ravines and dolines</td>
</tr>
<tr>
<td>Frost processes</td>
<td>Circles, nets, polygons, steps and stripes</td>
</tr>
<tr>
<td>Wind action</td>
<td>Dunes (e.g. embryonal and tail dunes), unspecified sandy deposits, ventifacts and wind erosion in vegetation</td>
</tr>
<tr>
<td>Nivation processes</td>
<td>Nivation hollows, snow-patch pavements and perennial snow-patches</td>
</tr>
<tr>
<td>Slope processes</td>
<td>Rock-fall scars, talus cones, debris flow tracks and accumulations, protalus ramparts, avalanche tracks and accumulations, gelifluction sheets and lobes, block streams, ploughing and braking blocks and land slide scars</td>
</tr>
<tr>
<td>Coastal and littoral processes</td>
<td>Cliff and cliff with caves, stacks, edge of abrasion platforms, seaweed accumulations, ice push ridges, thermokarst in buried ice, active beaches (sandy) and driftwood accumulations</td>
</tr>
<tr>
<td>Fluvial processes</td>
<td>Small streams, water falls, fords, rapids, ravines, sink holes, wells and active alluvial deposits</td>
</tr>
</tbody>
</table>
lar. They first introduced permafrost and related phenomena, then active layer processes and patterned ground, thirdly slope processes and finally fluvial, aeolian, coastal and weathering processes and landforms in different orders. Embleton and King (1975) had deficiencies in their system because the coastal and fluvial phenomena were not classified, although these were discussed briefly in the introduction. Åkerman (1980) treated all common periglacial phenomena and the distinction to the previous was only in the order of themes.

Most of the classifications are based on the observations of continuous permafrost regions where the phenomena can differ from the marginal periglacial areas processes [e.g. two-sided freezing (French 1988: 151)]. How proper are these systems then for classifying periglacial landforms in different cold environments, for example in the subarctic Fennoscandia? In general, it is probable that any of the above presented classifications would be suitable but every research may need a somehow adjusted approach because periglacial phenomena vary geographically.

The classification utilised in this study was

### Lowland Britain

<table>
<thead>
<tr>
<th>Main division</th>
<th>Periglacial landforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice-wedges and tundra polygons</td>
<td>Ice wedges and ice-wedge casts, tundra polygons, sand wedges and sand-wedge polygons and soil wedges</td>
</tr>
<tr>
<td>Pingos and related ground-ice phenomena</td>
<td>Pingos, pingo ramparts and scars, palsas and mineral palsas, seasonal frost mounds, icing and thermokarst depressions (alases, thaw lakes, ground-ice slumps)</td>
</tr>
<tr>
<td>Active layer processes: cryoturbation and patterned ground</td>
<td>Circles, polygons, irregular networks, stripes, step-like, oval, lobate and garland patterns and involutions</td>
</tr>
<tr>
<td>Mass wasting and slope evolution</td>
<td>Skinflows and active-layer detachment failures, Mudflows and debris flows, Ground-ice slumps, Slopewash (colluvium, gelifluctates)</td>
</tr>
<tr>
<td>Fluvial and aeolian processes</td>
<td>Asymmetrical and symmetrical valleys, Dells and braided river channels, Loess, dunes, coversands, ventifacts, Niveo-aeolian deposits</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main division</th>
<th>Periglacial landforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frost weathering</td>
<td>Block fields, slopes and streams, debris-mantled slopes and tors</td>
</tr>
<tr>
<td>Patterned ground</td>
<td>Circles, polygons etc. (see above)</td>
</tr>
<tr>
<td>Solifluction landforms</td>
<td>Solifluction lobes, steps, terraces and sheets, boulder sheets and lobes and ploughing boulders</td>
</tr>
<tr>
<td>Talus slopes and related landforms</td>
<td>Talus slopes (sheets and cones), avalanche cones, tongues and tracks, debris cones and flows, protalus ramparts and rock glaciers (protalus and morainic rock glaciers)</td>
</tr>
<tr>
<td>Nival, fluvial, aeolian and coastal features</td>
<td>Nivation hollows and benches, cryoplanation erraces, stratified slope deposits (grèzes littées et éboulis ordonnées), deflation surfaces and pavements, wind-patterned ground (deflation scars, wind stripes and crescents), turf-banked and deflation terraces and periglacial shorelines</td>
</tr>
</tbody>
</table>
adapted from the systems of Embleton and King (1975), Ballantyne and Harris (1994; Table 4) as well as French (1996; Table 5). However, the differences to Washburn (1979; Table 2) and Åkerman (1980; Table 3) are minor. The main division of the landforms is based on processes, although patterned ground features are grouped together. The subdivision of the patterned ground group is based on Washburn (1956, 1979) with minor alterations (van Everdingen 2005: 53). Moreover, sorted fields, such as boulder depressions, are included in this class (see Lundqvist 1962). In the group of slope features, the terms sorted and non-sorted are used instead of turf- and stone banked to describe the general sorting of the solifluction landforms, as recommended by Ballantyne and Harris (1994: 208–209).

### 2.2 Description of periglacial landforms

#### 2.2.1 Permafrost landforms

Permafrost is defined as ground (soil or bedrock) in which the temperature remains at or below 0°C for at least two consecutive years (Muller 1947; 3; van Everdingen 2005: 55). Northern Finland is located in the zone of discontinuous and sporadic permafrost (Brown et al. 1997) and palsas are the only true permafrost features (Seppälä 1997b), albeit that pingo-like features and rockglaciers can be found from neighbouring subarctic regions (e.g. Ostrem 1971; Åkerman & Malström 1986; Lagerbäck & Rodhe 1986). Permafrost has also been found in small peaty earth hummocks called pounus (e.g. Ruuhijärvi 1962; Piironen 1994; Seppälä 1998; Luoto & Seppälä 2002b) as well as in bedrock (King & Seppälä 1987, 1988; Kukkonen & Safanda 2001) and minerogenic ground (Hirvas et al. 2000, 2005; Vanhala et al. 2005).

Palsas are 0.5–10 m high permanently frozen peat or partly mineral soil hummocks that occur widely in the circumpolar discontinuous or sporadic permafrost zone with slightly continental climate and with thin snowcover (Fig. 2; Lundqvist 1969; Seppälä 1972a, 1988, 2004a; Moore 1984; Nelson et al. 1992; Gurney 2001). Ahman (1977: 38-42) has described five different morphological types of palsas and palsa mires: (1) 1–1.5 m high and extensive palsa plateaus, (2) 2–6 m high and 50–500 m long esker or ridge-form (Seppälä 1988: 255) palsas, (3) 1–2 m high and 25–100 m long string palsas, (4) 2–6 m high circular conical or dome-shaped (Seppälä 1988: 255) palsas and (5) palsa complexes where palsas of different morphology and/or in various stages of development exist (Fig. 2).

Different theories for palsa formation have been presented, for example snowcover, vegetation and buoyancy hypothesis (for summary see Seppälä 1994a; Gurney 2001). The snowcover theory has been experimentally tested

Table 5. French’s (1996) classification system of periglacial phenomena.

<table>
<thead>
<tr>
<th>Main division</th>
<th>Periglacial landforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permafrost and ground ice</td>
<td>Palsas, rock glaciers, seasonal frost mounds, ice wedges, pingo and ice-cored mounds (e.g. Hydrolaccoliths)</td>
</tr>
<tr>
<td>Thermokarst</td>
<td>Alases, ice-wedge thermokarst terrain, retrogressive thaw slumps, thaw lakes and depressions</td>
</tr>
<tr>
<td>The active layer</td>
<td>Patterned ground (circles, polygons, nets, steps and stripes)</td>
</tr>
<tr>
<td>Hillslope processes</td>
<td>Solifluction sheets and lobes, ploughing blocks, slopewash (nivation, Grèzes litées), debris flows and avalanches</td>
</tr>
<tr>
<td>Fluvial processes and landforms</td>
<td>Icing, braided channels, periglacial sandurs and asymmetrical valleys</td>
</tr>
<tr>
<td>Wind action and coastal processes</td>
<td>Ventifacts, stone pavements, deflation depressions, loess, sand dunes and sheets, ice-push features, cliffs and cold climate deltas</td>
</tr>
</tbody>
</table>

Periglacial phenomena
palsas are considered to originate as a result of the growth of segregation ice by cryosuction and their inner structure is mostly composed of segregated ice, frozen peat and silty mineral soil with small ice crystals (Seppälä 1988: 263–266; Fig. 1). The peat cover is essential for the survival of the frozen core and the insulation is based on the thermoconductivity of peat (see Williams & Smith 1989: Table 4.1, 113). For example, Railton and Sparling (1973) and Seppälä (1979a) have described the cyclic development of the palsas with different aggregation and degradation stages (see also Zuidhoff & Kolstrup 2005: 57–59). At present, palsas are generally degrading throughout their distribution range (Fig. 3), probably because of the regional climate warming (Matthews et al. 1997; Zuidhoff & Kolstrup 2000; Zuidhoff 2002). In Finland, the sizes of the features generally range from a few tens of square metres to one hectare and they are water or vegetation covered (Fig. 4; cf. Luoto & Seppälä 2003). Thawed and collapsed palsa may leave a circular peat rampart i.e. rim ridge around the thermokarst depression (e.g. Svensson 1969; Seppälä 1988: Figure 11.6a).

In general, the distribution of the thermokarst ponds is closely related to the occurrence of palsas but thermokarst features have wider vertical and horizontal distribution at the landscape scale and they can be found from areas where palsas have disappeared (Luoto & Seppälä 2003).

2.2.3 Patterned ground

Patterned ground landforms are more or less symmetrical structures visible at the ground surface and their size and shape is dependent on the topographical location and formative processes (Fig. 5; cf. Troll 1944). No consensus exists on what features belong to patterned ground. Washburn (1956, 1979) divided patterned ground based on (1) geometry to circles,
polygons, nets, steps and stripes and (2) sorting to sorted and non-sorted features. Sorted patterned ground is defined by alternation of fine and coarse soil material, whereas non-sorted patterned ground is formed by microrelief and/or vegetation differences (see Washburn 1956: 826–838). Some researchers have used a broader definition that also includes solifluc- tion landforms (e.g. van Everdingen 2005: 53), boulder depressions (Lundqvist 1962), taluses (Kejonen 1997) and even palsas (Meier 1987: 192).

Several hypotheses for patterned ground formation have been proposed (e.g. Washburn 1970; Nicholson 1976; Mackay 1980; Ray et al. 1983; Schunke & Zoltaï 1988; van Vliet-Lanoë...
1991; Werner & Hallet 1993; Kessler & Werner 2003; Peterson & Krantz 2003; Matsuoka et al. 2003; for reviews see Washburn 1956, 1997) but it is still widely accepted that many of them are polygenetic in origin (e.g. French 1996: 142; Mann 2003). For example at a local scale, microclimate, topography, soil properties, moisture availability, vegetation cover and snow distribution are important factors (e.g. Matthews et al. 1998). Furthermore, similar features can be formed due to different processes and the same process may produce dissimilar features (Washburn 1979: 157).

Circles, polygons and nets are features whose mesh is dominantly circular, polygonal or net-like. Sorted patterns have a border of stones surrounding finer soil material and non-sorted patterns are often margined by vegetation and they lack a stony border. A furrow or a crack may delineate non-sorted polygons and nets (Washburn 1956: 826–833). The main processes responsible for the formation of circles, polygons and nets are differential frost heave, mass displacement and/or frost sorting and, in addition, soil cracking for polygons (e.g. Washburn 1970: Table 1, 1979: 160–170).

The diameter of the circles ranges commonly from 0.5 to three metres. Central areas of the non-sorted circles tend to be dome-shaped (Fig. 6) and bare-soil circles may be cracked to non-sorted polygons. Circles are predominant in different periglacial environments (Washburn 1979: 128). Several morphological types of sorted and non-sorted circles exist. Earth hummocks (e.g. Nicholson 1976; Mackay 1980; Schunke & Zoltai 1988), peat pounus (e.g. Salmi 1972; Seppälä 1998; van Vliet-Lanoë & Seppälä 2002), stony earth circles (e.g. Williams 1959) and mud or frost circles (e.g. Shilts 1978; Harris 1998; Peterson et al. 2003; Walker et al. 2004) are different kinds of non-sorted circles (see van Everdingen 2005: 53), although Washburn (1956: 830) classified earth hummocks as non-sorted nets. Stone pits (e.g. Lundqvist 1962: 21–24; Seppälä 1987: 48) and debris islands (Washburn 1956: 827) have a different appearance than normal stone-bordered sorted circles (Fig. 7). For example, Hallet (1998), Kessler et al. (2001), Holness (2003) and Haugland (2004) have studied sorted circles more recently.

The size of the non-sorted polygons varies from five centimetres to even 100 m and the diameter of the sorted features can range from ten centimetres to ca. ten metres (Fig. 5; Washburn 1979: 133, 142). Non-sorted polygons are predominant in the continuous permafrost.
regions but small features are also found in areas of seasonal frost (e.g. Ballantyne & Matthews 1983). Sorted polygons occur in different periglacial environments, respectively (Washburn 1979: 133–145). In general, the processes forming the sorted polygons are often the same as in the other sorted patterned ground but soil cracking is in several circumstances the initial process (e.g. Washburn 1956, 1970; Goldthwait 1976; Nicholson 1976; van Vliet-Lanoë 1991; Kessler & Werner 2003).

Nets are intermediate features whose mesh is neither dominantly circular nor polygonal because the formative mechanisms have been weak and/or mixed or the features have stretched on slopes. Otherwise, the sizes,
processes and distributions resemble circles and polygons (e.g. Washburn 1979: 146–147; Ballantyne & Matthews 1983; Haugland 2004: 5). In general, nets have been described from different periglacial environments (e.g. Dabski & Gryglewicz 1998; Hodgson & Young 2001). However, confusion of the circles, polygons and nets is relatively common in the literature (Lundqvist 1962: 29; Ballantyne & Harris 1994: 195).

Sorted fields are areas with a pure boulder material on the ground surface and they form no characteristic patterns (Lundqvist 1962: 61–63). However, they are separated from the frost weathered block fields (Chapter 2.2.5). Boulder depressions are the most common type of the sorted fields and they are mainly described from different parts of Fennoscandia (e.g. Lundqvist 1951; Ohlson 1964; Aartolahti 1969; Piïrola 1969; Seppälä 1982b; Söderman 1982; Hättestrand 1994). Boulder depressions are flat barren fields of pure boulder material situated in shallow depressions in the landscape (Högboom 1905: 27). Features are the most typical in forested areas but they also occur above the treeline in the barren fell areas (Fig. 8). Boulder depressions’ diameters vary from some metres to several hundred metres and the small forms resemble stone pits. The largest boulders are typically at the surface and the material finer downward. Features are formed by frost heave and sorting but boulders can be split by frost wedging (e.g. Lundqvist 1962: 73–76).

According to Washburn (1956: 833–834) steps are features with step-like form and downslope border of vegetation or stones embanking an area of relatively bare ground upslope (Fig. 9). Steps are usually derived from circles, polygons, or nets rather than developed independently. Features are normally less than one metre high and locate on 5°–15° slopes (Washburn 1979: 149). The sorted steps have stony riser and they are probably derived from sorted circles or polygons. The non-sorted steps have often vegetated riser and they are derived mainly from different hummocky non-sorted circles. In general, studies on the step-like patterned ground are quite limited (Washburn 1969: 150–151; Walsh et al. 2003a).

Stripes are features with a striped pattern oriented down the steepest available slope. Sorted stripes are formed of parallel stony lines whereas non-sorted stripes are a set of vegetated and relatively bare ground lines (Fig. 10; Washburn 1979: 151–156). Stripes can be some hundred metres long and up to two metres wide or even more. Features occur on the slope gradients from two to ca. 30° and rarely up to 40°. Hummocky stripes are one
type of the non-sorted features where hummocks are lined up to form the stripes (e.g. Lundqvist 1962: 58–59). Stripes occur in many environments and non-sorted have somewhat the same distribution as the non-sorted circles and polygons although stripes appear to be less common (Washburn 1979: 151–156). For example, Ray et al. (1983), Muir (1983), Werner and Hallet (1993), Hall (1994), Francou et al. (2001), Holness (2001) and Matsuoka et al. (2003) have studied the formation of sorted stripes. Studies on the non-sorted stripes are rather limited (for exceptions see Washburn 1947: 94, 1969: 151–154; Lundqvist 1962: 58–59; French 1974).

Figure 9. *Ca.* 60 cm high non-sorted steps on a valley slope northwest of Suophášoiví fell (69°30'6"N, 26°24'19"E / 430 m a.s.l. / 31st of July 2002).

Figure 10. Non-sorted stripes on a fell slope southeast of Uhc-Áhkováráš fell (69°32'41"N, 26°9'14"E / 370 m a.s.l. / 5th of July 2003). Width of the bare ground stripes are *ca.* 0.5 m.
2.2.4 Solifluction and other slope phenomena

Periglacial slope processes can be subdivided to two main types (1) solifluction and (2) more localised rapid slope failures that occur sporadically often during thaw season. Solifluction is a slow downslope movement of soil mass usually associated with freeze-thaw cycles and frost heave (Andersson 1906: 95–96; Matsuoka 2004: 984). The second main subtype of the mass wasting phenomena (rapid mass movements) contains a variety of falls, avalanches, flows and slides (e.g. McRoberts & Morgenstern 1974; Washburn 1979: 192–197; Innes 1983; Nyberg 1985; Ballantyne & Harris 1994: 118).

Solifluction can be considered as a collective term, which includes frost creep resulting from nearly vertical settlement of soils heaved normal to the slope and gelifluction representing downslope displacement of ice-rich soil during thawing (e.g. Washburn 1979: 201). Both frost creep and gelifluction operate together and the term solifluction is typically used to describe their combined effects (Matsuoka 2004: 984). Solifluction may operate even on one degree slopes and the annual rates of downslope movements varies between ca. 0.5 and 10 cm a
and 10 cm a
(Matsuoka 2004: 984). Important environmental determinants for the processes are soil moisture, slope gradient, grain size distribution and vegetation cover (Fig. 1; Washburn 1979: 198–204; Pissart 1993; Matsuoka 2001a). Solifluction produces diverse set of landforms such as sorted and non-sorted sheets, lobes and terraces (e.g. Rapp 1960; Washburn 1967; Benedict 1970; Harris 1987, 1996; Lewkowicz 1988; Matthews et al. 1993; Matsuoka 2004).

Solifluction sheets are relatively smooth and continuous debris mantles that cover large areas up to several square kilometres (Washburn 1979: 214; Ballantyne & Harris 1994: 205–212). Non-sorted solifluction sheets are partly or totally vegetation covered and sorted sheets have stony riser or they may be block-covered (Fig. 11; Ballantyne & Harris 1994: 209). Washburn’s (1979: 219) block slopes and partly block fields are similar to the boulder sheets and can be included into this class (cf. Dahl 1966). In solifluction sheets, the whole slope is in a rather uniform movement and they may terminate downslope in regular risers i.e. solifluction terraces (Matsuoka 2004: 986). Solifluction sheets are generally more common in gently sloping polar regions but they can also be found in mountain areas (e.g. Francois & Bertran 1997). Topographically, sheets locate typically at upper slope areas (Ballantyne & Harris 1994: 205–212).

Figure 11. Sorted solifluction sheets on the eastern and southeastern slopes of Suombatoaivi fell (69°38'5"N, 26°12'10"E / 430–500 m a.s.l. / 14th of August 2002).
tyne & Harris 1994: 205). According to French (1996: 156) they are the least studied but the most widespread solifluction landforms.

Solifluction terraces, also termed benches by Washburn (1979: 214–215), are up to three metres high terrace-like landforms often situated in valley-floor or in other similar topographical locations where the slope gradient decreases (Ballantyne & Harris 1994: 115, 205–206). The longest dimension of the terraces tends to be parallel to the slope and they develop on the slopes or foot of the slopes where the movement rates are relatively uniform along the contours. Vegetation, which has a restraining effect upon movement, can assist the soil thickening and terrace growth (Benedict 1976: 60; Washburn 1979: 214–215). Features have been under investigation, for example, by Dongxing et al. (1993) in Qinhai-Xizang Plateau, China. In general, non-sorted solifluction terraces are more widely distributed and more common than sorted features (Benedict 1976: 60).

Solifluction lobes have a tongue-like appearance with relatively steep frontal riser up to 1.5 m high (Washburn 1979: 216; Matsuoka 2004: 986). Lobes occur often on relatively steep mountainous regions where the flow is channelized (Benedict 1976: 60) but they have been described from different periglacial environments (French 1996: 156). After Matsuoka (2004: 986) the lobes are the most widespread solifluction features and non-sorted are more common than sorted ones (see Benedict 1976: 60). The solifluction lobes have been studied, for example, by Nesje et al. (1989), Yamada et al. (2000), Hugenholtz and Lewkowicz (2002), Matsumoto and Ishikawa (2002) as well as Jaeschke et al. (2003).

Solifluction streams are narrow linear deposits of debris or coarse block material (Washburn 1979: 216). Most of the described solifluction streams have been sorted block streams (e.g. Andersson 1906: 97–104; Washburn 1979: 219; Åkerman 1980: 105; Tyurin 1983; Harris et al. 1998; Boelhouwers et al. 2002; Boelhouwers & Sumner 2003). Instead, the descriptions of non-sorted streams are rather limited (e.g. Washburn 1947: 88–96).

Ploughing blocks, also termed ploughing boulders, are a kind of solifluction feature consisting of isolated, commonly boulder-sized stones that leave a linear trough upslope and form a low ridge downslope (Fig. 12). The size of the depression and ridge are directly connected to the size of the block (Washburn 1979: 223; Hall et al. 2001: 223). Ploughing blocks have been described mainly from the

Figure 12. Ploughing block with downslope ridge west of Guivi fell (69°37′14″N, 26°22′25″E / 480 m a.s.l. / 19th of June 2002). The backpack is 45 cm high.
alpine region (e.g. Tufnell 1972; Reid & Nesje 1988; Ballantyne & Harris 1994: 216–218; Ballantyne 2001; Berthling et al. 2001). By contrast, with ploughing blocks, which move faster than the surrounding material, blocks which impede solifluxion are termed braking blocks (Fig. 13). Soil, stones and vegetation can be piled up on their upslope side and a depression can be created on the downslope side of the block (Åkerman 1980: 105).

Debris flows are rapid mass movements of water saturated (10–50%) soil material (Innes 1983: 469–470, van Everdingen 2005: 16). For example, Brunsden (1979) has classified them into catastrophic, hillslope and valley-confined flows. Extreme rainfalls of high intensity trigger debris flows during the summer or autumn (Ballantyne & Harris 1994: 118). They often start as a debris slide but quickly the movement changes from sliding to viscous slurry flow. The resulting debris flow track can be ribbon-like, flanked by bouldery levées and terminate in a few metres to 20 m wide lobate front (Rapp 1986: 59–60). Debris flows occur in mountainous environments but they are most common in periglacial regions (e.g. Rapp 1986; Albjär et al. 1979). They are attributed to weathering and falling of rock material from the rock faces (Fig. 14). The rock material in the talus has fall sorting, that is, the largest blocks rest at the base of the talus and the smaller blocks and stones cover the middle and top parts of the formation. If the cliff face is relatively low there can also exist reverse sorting. Stratification of the talus tends to be poor to absent (Washburn 1979: 231–234). Talus sheets, talus cones and coalescing talus cones are different type of talus landforms. Secondary processes such as snow avalanches, slushflows, debris flows and protalus rock glacier formation can modify talus

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Figure 13. Large (one metre high and over two metres wide) block preventing the soil creep on the slope of Guivi fell (69°37’18”N, 26°24’33”E / 515 m a.s.l. / 18th of July 2004).

### 2.2.5 Periglacial weathering features

Weathering processes are probably more complicated than previously thought in periglacial environments (e.g. Ballantyne & Harris 1994: 163; French 1996: 7, 40–45). Furthermore, the role of chemical denudation may be underestimated (e.g. Rapp 1960; Thorn et al. 2001). Traditionally researchers have concentrated on frost-weathering (McGreevy 1981; Lautridou & Ozouf 1982; Matsuoka 2001b; Hall et al. 2002), that is disintegration and breakup of soil or rock material by the combined action of frost shattering, frost wedging and hydration shattering (van Everdingen 2005: 30). However, the exact mechanics of frost weathering are still incompletely understood despite several hypotheses have been presented (for summary see Ballantyne & Harris 1994: 163–165). Herein the focus will be on the landforms produced by different weathering processes.

In general, block fields can be divided into autochthonous that consists mainly of the products of *in situ* weathered bedrock, and allochthonous, in which boulders have some other origin, for example glacial (Ballantyne & Harris 1994: 173). The periglacial block fields are surficial layers of moderate-sized or large angular shattered rocks formed in cold environments (Washburn 1979: 219; van Everdingen 2005: 6–7) and they are mainly autochthonous. According to Rudberg (1977: 94) blocks should cover over 50% of the land surface in the block fields. Block slopes are not treated here because they have distinct connection to frost creep and gelification processes and were described among the solifluction landforms (cf. Washburn 1979: 219). Important processes in the formation of the block fields are mechanical frost-weathering, eluviation of fines, frost sorting and solifluction (Fig. 1; Washburn 1979: 219–221). However, the age and genesis of many extensive fields around the world is problematic (for summary see French 1996: 236). Dahl (1966), Klemann and Borgström (1990), Nesje and Dahl (1990) and Dredge (2000) among others, have studied block fields.

A tor is a residual mass of bare bedrock that rises above its surroundings, is isolated by freefaces on all sides, and owns its formation to differential weathering and mass wasting (e.g.
Linton 1955: 476). Sizes of tors range from a few metres to tens of metres and they occur often in upland areas on summits and slopes (Fig. 15; Washburn 1979: 78). Different genesis for the formation has been suggested (e.g. Linton 1955; Pullan 1959; Demek 1964; Dahl 1966; Selby 1972). Proposed processes include frost action, mass wasting, wind action, and sub-surface weathering and later exhumation (Fig. 1; Washburn 1979: 78). Tors may have various origins and may evolve under different climate conditions (French 1996: 236–238). In general, tors are common in periglacial areas but tors cannot be kept as clear indicators of periglacial environment (e.g. see Embleton & King 1975: 174–175; French 1996: 238).

2.2.6 Nival phenomena

Nival phenomena are often associated only with the erosive nivation process despite the fact that depositional processes and landforms such as niveo-eolian phenomena (e.g. Washburn 1979: 266–267) and protalus ramparts (e.g. Washburn 1979: 234–235; Ballantyne & Harris 1994: 236–240) also exist. However, depositional phenomena are not treated here because of their infrequency in Fennoscandia (e.g. Seppälä 1987).

Nivation is not a single process but rather a collective term describing the erosional processes related to the snow patches or snow-banks (Thorn 1988: 10–11). It is the combined action of intensive freeze-thaw activity, enhanced chemical weathering, slopewash and transport of debris by solifluction (Thorn 1988: 11–17; cf. Fig. 1). In general, the zone of effective erosion is around the edges of a snow patch where meltwater is available but the ground is not protected with insulating snowcover against atmospheric freeze-thaw cycles (Embleton & King 1975: 130). Further information on the problematic nivation phenomena can be obtained from Lewis (1939), Thorn (1979, 1988), Thorn and Hall (1980, 2002) and Christiansen (1998). Thorn (1988: 26) recommended not to use the term nivation because it is rarely possible to assess the degree to which nivation has modified the location of a contemporary snow patch, however, it has still been relatively widely used in the scientific literature (e.g. Ballantyne & Harris 1994: 245).

Nivation [or snow accumulation (Thorn 1988: 27)] hollows are shallow depression- or step-like features often ranging from a few metres to several tens or even hundreds of metres length and width (e.g. Cook & Raiche 1962; Embleton & King 1975: 135; Ballantyne 1978). Nivation hollows develop often along
lee slopes where the snow is forming large snowbanks (Embleton & King 1975: 135). Lewis (1939: 153) recognised three different nivation hollow types: transverse, longitudinal, and circular. Transverse hollows (nivation benches) are step- or terrace-like features cut into the hillside. They are the most common nivation features (Åkerman 1980: 106). Terrace-like nivation hollows can be initial stages of cryoplanation terraces (e.g. Priesnitz 1988).

Longitudinal nivation hollows follow the direction of maximum ground slope and they are generally associated with small stream courses (Fig. 16; Embleton & King 1975: 137; Åkerman 1980: 108). Circular nivation hollows are largely independent of structural or water-eroded features and they occur more often on gently sloping ground. The diameter of the circular features can range from a few tens of metres up to one kilometre. The largest circular hollows are called nivation cirques (e.g. Watson 1966) and resemble real cirques formed by glaciers. A continuum between large snow patch hollows and glacial cirques probably exists (Embleton & King 1975: 138, 142-143; Thorn 1988: 22-23).

Stone pavements consist of closely packed stones or boulders whose flat surfaces are uppermost and at a level with each other. The sizes of the features range from a few metres to some tens of metres. Common occurrence areas are on valley floors, near lakes or streams, and below breaks of slopes in different periglacial environments (Embleton & King 1975: 143; Washburn 1979: 173). The origin is incompletely understood but supposed processes responsible for the formation are upfreezing of stones, ground saturation and removal of fines by meltwater, the rotation and shifting of the stones in the saturated ground under their own and overlying snow and icing weight (Washburn 1979: 173). For example, Mackay and Mackay (1976) and Christiansen (1998) have studied stone pavements.

2.2.7 Aeolian processes and landforms

Aeolian activity produces both erosion and depositional features in cold climates (e.g. Niessen et al. 1984; Seppälä 2004b). Deflation depressions (Fig. 17) and surfaces, ventifacts (e.g. Schlyter 1995), pavements (e.g. Schöhage 1969), wind patterned ground and turf-banked terraces (for review see Ballantyne & Harris 1994: 261-267) are different types of erosion features. Deposition processes can form fea-
tures such as sand dunes (e.g. Carter 1981), cover sands (e.g. Maarleveld 1960) and loess-like silts (e.g. Péwé 1955; Pye 1984). Herein the focus will be on the deflations and dune landforms and more about aeolian phenomena in periglacial regions can be obtained from Åkerman (1980: 228–257), Koster (1988) and Seppälä (2004b).

Wind deflation is the blowing out of sand and finer particles from the ground cover and their transportation by the wind (French 1996: 206). The resulting features are different sized deflation surfaces and depressions (Fig. 17). The deflation surfaces are from less than one metre to tens of metres wide and only a few centimetres to metre deep areas, whereas the deflation depressions are from less than one metre to over ten metres deep and up to hundreds of metres in diameter (e.g. Seppälä 1995b: 799; French 1996: 206). Deflation of the fine sand deposits usually ceases when the level of ground water or underlying ground moraine is reached. At the bottoms of the deflation basins can be stone pavements (cf. Chapter 2.2.6; Seppälä 2004b: 174). Wind can also erode peat deposits and features such as palsas (e.g. Fig. 4; Seppälä 1972b; Luoto & Seppälä 2000; Seppälä 2003a).

In periglacial regions, sand dunes have been mainly formed during Pleistocene deglaciation and are inactive and stabilized nowadays (Embleton & King 1975: 191). However, in some areas, dunes are still developing (e.g. Seppälä 2004b: 197–206). The sizes of the dune ridges range from less than one metre to 30 m high and up to several hundreds of metres or even kilometres long. Furthermore, the dune areas range from less than one hectare to several thousands of square kilometres (Washburn 1979: 264–265). In general, the most common dune type is parabolic where arms are pointing away from the direction of movement (e.g. Seppälä 1971, 1972c; Carter 1981; Koster 1988). Linear features (transverse and longitudinal) are rather seldom.

Figure 17. Deflation depression formed in a sand dune on the eastern slope of Geatgielas fell (69°27'2"N, 26°22'22"E / 410 m a.s.l. / 24th of June 2003).
3 STUDY AREA

3.1 Location and topography

The study area is located in the northernmost Finnish Lapland over 300 km north of the Arctic Circle close to the Norwegian border (SW corner 69°22'39"N, 25°58'46"E and NE corner 69°38'55"N, 26°28'54"E) (Figs. 18 & 19). The cover of the study area is 600 km² (20 x 30 km). The topography of the Báišduattar – Æilegas region is characterized by gently sloping fells (Figs. 19 & 20). The fell summits are relatively flat and rounded although tors are found in many places (Kaitanen 1969, 1989; Fig. 15). In general, valleys between the fells and groups of fells are wide and flat-bottomed, but there are also some relatively steep-sided valleys such as the polygenetic Geavvu canyon in the east (see Figs. 14 & 19). Small-scale topographical variation prevails in the valleys where glaciofluvial accumulations are abundant and on the slopes where the glacial melt water channels dominate (Figs. 20 & 21).

Elevations in the area range from 110 to 641 m a.s.l. with a mean of ca. 370 m calculated from the digital elevation model (see Chapter 4.1.3). The highest fells are Guivi (640.5 m a.s.l.), Guovdoaivi (ca. 620 m a.s.l.) and Lánká (619.8 m a.s.l.) (Fig. 19). Furthermore, there are about 15 other over 550 m high fells mainly located in the northeastern part of the region. Most of the study area is in a relative narrow altitude zone, because over 60% of the area is located between 300 and 400 m a.s.l. Relative relief varies locally from less than ten to more than 200 m.

3.2 Bedrock and general geology

Geologically, the study area belongs to the Pre-Cambrian ca. 1.9 billion years old granulite complex (Mikkola 1941; Meriläinen 1976). The main rock types are fine- and coarse-grained garnet-quartz-feldspar gneisses, but there exist small areas of quartz, diorites, granodiorites and gabros (Meriläinen 1965). Present relief of the study area has formed by tectonic block movements and denudation phases during the last 25 million years. The fell groups of the Báišduattar and Æilegas are two of the seven horsts that have been lifted up by block movements in the Tertiary 25–10 million years ago (Mikkola 1932: 31–34; Tanner 1938: 218). Afterwards, the tectonic blocks have split and erosion has rounded them into separate fells and groups of fells. Some of the split lines can be seen in the present landscape as high angle shear zones and fracture lines (Fig. 20; Geological map 1:1 000 000 1987).

3.3 Weichselian glaciation, deglaciation and soil types

Glaciers in the Weichselian have shaped the general topography of the area and formed surficial deposits during the last twenty thousand years. However, the glaciers eroded the bedrock only slightly because of three main reasons (Kaitanen 1989: 7–10). Firstly, the study area is located in an interlobate zone between the Finnmark and Tuloma ice streams where the ice flow was very weak (Punkari 1996: 16). Secondly, Kaitanen (1989: 7) estimated that the ice thickness could not exceed 1200 m even during the glacial maximum and the ice cover was mostly less than 600 m thick during the other glacial phases. Thus, the thickness of the ice on the fells has generally been less than 400 m. Thirdly, Kaitanen (1989: 7) also suggested that the ice could have been cold based, which would prevent basal erosion (cf. Hättestrand & Stroeven 2002). Altogether, the weak erosion of the continental ice sheet is clearly demonstrated by the presence of numerous preglacial weathering remnants (e.g. Kaitanen 1969; Fig. 15).

The deglaciation of the Báišduattar – Æilegas area started ca. 10 000 years BP (uncalibrated). The ice margin retreated approximately
60–250 m a⁻¹ toward the southwest and the ice thinning ranged from one to five metres per year depending on the deglaciation stage (Seppälä 1980: 319; Koskinen 2005). The local topography had a significant effect on the deglaciation pattern. Therefore, the retreat rate of the ice could have been less than generally estimated in the fell areas. Towards the end of the deglaciation the ice mass became more or less stagnant due to the thin ice cover and rugged topography. At first, the summits of the fells were released under the continental ice and were subject to frost processes in severe periglacial conditions. When about half of the study area was deglaciated ice-dammed lakes formed in the central parts of the area (Koskinen 2005: 48). They existed probably only from some years to at the most a few decades (e.g. Seppälä 1980). The whole study area was finally released from under the ice ca. 9850–9800 years BP (Seppälä 1971: 61, 1980: 318).

Glacigenic till is the predominant soil type covering roughly 80% of the study area but this estimate includes blocky surficial material as well. On the fells and slopes the moraine layer is thin (0–3 m) but at the bottoms of the valleys its depth may increase up to ten metres (Syrlä 1964). Block fields are more frequent on the fell slopes and above the treeline but they are not, like in many parts of Northern Finland, abundant on the fell summits (e.g. Fogelberg & Seppälä 1986). The blocks are generally relatively rounded and have commonly a glacigenic origin although also small frost shattered block fields exist in the area. Most of the glacigenic deposit is basal till but there are some areas in the northeast and south were the hummocky ablation moraine dominates.
Sand and gravel deposits, which cover ca. 7% of the area, are mainly located in the valleys where the glaciofluvial action was predominant during the deglaciation. At some locations, fluvial and aeolian processes have affected the glaciofluvial deposits and formed secondary sand and gravel deposits. Sand dunes can be found in the southeast and fluvial deposits in the major river valleys in the northern and northeastern part of the study area (Fig. 19). Three considerable esker systems (see next chapter 3.4) and some smaller glaciofluvial landforms such as kamehummocks occur in the region. In general, the material of the glaciofluvial deposits is sorted relatively poorly. The organic deposits are prevalent in the wide flat-bottomed valleys in the central parts of the study area. The total cover of peat is about 11%. Peat layers are generally thin (less than one metre) but in the extensive palsa mires, for example in Biesjaaggi and Čullovejeaggagi mires, the deposits can be up three metres thick (e.g. Lappainen & Hänninen 1993). Silty soils are rather common in the valleys between Áitečohkka and Stuorra Biesvárrri fells. The silty sediments deposited at the bottoms of the temporary ice-dammed lakes during the deglaciation (see above) and are often covered by organic material at present.

3.4 Geomorphology of the Báíšduattar – Áilegas

General relief of the study area is governed by bedrock topography, as usual in Northern Finland (Fogelberg & Seppälä 1986), although long term fluvial erosion has modified the landscape significantly in the northwest (Figs. 19 & 20). The medium-scale topographical variation is mainly caused by glaciofluvial action and most of the small-scaled landforms are frost formed (cf. Seppälä 2005b). Bedrock landforms are not very abundant but tors are found on many fell summits (e.g. Fig. 15; Kaitanen 1989: 9). In addition, a few variously oriented fracture lines and valleys occur in the area (Fig. 20). The most significant is the Geavvu canyon, which is also modified by glaciofluvial processes.

In general, glacial landforms are rare due to weak glacial erosion and unfavourable depositional conditions. However, pre-Weichselian cirque-like bedrock landforms (Kaitanen 1969: 46) and a few large drumlinoids occur in the study area (Map of Quaternary geology 1:1 000 000 1988). Kettle holes that can be over 20 m deep are rather common glacial landforms. Furthermore, hummocky moraines dominate relief variability in some areas, for example near the Sieddejávrrit and Básijávri lakes. More detailed description of the textural and structural characteristics of the glacial depositional landforms is given by Karzewski (1975).

Glaciofluvial action was very intensive during the deglaciation (e.g. Seppälä 1980). Stagnant ice produced a huge amount of melt water that grooved a number of subglacial, marginal and extramarginal channels into the moraine cover and even into the surface of bedrock (Koskinen 2005). The most abundant glaciofluvial channel types are marginal and submarginal, which predominant on the fell slopes (Fig. 21). At the higher altitudes, between the fell summits, occur many overflow channels that may continue as subglacial channel into the valleys. Extramarginal channels are in the minority and they usually locate on outwash plains.

Glaciofluvial deposition landforms are relatively abundant but their distribution is limited to the valleys (e.g. Seppälä 1993a: 270). Luopmošjáguotkku esker in the southern part is a typical 10–30 m high steep-sided mid-valley esker (Fig. 22). It is oriented from southwest to northeast representing the general retreat direction of the ice edge during the deglaciation. Kettle holes and kamehummocks (5–25 m high) dominate most of the marginal areas, which are often better sorted than the esker ridges. In the middle part of the study area there is situated a discontinuous and ca. 15–35 m high esker system that is mainly southwest northeast -oriented. The northernmost west-east -directed Goike-Sitnogohpi esker has more undulating topography than the previous resembling kame-esker. The hummocks
Figure 19. Generalised map of the study area. The forest and mire data are obtained from biotope database (© Metsähallitus 2006). The vertical interval of contours is 20 m (© National Land Survey of Finland, Licence number 49/MYY/06).
Figure 20. Three-dimensional terrain view of the study area. The terrain view was produced using the shaded relief surface model derived from the created digital elevation model (sun angle = 45°, azimuth = 315°) (Chapter 4.1.3).
are from five to 25 m high and the tops are usually deflated. In addition, kame-landforms, glaciofluvial deltas, outwash plains and small valley trains exist in the study area.

The ice-dammed lakes in the central and southern parts of the area have left several shore marks commonly between the altitudes of 330 and 360 m a.s.l. (Seppälä 1993a; Koskinen 2005: 48). The long-term fluvial action has shaped the topography clearly more than the shore processes. Preglacial fluvial action has grooved over 100 m deep river valleys to the northwest (Figs. 19 & 20). At present, the Áhkojohka and Čullovejohka rivers have a minor role in the relief alteration despite the fact that spring floods can be very drastic (see Chapter 3.7).

Sand dunes and deflations represent aeolian landforms of the study area. The dunes were formed relatively soon after the deglaciation, whereas deflation is the most significant aolian process nowadays (e.g. Seppälä 1971). The
sand dunes are located in the southeastern corner east of the Luopmošjáguotkku esker that offered material for wind transportation. The dunes are mostly parabolic and longitudinal indicating the direction of the affective winds from the northwest (Seppälä 1971: 15, 1993a). Wind has not only eroded the dunes and glaciofluvial landforms but also morainic hummocks. Seppälä (1971) gives a detailed description of the aeolian processes from an area about 20 km southeast of the Báišduattar – Åílegas area.

Biogenic processes have mainly levelled the general topography but together with the frost action they have generated small-sized cryogenic hummocks (van Vliet-Lanoë and Seppälä 2002) and permafrost cored palsas. At present, the frost phenomena are one of the most efficient processes that modify the land surface in the study area. The main processes on the level ground are cryoturbation and frost sorting and on the slopes solifluction. The human influence on the topography has been very limited throughout history. The most widespread but indirect modification has been reindeer husbandry. The area is locally overgrazed (Heikkinen & Kalliola 1989), which has enabled small-scale water and wind erosion. Reindeer may also affect the formation of non-sorted patterned ground (Chapter 6.2.3).

3.5 Previous periglacial research in the study region

Previous periglacial studies in the Báišduattar – Åílegas area have concentrated on the specific processes or landforms and no one has performed an extensive regional geomorphological mapping. Söderman (1980) studied mainly slope processes in North Finland and he had one study area located in the fell group of Åílegas. King and Seppälä (1987) investigated permafrost distribution in Northern Finland with geoelectrical soundings and they had three experiment sites in Åílegas. Seppälä (1993a) has described the properties of sand dunes of the southwestern parts. Kejonen (1994) studied the present and ancient solifluction in the Åílegas area using different types of measuring lines, a laseroptical geodimeter, block towers dug in the ground, pollen analysis and radiocarbon dating. Luoto and Seppälä (2002a, 2003) have modelled palsas and thermokarst ponds and their study area included the Báišduattar – Åílegas area. Seppälä (2003a) studied surface abrasion of palsas near Lake Áhkojávri. In the same area Rönkkö and Seppälä (2003) investigated the active layer of palsas using field measurements, surface characteristics and statistical analyses. Hjort and Seppälä (2003) described briefly topographical characteristics of active and inactive patterned ground in the northeastern part of the present study area. Moreover, Luoto and Hjort (2004, 2005, in press) as well as Hjort and Luoto (2005, 2006) modelled with different statistical techniques the distribution of patterned ground in the same region.

Most of the periglacial studies performed near the Báišduattar – Åílegas have been carried out in the Skallovarri – Vaisjeaggi area some 45 km to northeast from the present study region. For example, Seppälä (1982a, 1990, 1994b, 1995a, 1998, 2003b, 2005c) has made numerous field experiments with pounus and palsas in the area. In addition, the studies of van Vliet-Lanoë and Seppälä (2002) as well as Luoto and Seppälä (2002b) focused on pounus. Some investigations have been carried out in the Muotkatunturit (Muotkuodduara) and Kaamasjoki (Gámasjohka) – Kiellajoki (Giellasjohka) regions, which are located south and southeast of the study area. For example, Piirola (1969, 1972) studied patterned ground and Kejonen (1979) solifluction phenomena in the Muotkatunturit fell area, and Seppälä (1971) aeolian processes in the Kaamasjoki-Kiellajoki river basin. Furthermore, Ruuhijärvi (1962) has investigated palsas in Petsikko ca. 25 km to the east and Hietaranta and Liira (1995) as well as Liira and Hietaranta (1998) who have studied talus slopes in the Geavvu river valley close to Kevo research station. Vorren (1967), Svensson (1971), Åhman (1977), Jahn and Siedlecki (1982), Malmström and Palmer (1984) as well as Meier (1987, 1991) are examples of...
preglacial studies conducted in northern Norway fairly close to the present study area.

3.6 Past and present climate

Northern Fennoscandia is climatically a unique area when compared to the other areas at corresponding latitudes. The climate is relatively mild due to the Gulf Stream that brings heat energy from the Gulf of Mexico to the North Atlantic. Part of this energy is transported to Northern Fennoscandia by cyclones and westerly winds (Arvola 1987). Light and radiation conditions at the study region are typical of high-latitude areas, respectively. For example, the sun does not rise above the horizon between 26th of November and 15th of January and the sun does not set between 17th of May and 26th of July.

Climamorphologically the region belongs to the zone of discontinuous permafrost (Seppälä 1997b). Based on the geoelectrical soundings, permafrost is probably widespread at the altitudes above 500 m and it can be up to 50 m thick (King & Seppälä 1987, 1988). In the valleys, only sporadic permafrost is present. A short review of the climate history of the Holocene is made before a more detailed description of the present climate of the study area is given, because periglacial processes act over a wide time span (Washburn 1979: 15) and the landforms can be stabilized and again reactivated because of regional or global climate change.

The most favourable condition for the periglacial processes was after the deglaciation ca. 9800 years BP before the area was covered by vegetation. However, this period was quite short but still long enough to produce distinct marks of frost action (e.g. Kejonen 1997; cf. Cook-Talbot 1991). The relatively cold climate phase lasted until 8700–8600 BP and it is estimated that the mean air temperature could have been ca. 2°C lower than at present (Seppälä 1971: 73–79). The colder period was followed by a long (8300–4000 BP) warmer phase with the Holocene thermal maximum at ca. 8000–6000 BP when the temperatures may have been 1.5–3°C and treeline 200 m higher than at present (Eronen 1979: 108–110; Seppä & Birks 2002: 195–197; Kultti 2004: 24). Between 5000 and 4500 BP the temperature and treeline started to degrade (e.g. Kultti 2004: 24–25) and the climatic conditions were again more favourable for the periglacial processes (Kejonen 1997: 103). Besides the climatic cooling, the lowering of the treeline was also attributed to the glacio-isostatic land uplift that has been about 60 m after the climatic optimum in the study area (Kejonen 1994: 53). During the last 4000 years climate has been relatively cool with some colder stages, for example, between 2900 and 2100 BP (Kultti 2004: 26) and during the Little Ice Age ca. 150–400 years ago (e.g. Karlén 1976; Matthews & Briffa 2005).

The present climate of the study region is subarctic (Seppälä 1976a) and relatively continental despite the distance to the Arctic Ocean is only about 100 km (Tuhanen 1980: 78). Climatological characteristics of the study region are presented based on the measurements conducted at the Kevo Meteorological Station (69°45′N, 27°01′E), which is located about 35 km apart from the study area to the northeast (Fig. 18; Table 6). It is notable that the climate parameters are measured in a forested valley at 107 m a.s.l. and may give too generalised a view of the climate of the Bäisduttar – Åilegas area (e.g. Seppälä & Hassinen 1997). Therefore, climatological features of fell areas are also discussed briefly.

The following meteorological data are taken from Climatological Statistics in Finland 1961–1990 (1991) and Atlas of Finland (1987), if not otherwise mentioned. The mean annual air temperature (MAAT) was –2.0°C during the period 1962–1990 and it has varied between +2.3°C and –6.7°C. The warmest month, on average, was July (12.7°C) and coldest January (–15.7°C). The lowest measured temperature was –47.9°C (1966) and the highest was +32.9°C (1988). Mean of the freeze index was –2052.7 (std = 393.4), mean of the thaw index was 1372.7 (std = 108.2) and mean of the total temperature sum was –681.6 over the period 1980–1991 (for more details see Seppälä & Hassinen 1997: 154–155). In gener-
al, these values indicate the presence of rather diverse set of periglacial phenomena (Harris S.A. 1982a).

On average, there are 230 frost days (maximum temperature of day < 0°C) in a year. The mean number of the frost days at ground level (minimum temperature at ground level < 0°C) is 258 and the ground level frost can occur in summer months too. October and May are the most important months when the freeze-thaw–cycles are considered since at these times temperatures fluctuate on either side of 0°C all the time (Seppälä 1976a: 3). According to Liira and Hietaranta (1998: 4), there has been on the average ca. 80 freeze-thaw–cycles per year. Frost begins to form between the end of September and beginning of October. Maximum soil frost depth in till ground is about 210–220 cm at sites cleaned of snow and in open snow covered areas ca. 130 cm, but frost can occur considerably deeper when snow cover is thin (cf. Seppälä 1976a: 9–10). The seasonal ground frost remains in the open areas generally until mid-June.

The mean annual precipitation was 395 mm and the average number of rainy days in a year was 231 (63%). The mean cloud cover was 5.9 octas (70–75%) and the mean relative humidity of air was ca. 80%. Precipitation was highest in July-August when about 31% (122.5 mm) of the total rain amount of the year fell. The driest season was February-May when the mean precipitation varied between 17.4 mm and 23.2 mm per month. On average, there was 173 days when snowfalls occurred and only July and August were without any snowfall. Permanent snowcover develops after the end of October and it will last on open areas generally until 20th of May and in forests until 25th of May (on average 210 snowcover days). The mean maximum thickness of snow was 69 cm.

The mean annual wind speed was 2.9 m/s and the percentage of calms was 12. The predominant wind direction was southeasterly, 29% of the winds with a mean of 2.7 m/s, but the strongest winds blew from the northwest (mean = 4.6 m/s). The winds are, in general, stronger in winter and the highest monthly mean is obtained in February (5.3 m/s). However, the wind measurements made at the Kevo Meteorological Station should be treated with caution because topography has a significant effect on the wind pattern (see Mansikkanemi & Laitinen 1990; Seppälä 2002).

The climatological conditions of the Báisduattar – Áilegas area, especially above the treeline, may differ considerably from circum-

<table>
<thead>
<tr>
<th>Climate parameter</th>
<th>Mean annual</th>
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<tbody>
<tr>
<td>Air temperature</td>
<td>-2.0°C</td>
</tr>
<tr>
<td>Freezer / thaw index</td>
<td>-2052.7 / 1372.7</td>
</tr>
<tr>
<td>Total temperature sum</td>
<td>-681.6</td>
</tr>
<tr>
<td>Number of frost days (air / ground surface)</td>
<td>230 / 258</td>
</tr>
<tr>
<td>Frost depth (with / without snowcover)</td>
<td>130 / 210 cm</td>
</tr>
<tr>
<td>Precipitation</td>
<td>395 mm</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>80%</td>
</tr>
<tr>
<td>Number of snowcover days</td>
<td>210</td>
</tr>
<tr>
<td>Maximum snow thickness</td>
<td>69 cm</td>
</tr>
<tr>
<td>Wind speed</td>
<td>2.9 m/s</td>
</tr>
</tbody>
</table>
stances prevailing in the forested valley where the Kevo Meteorological Stations is located (e.g. Huovila 1987a; Seppälä & Hassinen 1997). Fair differences could be expected to occur in the temperatures, snow distribution and wind speeds. The average wind speed has been measured to be significantly higher on the fells (Mansikkaniemi & Laitinen 1990: 14–15). The distribution of the snow is very dependent on the wind speed and direction, vegetation cover and topography (e.g. Mckay & Gray 1981: 154–166). For example, the snow cover can be in the birch forests from 50 cm to 70 cm, on the alpine heaths 20–30 cm (Kärenlampi 1972: 64), but on the fell summits snow thickness can be less than 5 cm and it can occasionally disappear during the winter (e.g. Kallio et al. 1969; Clark et al. 1985). In general, the snow thickness and duration have a significant effect on the ground temperatures and thus on frost activity (e.g. Goodrich 1982).

The MAAT of the study area could be at maximum 3.45 degrees lower on the highest fells than at the Kevo if only adiabatic lapse rate, but other factors can also obscure the temperature distribution (e.g. Huovila 1987a; Holgrem & Tenow 1987). The air temperature is measured to be on the alpine heaths from two to 3.5°C lower than in the forested valleys in summer, but in winter, the fells can be generally 1–2 degrees warmer due to inversion and cold air ponding in valleys (Kärenlampi 1972: 56–61; Helimäki 1974: 23–25). The difference can be over 20°C in midwinter but these extreme situations are rather temporary (Huovila 1987b: 24). Taking into account the previous facts, the MAAT of the study area is estimated to be between −2°C and −4°C depending on the altitude. However, it is worth of noting that considerable valleys exist above the treeline in the northeast where the cold air can drain during the inversions and thus the coldest locations do not have to be summit areas.

3.7 Hydrology

The study area is on the watershed of the Tenojoki (Deatnu) and Paatsjoki catchments. About 85% (518 km²) of the area is a part of the Tenojoki drainage basin (total area = 14 891 km² and percentage of lakes, L% = 3.1) and the rest of the area (82 km²) belongs to the Paatsjoki catchment (14 512 km², L% = 12.4) (Ekholm 1993). The main rivers are the Deatnu (only 2 km in the study area), Ākojohka and Čullovejohka (Fig. 19). A number of smaller streams occur in the area and 20–25% of them are temporary, i.e. they dry during the summer (Anonymous 2002). The largest lakes are Stuurrajávri (2.53 km²), Nuorttajávri (1.94 km²) and Biesjávrrit (0.57 km²) and the total cover of the lakes and ponds is ca. 8 km² (L% = 1.3) (Fig. 19).

Hydrologically, the Báišduattar – Áilegas area is a typical subarctic region with a high but short-term flood peak (Fig. 23). The short and drastic spring floods are the result of rapid snowmelt and the lack of significant lake basins that would attenuate flood peaks. The subarctic nature of the Deatnu river is displayed by the high spring flood discharge, which is on average ten to fifteen times higher than wintertime discharge (Mansikkaniemi 1970: 6, 1972: 15–16). In addition, the rise of the water level in the Deatnu river can be remarkable. Generally, the water rises during the spring floods from two to four metres over the normal level, but it may rise from five to ten metres because of ice dams (Mansikkaniemi 1972: 16).

3.8 Vegetation

The vegetation of the area is characterized by subalpine mountain birch forests (Betula pubescens ssp. czerepanovii) and alpine heaths (Fig. 19). In the lower altitudes and in the deep river valleys occur small scattered scots pine (Pinus sylvestris) forests. In general, forests cover about 37% of the study area (Anonymous 2002). In the mid-sixties, the larvae of the moth Epirita autumnata caused extensive birch forest damage in northernmost Finland (e.g. Kallio
Consequently, most of the birches in the southeastern part of the study area were defoliated (Fig. 24), although the cover of the damaged area was only ca. ten square kilometres (Seppälä & Rastas 1980). In general, the recovery of the damaged areas has been rather slow (Fig. 24; e.g. Heikkinen & Kalliola 1989: 34).

Based on the vegetation zonation, the region belongs to the subarctic zone north of the northern limit of the continuous pine forest (e.g. Hustich 1960) or to the orohemiarctic zone (Ahti et al. 1968). In the continentality-oceanicity division, the area is situated in the continental sector (e.g. Oksanen & Virtanen 1995). The birch forests are mainly different kinds of Empetrum types in the study region (see e.g. Heikkinen & Kalliola 1989). The most common types are Empetrum-Lichenes and Empetrum-Lichenes-Pleurozium birch forests and the former usually forms the altitudinal forest limit. The treeline lies generally between 360–420 m a.s.l. and the alpine vegetation occur above this elevation zone.

The barren fell areas (regio alpina) are dominated by Empetrum and Betula nana types of alpine heaths (e.g. Fig. 21; Heikkinen & Kalliola 1989). Total cover of the alpine heaths is about 270 km² (ca. 45%), but this value also includes secondary alpine i.e. subalpine heaths (for more details see Josefsson 1988; Heikkinen & Kalliola 1989: 27–28). On the fell summits, the height of the vegetation is usually from a few centimetres to 20 cm and, in the valleys, the height can exceed 100 cm. The uneven distribution of the snowcover has a significant effect on the vegetation in the alpine belt (e.g. Kalliola 1939). Mires, which cover ca. 10% of the study area (Fig. 19), belong to the palsa and subalpine mire types (Ruuhijärvi 1960). In more detail, the most common types are heathy hummocky, Salix – Betula nana and dwarf shrub bog types (Heikkinen & Kalliola 1989).
Study area

Figure 24. Only partly recovered open mountain birch (Betula pubescens ssp. czerepanovi) forest damaged by larvae of the moth Epirrita autumnata in the south-eastern part of the study area (69°23'47"N, 26°27'1"E / 340 m a.s.l. / 5th of August 2003).
4 MATERIALS AND METHODS

4.1 Modelling data

4.1.1 Resolution

The modelling resolution (i.e. the size of the modelling square utilised in this study) was 25-ha (500 x 500 m). At first, periglacial landforms were test modelled at four different resolutions (1, 4, 25 and 100 ha) (Hjort, unpublished data) but explicit performance differences did not occur when the models were compared using a critical ratio test (for more details see Pearce & Ferrier 2000). Therefore, the mesoscale resolution (cf. Summerfield 1991: 13) was chosen based on: (1) the nature of the response variable, (2) the accuracy and quality of the predictor data and (3) the previous modelling studies. Firstly, the distribution, cover and accuracy of the response affect the proper modelling resolution. For example, the use of too fine resolution increases the sample size without a concomitant increase in primary information while artificially enhancing the degree of autocorrelation and pseudoreplication in the statistical analysis (Hurlbert 1984). Secondly, the quality of the databases from which the predictors are compiled has to be taken into account (Chapter 4.1.3). Thirdly, a 25-ha resolution has shown to be appropriate in periglacial and other landscape scale modelling studies (Luoto et al. 2001, 2002; Luoto & Hjort 2004, in press; see also Niessen et al. 1992).

4.1.2 Periglacial landforms

Periglacial landforms were mapped and converted to grid-based modelling data in a five step process (Fig. 25). First, detailed stereoscopic interpretation of black-and-white aerial photographs (1:31 000) was performed to map and identify periglacial features from the study area. In addition to the aerial photographs, topographic maps (1:20 000) were used in the preliminary survey. Many of the periglacial landforms are relatively small-sized and their direct identification from the available aerial photographs is impossible and, therefore, the potential landform sites were mapped to be checked in the field. Stereoscopic photo interpretation was conducted during the springs of 2002 and 2003 and the results were drawn on the working maps (1:10 000).

Second, periglacial landforms were mapped utilising pre-mapping results and black-and-white aerial photographs (1:31 000) in the field during the summers of 2002 (18th of June–24th of October) and 2003 (10th of June–26th of October) in 100 field workdays. The positions of the features were mapped with a GPS-device (Garmin eTrex personal navigator). Landform type and activity (active/inactive) was defined visually in situ and the interpretations were documented in a notebook. The size of the mapped landform was estimated and classified into four classes: <10 m, 10–30 m, 30–50 m or > 50 m in diameter. The features less than 50 m were located with a single GPS point and, if necessary, two or several points were used to define the borders of the larger landforms. If the features size could not be estimated, for

<table>
<thead>
<tr>
<th>I</th>
<th>Stereoscopic photo interpretation</th>
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</thead>
<tbody>
<tr>
<td>II</td>
<td>Field mapping of landforms</td>
</tr>
<tr>
<td>III</td>
<td>Digitization of field mapping results and building of database</td>
</tr>
<tr>
<td>IV</td>
<td>GIS analyses</td>
</tr>
<tr>
<td>V</td>
<td>Selection of data for statistical analyses</td>
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</table>

Figure 25. The main steps of the compilation of response, i.e. periglacial, data.
example due to scattered distribution, only the location was taken with the GPS-device. Furthermore, the size measurements with a tape measure, and slope angle measurements with a Suunto clinometer, were performed for different types of small-sized landforms.

The activity of the features was defined based on the observations of lichen cover on the stones and blocks (Figs. 26A & B), rock weathering, frost heaving, general soil and vegetation disturbance (Fig. 26C) and vegetation density (Fig. 26D) (Goldthwait 1976: 34; Washburn 1979: 133; Cook-Talbot 1991: 128–130; Harris 1994: 187). Moreover, previous studies and activity measurements conducted in the region were used to gain an overall picture of the activity of a specific landform type (see Chapter 3.5). If the mapped landform had some indicator of activity, even on a relatively small area, it was classified as active (Luoto & Hjort 2005; Hjort & Luoto 2006). Also, it should be noted that a feature does not have to be recently formed to be determined active (Jahn & Siedlecki 1982; Ballantyne 1984).

Third, field-mapping results were digitized in a vector format on ortho-rectified aerial photographs utilising MapInfo Professional 7.0 software. The ground resolution of the digital aerial photographs was one metre. The location error of the ortho-rectified aerial photographs is estimated to be from three to six metres in northern Finnish Lapland (National Land Survey of Finland 2004a) but the relative error between different images was significantly more when planimetric root-mean-square error (RMSE) was calculated with 21 test sites. The RMSE was 18.0 m and it was calculated with the equation:

$$RMSE = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} e_i^2}$$

where $e_i$ is the distance difference between test points in metres (e.g. Zhang & Goodchild 2002: 76). This inaccuracy was taken into account in the selection of the modelling resolution (Chapter 4.1.1). Landform fields over 50 m in diameter were vectorized as polygons in true spatial size and shape and features less than 50 m were digitized only as points.

Attribute information was attached to each mapped landform. The final database of the periglacial landforms contained: (1) identification number (id) for each object, (2) landform type classification (indicated by code), (3) activity classification (active/inactive) and (4) size information (five classes).

Fourth, the maps of the active landforms were converted into 10 m raster grids in ArcView GIS 3.2 to calculate the cover of the features in each modelling square. The landform cover was calculated by the ZONAL function in the GRID module of Arc/Info 8.2 and the results (in hectares) were used to produce the modelling data sets. The cover information was directly used in abundance modelling, if the modelling criteria were fulfilled (see below). A binary variable (1 = present, 0 = absent), indicating the occurrence of the landform, was allocated in each modelling square. The square was selected to be ‘present’ if the cover was over zero hectares. In addition, the features without size information were converted to binary form.

Finally, landform types and modelling squares were selected for the distribution and abundance modelling. The landform should be fairly abundant to be used in statistical analyses (e.g. Guisan & Zimmermann 2000). However, the proportion of the present squares prevalence can vary considerably in binary data (e.g. McPherson et al. 2004; Segurado & Araújo 2004). In this study, the prevalence had to be 5–95%. This quite wide range was used because the other evaluation measure, namely AUC of ROC plot (see Chapter 4.2.3), is practically immune to prevalence-related artefacts (McPherson et al. 2004: 822). The abundance modelling was focused on the present squares and landforms types whose cover varied notably, respectively.

In general, water cover can hamper the detection of real causal relationships between response and predictor variables. To remove this bias all squares containing water cover should be removed but this would reduce the number of modelling squares too drastically. Thus, it was decided to remove part of the water-covered squares based on the data exploration.
and solar radiation, soil type and vegetation. In addition, a group of spatial variables were compiled to use in hierarchical partitioning (Chapter 4.2.3). In general, spatial variables can be gathered from five main sources: (1) field work, (2) digital and paper maps, (3) remote sensing, (4) maps obtained from GIS-based modelling and (5) other digital databases (Guisan & Zimmermann 2000: 156). Here, the predictors were collected mainly from the second, fourth and fifth groups (Fig. 27). The fieldwork is usually too laborious an information collection method because the predictors should be more easily obtained than the response (Guisan & Zimmermann 2000). Remote sensing (RS) provides an opportunity to collect spatially continuous information of environmental factors but RS data were not directly used in this study. However, the utilised vegetation information was based on field survey and remotely sensed data (Sihvo 2001).

In the distribution modelling, the land area should be over one hectare. In the abundance modelling, the limit was strict; the proportion of the land cover in the square should be over 95% because even relatively low water cover may cause problems in the analyses.

### 4.1.3 Predictor variables

The compilation and selection of appropriate predictor (i.e. explanatory) variables for the statistical analyses can be a complicated and difficult task without a comprehensive process-environment understanding. There are neither universal criteria nor widely accepted guidelines and hence the study aims guide the procedure. The predictors used in this study were collected from several information sources and classified into five main groups, namely topography, soil moisture, temperature and solar radiation, soil type and vegetation. In addition, a group of spatial variables were compiled to use in hierarchical partitioning (Chapter 4.2.3). In general, spatial variables can be gathered from five main sources: (1) field work, (2) digital and paper maps, (3) remote sensing, (4) maps obtained from GIS-based modelling and (5) other digital databases (Guisan & Zimmermann 2000: 156). Here, the predictors were collected mainly from the second, fourth and fifth groups (Fig. 27). The fieldwork is usually too laborious an information collection method because the predictors should be more easily obtained than the response (Guisan & Zimmermann 2000). Remote sensing (RS) provides an opportunity to collect spatially continuous information of environmental factors but RS data were not directly used in this study. However, the utilised vegetation information was based on field survey and remotely sensed data (Sihvo 2001).
The most commonly used and very versatile source for predictors in spatial modelling is a digital elevation model (DEM) (e.g. Moore et al. 1991; Franklin 1995; Etzelmüller et al. 2001; Evans 2004). Therefore, a raster DEM with 20 m grid size was calculated by linear interpolation from digital contour lines using Arc/Info’s TOPOGRID command (ESRI 1991; see Fig. 20). The utilised interpolation method is designed for the creation of hydrologically correct DEMs (Hutchinson 1993). The contour lines (5 m vertical interval) are digitized from paper copies of the Finnish topographic maps (1:20 000) (National Land Survey of Finland 2004b). The quality of the created DEM was evaluated visually and by calculating RMSE with the equation (1) from height points (n = 50) not used in the interpolation (for more details see ESRI 1991; Hutchinson & Gallant 2000: 38–39). The vertical RMSE (relative accuracy) was 2.2 m (mean error = 1.6 m).

In this study, nine pure topographical variables were calculated from the DEM using an Arc/Info GRID (Table 7). Altitude and slope angle are commonly used topographical parameters in general geomorphological (e.g. Evans 1972, 2004; Mark 1975; Moore et al. 1991) and periglacial studies (e.g. Etzelmüller et al. 2001). The altitude and slope angle are key surrogates of many different environmental factors like air temperature, snow distribution and potential energy of an area (Table 7).

A slope map of the study area was produced from the DEM by the SLOPE function in the GRID module (ESRI 1991; Fig 28A). The slope angle for each grid cell is calculated from a 3 x 3 neighbourhood using the average maximum technique (e.g. Zevenbergen & Thorne 1987). Mean altitude in metres and mean slope angle in degrees were calculated directly from the DEM and the slope map by the ZONALMEAN command (ESRI 1991). Standard deviation of altitude and slope angle was calculated by the ZONALSTD command, respectively. In general, the standard deviation of a parameter provides a more stable statistic than ranges and extremes (Evans 1972: 31–32). However, the relative altitude, also called local relief (e.g. Mark 1975: 167), was calculated from the DEM by the ZONALRANGE command and maximum slope angle was calculated from the slope map by the ZONALMAX command.

Elevation–relief ratio is a hypsometric varia-
ble that describes the topographical setting in an area. This ratio value is the best approximation of the most common hypsometric value, namely the hypsometric integral (Mark 1975: 173). The elevation–relief ratio \( E \) was calculated with the equation (Pike & Wilson 1971: 1079):

\[
E = \frac{Z_{\text{mean}} - Z_{\text{min}}}{Z_{\text{max}} - Z_{\text{min}}}
\]

where \( Z \) is the elevation. The value of the elevation–relief ratio varies from zero to one. The value close to 0.5 indicates normally distributed and values close to zero or one very skewed elevation distribution in the modelling square (Fig. 29A).

Concave topography represents accumulation areas for moisture and soil material, but also for cold air during wintertime ground inversions (e.g. Geiger 1965: 393–403; Harris S.A. 1982b). The proportion of concave and flat (slope < 2\(^\circ\)) topography was calculated as a percentage for each modelling square. The total curvature (see ESRI 1991) and slope maps were used to calculate the proportion of concave and flat topography. In general, curvature can be divided into two parts, profile (i.e. vertical) and plan (i.e. horizontal or contour) curvature, but it is more convenient to use total curvature to determine the convexity or concavity of an area (Mark 1975: 170; Gallant & Wilson 2000: 56).

Four surrogates for soil moisture were calculated (Table 8). Three of them were derived from the pit-filled DEM and one, namely water cover, from the vectorized basic map data. Arc/Info’s FILL command was used to fill up sinks and level peaks to ensure a continuous drainage network. Sinks and peaks are either errors in DEMs due to the resolution of the data or rounding of elevations to the nearest integer value (ESRI 1991) or they may be natural depressions like lake basins and kettle holes.

The topographical wetness index is a commonly used indirect soil moisture indicator in square-based spatial analyses (e.g. Moore et al. 1991; Franklin 1995; Walsh et al. 1998). The topographical wetness index \( \omega \) was calculated using the following formula:

\[
\omega = \ln \left( \frac{A_c}{\tan \alpha} \right),
\]

where \( \ln \) denotes the natural logarithm, \( A_c \) represents the upslope contributing area and \( \alpha \) the slope angle (Beven & Kirkby 1979; Moore et al. 1991; Fig 28B). The mean, standard devi-

### Table 7. Pure topographical variables and their description (Moore et al. 1991; Florinsky 1998; Etzelmüller et al. 2001).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Mean altitude (m)</td>
<td>Temperature, snow distribution, potential energy, radiation intensity, windiness, cloudiness, vegetation zone, moisture distribution</td>
</tr>
<tr>
<td>Relative altitude (m)</td>
<td>Relief variability, potential energy, water flow, moisture distribution</td>
</tr>
<tr>
<td>Standard deviation of altitude (m)</td>
<td>Topographical roughness, variability of temperature, snow distribution etc. (see mean altitude)</td>
</tr>
<tr>
<td>Mean slope angle (°)</td>
<td>Potential energy, water flow, snow distribution, radiation, soil thickness</td>
</tr>
<tr>
<td>Standard deviation of slope angle (°)</td>
<td>Variability of potential energy, water flow etc. (see mean slope angle)</td>
</tr>
<tr>
<td>Maximum slope angle (°)</td>
<td>Maximal potential slope energy (see mean slope angle)</td>
</tr>
<tr>
<td>Elevation-relief ratio</td>
<td>Topographical setting in a grid, distribution of land area in relation to altitude (hypsometric variable)</td>
</tr>
<tr>
<td>Concave topography (%)</td>
<td>Water, snow and sediment accumulation, soil thickness</td>
</tr>
<tr>
<td>Flat topography (%)</td>
<td>Moisture and snow distribution</td>
</tr>
</tbody>
</table>

Materials and methods
ation and maximum of the topographical wetness index were calculated by ZONAL functions (see above; Fig. 29B). The water cover for each modelling square was calculated from the gridded water layer by the ZONALSUM command (ESRI 1991).

Temperature and solar radiation variables utilised in this study are presented in Table 9. The minimum air temperature layer was constructed using multiple linear regression, point measurements of air temperature (n = 34) and DEM-derived variables (Table 10; Luoto & Seppälä, unpublished data; Fig. 28C; cf. Virtanen et al. 1998). The mean of minimum air temperature (ºC) of year was calculated directly from the constructed temperature model by

Figure 28. Examples of the compiled environmental predictors at 20 m resolution: (A) slope angle, (B) topographical wetness index, (C) modelled minimum air temperature, (D) direct clear-sky short-wave solar radiation, (E) peat soil and (F) shrub cover (for more details see text).
The relative solar radiation was calculated from direct clear-sky short-wave radiation layers in four steps. First, the direct short-wave radiation was calculated for four days, namely summer and winter solstices as well as for ver-

nal and autumnal equinoxes, with a 60 minute interval at the 20 m grid resolution. The short-wave radiation maps were generated by the DEM and an Arc/Info Arc Macro Language (AML) routine. The utilised macro (shortwavc.aml) is based on the assumption that the

Figure 29. Examples of the compiled environmental predictors at 25-ha resolution: (A) elevation-relief ratio, (B) mean of topographical wetness index, (C) relative solar radiation and (D) mean of shrub cover. The DEM-based variables (A-C) included one square without data (water covered square) and shrub cover variable (D) 24 squares without information (lack of data in biotope database). The vertical interval of contours is 20 m (© National Land Survey of Finland, Licence number 49/MYY/06).
transmittance of a clear sky is 0.8, and it calculates the attenuation of the beam radiation attributed to lower sun-altitude angles (Kumar et al. 1997; Zimmermann 2003). The utilised AML routine takes into account overshadowing by high peaks, meaning that the routine detects pixels that are in the shadow of adjacent higher terrain for a given sun position. Second, the average of the direct solar radiation of the four days was calculated for each 20 m grid (Fig. 28D). Third, the mean of the estimate of solar radiation was calculated for each modelling square utilising ZONAL function as previously (see above). Fourth, the obtained values of radiation were divided by the maximum value of the study area to calculate the relative solar radiation for each modelling square (Fig. 29C).

Aspect, which can be thought of as the slope direction, is a common DEM-derived surrogate for solar radiation and air temperature (e.g. Evans 1972, 2004; Moore et al. 1991; Franklin 1995; Etzelmüller et al. 2001). An aspect map of the study area was produced from the DEM by the ASPECT function in the GRID module. The output value was the compass direction of the aspect. The aspect majority was calculated directly from the aspect layer by the ZONALMAJORITY command (ESRI 1991).

Different soil types have dissimilar properties upon which periglacial processes act (e.g.
Washburn 1979: 11–15, 67–68). For example, peat and glacigenic soils are more susceptible to ice lens formation and intensive frost heave than sand and gravel (Williams & Smith 1989: 30–32). The cover of four soil types was calculated for each modelling square from a digital soil map by the ZONALSUM command. The soil map was constructed based on a Quaternary deposit map 1:400 000 (Kujansuu 1981), biotope data (Anonymous 2002) and field observations. Soil types were first digitized as vectors and then converted to 20 m grids (e.g. Fig. 28E).

The utilised soil types were peat, glacigenic deposit (till), sand and gravel as well as rock terrain (Table 11). Peaty areas were determined based on the biotope data (Eeronheimo 1996: 26–27) although the Quaternary deposit map was used as a base data (Kujansuu 1981). The thickness of the peat layer is estimated to be generally more than 10 cm but it can be discontinuous. Glacigenic till was digitized based on the Quaternary deposit map and it included blocky surficial material (see Chapter 3.3). Glaciofluvial, fluvial and aeolian deposits were determined based on the Quaternary deposit map and field observations and they were classified into the same group, namely sand and gravel. Rock terrain was obtained from the biotope data to represents areas where the surficial deposits are thin, generally less than 50 cm thick (cf. Eeronheimo 1996: 19–20).

Vegetation cover is an important indirect environmental factor but it has a diverse effect on the process activity (e.g. Washburn 1979: 17; Clark et al. 1985; Matthews et al. 1998). Four variables, mean and standard deviation of shrub cover and canopy cover, were compiled to represent differences in the vegetation coverage (Table 12). The vegetation information was obtained from the biotope data and the basis of mapping can be found in Eeronheimo (1996: 11–12) and Sihvo (2002: 39–40). The shrub cover varied between 0% and 85% and the canopy cover from 0% to 60% in the study area. The calculations were performed, as previously, in Arc/INFO GRID from raster (20 m) data layers (Figs. 28F & 29D).

### Table 11. Soil type variables and their description (Washburn 1979: 11, 14–15; Goodrich 1982; Williams & Smith 1989: 89–90).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat cover (100 m²)</td>
<td>High water-holding capacity, non-conductor (dry peat), dense to moderate vegetation coverage</td>
</tr>
<tr>
<td>Glacigenic deposit cover (100 m²)</td>
<td>Frost susceptible, high water-holding capacity, different size of soil particles</td>
</tr>
<tr>
<td>Sand and gravel cover (100 m²)</td>
<td>Frost resistant, dry, sparse ground layer vegetation</td>
</tr>
<tr>
<td>Rock terrain cover (100 m²)</td>
<td>Thin or absent soil cover, rock material, heat conductor</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean shrub cover (%)</td>
<td>Snow thickness and distribution, soil moisture and temperature</td>
</tr>
<tr>
<td>Standard deviation of shrub cover</td>
<td>Variability of snow thickness etc. (see mean shrub cover)</td>
</tr>
<tr>
<td>Mean canopy cover (%)</td>
<td>Snow thickness and distribution, air temperature</td>
</tr>
<tr>
<td>Standard deviation of canopy cover</td>
<td>Variability of snow thickness etc. (see mean canopy cover)</td>
</tr>
</tbody>
</table>

Washburn 1979: 11–15, 67–68). For example, peat and glacigenic soils are more susceptible to ice lens formation and intensive frost heave than sand and gravel (Williams & Smith 1989: 30–32). The cover of four soil types was calculated for each modelling square from a digital soil map by the ZONALSUM command. The soil map was constructed based on a Quaternary deposit map 1:400 000 (Kujansuu 1981), biotope data (Anonymous 2002) and field observations. Soil types were first digitized as vectors and then converted to 20 m grids (e.g. Fig. 28E).

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Spatial variables were compiled for the hierarchical partitioning analyses to detect the independent effect of environmental predictors (Table 13; see Chapter 4.2.3). Autocovariates that describe patch-like autocorrelation (Legendre 1993: 1659) were calculated for each landform type used in the modelling: (1) the autocovariate for binary response is the number
of occupied neighbouring squares divided by the total number of neighbouring squares and (2) the autocovariate for continuous response is the total landform cover of neighbouring squares divided by the total number of neighbouring squares (Augustin et al. 1996; Luoto et al. 2001; Heikkinen et al. 2004). The number of the neighbouring squares varied from three to eight. In addition to autocovariates, centred geographical coordinates, \(x\) and \(y\), of the modelling square were compiled (see Franklin 1998: 737). These variables describe possible trend structures of the responses (Legendre 1993: 1662). The utilised horizontal coordinate system was the Finnish National Grid Coordinate System (Gauss-Krüger projection with central longitude 27º) (see Atlas of Finland 1984).

### 4.1.4 Predictor variable selection and data split

The total number of environmental variables was high (24) and some of them were highly correlated, Spearman’s rank correlation coefficient \((R_s)\) up to 0.975, which could produce severe statistical problems and uncertainties in the modelling (Sokal & Rohlf 1981: 459–460). Therefore, the most highly correlated environmental variables \((R_s > 0.75)\) were excluded from the distribution and abundance modelling. This rather liberal limit was chosen because, firstly, the effect of the multicollinearity could be explored by the hierarchical partitioning method (Chapter 4.2.3) and, secondly, it was desired to gain versatile collection of predictors. When two predictors were highly correlated, the selection was based on the reliability and interpretability of the variable.

The final modelling data were randomly divided into model calibrating (70%) and model evaluation sets (30%) (split-sample approach; see Van Houwelingen & Le Cessie 1990). The calibration datum was used to adjust the model (Chapter 4.2.2), whereas the evaluation datum was used to evaluate the quality of model predictions (Chapter 4.2.3). The random approach was used to ensure the similarity of the model calibration and evaluation sets (see Pearce & Ferrier 2000: 237). The randomisation was performed in Microsoft® Excel 2002 by the RAND function. The evaluation data cannot be considered totally independent because it is taken from the same area as the calibration data. Consequently, evaluation data should rather be kept as a quasi-independent data set (Guisan & Hofer 2003: 1235).

### 4.2 Statistical modelling

#### 4.2.1 Statistical formulation

Statistical formulation means the choice of (1) an optimal statistical approach with regards to the modelling context and (2) a suitable algorithm for modelling a particular type of response variable and estimating the model coefficients (Guisan & Zimmermann 2000: 158). Based on the study aims (Chapter 1), data exploration (distributions of the variables) and previous studies (e.g. Etzelmüller et al. 2001; Luoto & Seppälä 2002a; Luoto & Hjort 2004, 2005), the generalized linear modelling (GLM) method was chosen to be the main statistical approach. The other essential modelling method was hierarchical partitioning (Chapter 4.2.3).

An important statistical development of the last decades has been the advance in regression analyses provided by generalized linear models (GLMs) (e.g. Nelder & Wedderburn 1972; Guisan et al. 2002). GLM is more flexible and
better suited for analysing geomorphological relationships than the linear least square (LS) regression method that has implicit statistical assumptions (e.g. Atkinson et al. 1998: 1185). Technically GLMs are relatively close to linear regressions and thus relatively easy to utilise (e.g. Guisan et al. 2002).

GLMs are mathematical extensions of linear models that do not force data into unnatural scales; they allow for non-linearity and non-constant variance (heteroscedasticity) structures in the data (e.g. Guisan et al. 2002). GLMs have three components: (1) the response variables \( y_1, y_2, \ldots, y_n \) which are assumed to share the same distribution from the exponential family, (2) a set of parameters \( \alpha \) and \( \beta \) and predictor variables and (3) a monotone link function \( g \), which allows transformation to linearity and the predictions to be maintained within the range of coherent values for the response variable (McCullagh & Nelder 1989: 27). In GLMs, the explanatory variables \( x_i \) are combined to produce a linear predictor (LP), also termed as a linear component (e.g. Dobson 2002: 35), which is related to the expected value \( (\mu) \) of the response variable through a link function \( g() \):

\[
g(\mu) = \text{LP} = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik},
\]

where \( \alpha \) is a constant (intercept), \( \beta_k \) are regression coefficients and \( x_{ik} \) are predictor variables.

In GLMs, the model is optimised through deviance reduction that is comparable to LS models variance reduction (e.g. Guisan & Zimmermann 2000: 166). However, the regression coefficients of the model cannot be estimated with the ordinary least square method. Instead, maximum likelihood techniques, where the estimation method maximises the log-likelihood function, are used to calculate these parameters (e.g. Collet 2003: 52). Fitting the GLM is much the same as fitting the multiple LS regression where polynomial terms can be included in the set of predictors to account for non-linear and multi-modal responses. More information about the GLMs can be found from McCullagh and Nelder (1989) and Dobson (2002). Further, Luoto and Seppälä (2002a, 2002b, 2003), Lewkowicz and Ednie (2004), Luoto et al. (2004a) as well as Luoto and Hjort (2004, 2005, in press) have incorporated GLMs into periglacial studies.

A binary (i.e. dichotomous) response variable can have only two possible values, generally coded as one and zero, for example present/absent or active/inactive. Binary data are often modelled with logistic regression that belongs to the class of GLMs (Collet 2003: 58). In logistic regression, the relationship is expressed as a probability surface and the expected error structure is binomial. Logistic regression has been demonstrated to be a powerful modelling tool in solving different distribution problems (e.g. Nicholls 1989; Pereira & Itami 1991; Brito et al. 1999; Bledsoe & Watson 2001; Dai & Lee 2002; Luoto & Seppälä 2002a; Lewkowicz & Ednie 2004).

A simple logistic regression model is a normal regression model where the response is logged odds. The odds express the likelihood of an occurrence (i.e. phenomena present) relative to the likelihood of a non-occurrence. Logistic regression can be presented as:

\[
\text{logit (p)} = \log[p/(1-p)] = \text{LP},
\]

where \( p \) is the probability of the event and LP is the linear predictor (Collet 2003: 58). Binary GLM uses a logit link function; this means that the probability of obtaining a positive response is an s-shaped function when the LP is a first-order polynomial and a bell-shaped when the LP is second-order polynomial (e.g. Crawley 1993: 266). To calculate the probabilities as a function of the independent variables and the coefficients, an inverse logistic transformation has to be used (e.g. Collet 2003: 58):

\[
\hat{p} = \exp(\text{LP})/[1+\exp(\text{LP})].
\]

This transformation is necessary to obtain probability values between zero and one. More detailed description of the logistic regression method is presented by Cox and Snell (1989), McCullagh and Nelder (1989), Dobson (2002) and Collet (2003).
Moreover, univariate analyses were performed to explore, separately, the roles of each environmental variable on the distribution and abundance of the periglacial landforms. Several means to conduct univariate analysis exist (e.g. Pereira & Itami 1991; Luoto et al. 2001). Here, all environmental variables and their quadratic terms were included into the model and in each step one explanatory variable at a time was omitted and the change of the residual deviance was calculated (residual deviance of the whole model minus residual deviance after the exclusion) (see Crawley 1993: 192).

### 4.2.2 Model calibration

In model calibration, (1) the environmental variables will be selected to the final model and (2) the statistical model will be constructed (e.g. estimation and adjustment of model parameters) (Guisan & Zimmermann 2000: 166). The model calibration was performed using the statistical package R version 1.8.0, with standard `glm` function (Dalgaard 2002: 192; Venables & Ripley 2002: 183–210). The possibility of curvilinear relationships between explanatory and dependent variables were examined by including the quadratic terms of the predictors in the models (e.g. Crawley 1993: 192; Atkinson et al. 1998: 1185). The calibration was started by choosing link functions for the GLMs. A logit link function was chosen for the binary responses (McCullagh & Nelder 1989: 31–32). A Box-Cox transformation ($y^\lambda$) approach was used to define the optimal transformation to normalise the distribution of the continuous responses (Box & Cox 1964; cf. Dobson 2002: 109; Oksanen 2003: 66–67). The Box-Cox function was performed using the ‘MASS package’ and ‘boxcox’ command in the statistical software R 1.8.0 (Venables & Ripley 2002: 170–172). An identity link was then used for the normalised response (McCullagh & Nelder 1989: 31–32).

The variables were selected using a statistically focused backward elimination approach, in which predictors are excluded simply according to their statistical significance (see Crawley 1993: 192–193; Venables & Ripley 2002: 175–176). The selection started with a full model where all predictors were fitted and at each step one model component was manually omitted. Elimination was based on strict criterion ($p < 0.001$) for variable exclusion. This very low $p$-value was chosen because of the relatively high sample size, which tends to lower $p$-values compared to smaller sample sizes (McBride et al. 1993: 425). After all the non-significant predictors were eliminated, four to six omitted but potentially important predictors were tested for reinclusion into the model. The final GLM model was fitted with the selected significant terms only.

The proportion of the explained deviance $[(\text{null deviance} – \text{residual deviance} / \text{null deviance}) * 100]$ was calculated for the final distribution and abundance models to gain an overall picture of the success of the fitting. In addition, residuals were used to assess the success of the calibrations and the appropriateness of the selected probability distributions used for the responses in abundance modelling (e.g. Crawley 1993: 211–212; Dobson 2002: 19).

### 4.2.3 Model evaluation

Evaluation of the generated model is a vital step in the model building process (e.g. Fielding & Bell 1997; Guisan & Zimmermann 2000: 171–174; Pearce & Ferrier 2000; Rushton et al. 2004: 198). In this study, models were evaluated (1) quantitatively utilising evaluation data sets (discrimination measures and correlations), (2) descriptively and empirically using prediction maps and field observations (e.g. Guisan & Zimmermann 2000: 172) and (3) the results (environmental variables) of the GLM models were compared with the hierarchical partitioning results (see below). The distribution models were evaluated with all three approaches and abundance models with the first and third method.

The prediction ability of the abundance models were evaluated quantitatively by calculating Spearman’s rank correlation coefficient ($R_s$) between the predicted and observed val-
ues (e.g. Guisan & Zimmermann 2000: 173). There are not generally accepted measures of performance for binary models, respectively (e.g. Fielding & Bell 1997). Therefore, the discrimination ability of the distribution models were assessed with two different measures: (1) Cohen’s Kappa statistic ($\kappa$) (Cohen 1960) and (2) the AUC value (Metz 1978). Both utilised discrimination measures were calculated by the SPSS for Windows 11.0 software package. The most commonly used measure, namely the percentage of correct classification (PCC), was not utilised because PCC can be misleadingly high when frequencies of zeros and ones in binary data are very different (Pearce & Ferrier 2000: 230–231).

The Cohen’s Kappa coefficient measures the correct classification rate, proportion of correctly classified presences and absences, after the probability of chance agreement has been removed (Cohen 1960; Congalton 1991). According to Landis and Koch (1977: 165) models can be classified based on the Kappa statistics to: poor $\kappa < 0.4$; good $0.4 < \kappa < 0.75$ and excellent $\kappa > 0.75$. The Kappa value is dependent on a single threshold to distinguish between predicted presence and absence and thus falls into the class of threshold–dependent measures. An optimum probability threshold (accuracy of 0.01) was explored for each distribution model based on the $\kappa$ values of the calibration data (e.g. Segurado & Araújo 2004: 1559).

In general, a problem with the threshold–dependent indices is their failure to use all of the information provided by the classifier. One threshold-independent measure has received more attention in medical and ecological literature (e.g. Zweig & Campbell 1993; Fielding & Bell 1997: 44–46; Pearce & Ferrier 2000: 232–237), but also more recently in periglacial studies (Luoto et al. 2004a; Luoto & Hjort 2005; Hjort & Luoto 2005, 2006), than others; the area under the curve (AUC) of a receiver operating characteristic (ROC) plot. A ROC plot is obtained by plotting sensitivity values (true positive proportion) on the $y$-axis against their equivalent ($1 –$ specificity) values (false positive proportion) for all possible thresholds on the $x$-axis. This makes the area under the ROC function a threshold-independent and an unbiased measure (e.g. Pearce & Ferrier 2000: 232).

The AUC ranges from 0.5 for models with no discrimination ability to one for models with perfect discrimination. For example, a value of 0.9 for AUC means that the model can correctly discriminate between an occupied and unoccupied site 90% of the time. In other words, if a pair of evaluation sites (one where phenomena is present and the other where it is absent) is chosen at random, then there is a 0.9 probability that the model will predict higher likelihood of occurrence for the present site than for the absent site. Swets (1988: 1292) proposed a rough guide for classifying the AUC values of the models: $0.50–0.70 = \text{poor}$, $0.71–0.90 = \text{good}$, $> 0.90 = \text{excellent}$.

In addition to the different evaluation statistics, the prediction ability of the distribution models was evaluated visually and empirically utilising prediction maps and new field observations. A total of 136 modelling squares that were mapped as unoccupied but had a relatively high predicted probability of landforms presence [cf. commission errors (e.g. Congalton 1991)] were visited in the field during the summer 2004 (8th of July–21st of July). The causes of low probabilities of the present sites [cf. omission errors (e.g. Congalton 1991)] were detected using extrapolated prediction maps and obtained field knowledge. The predictions for the whole study area were calculated using calibration models.

Multivariate models are subjected to two notable problems: (1) predictor variables are frequently significantly intercorrelated (multicollinearity), which can produce spurious causality; and (2) specificity of the derived models to the used data set that makes model extrapolation questionable (MacNelly 1996: 228). The hierarchical partitioning (HP) method is designed to overcome these problems by using mathematical hierarchical theorem by which the explanatory capacities of a set of independent variables can be estimated (Chevan & Sutherland 1991: 92–94). HP does not produce a regression model but it helps to make better
deductions of the important environmental determinants. Furthermore, if two modelling approaches, in this study GLM and HP, agree on which predictors are the most important, then it is more likely that meaningful predictor variables have been found (e.g. MacNally 2002: 1397).

HP employs goodness-of-fit measures for each of the $2^k$ possible models for $k$ independent variables. An appropriate goodness-of-fit measure depends on the distribution of the response variable (MacNally 1996: 225). In HP, the variances are partitioned so that the total independent contribution ($I$) of a given predictor variable is estimated. Furthermore, the variation shared with another variable (i.e. cojoint contribution, $J$) can be computed (Chevan & Sutherland 1991: 92–93). For example, the independent impact of variable ‘mean altitude’ is estimated by comparing goodness-of-fit measures for all possible models involving ‘mean altitude’ to yield the independent explanatory power of this variable. In other words, the increase in model fit generated by ‘mean altitude’ is estimated by averaging its influence over all models in which ‘mean altitude’ appears. By these means, HP allows one to identify those predictor variables whose independent, as distinct from partial, correlation with a response variable may be important from variables that have little independent effect on the studied phenomena. The HP approach has been used, for example, in ecological studies by MacNally (1996, 2000, 2002), MacNally and Horrocks (2002) and Heikkinen et al. (2004). For more detailed description of the method see Chevan and Sutherland (1991) and MacNally (1996, 2002).

In this study, hierarchical partitioning was used to reveal the most likely causal variables by removing the effect of spatial autocorrelation as well as geographical trend by introducing spatial variables into the partition routine. HP was conducted using ‘hier.part package’ version 0.5–1 in statistical software R version 1.8.0 (Walsh & MacNally 2003). The maximum number of independent variables that can be used in the partition is 12. This limited the number of environmental variables to nine because three spatial variables (Chapter 4.1.3; Table 13) were included in every HP run. The environmental variables were chosen based on GLM modelling so that all variables in the final model were included. Additionally, if these variables and spatial variables did not sum up to 12, potentially important variables excluded from the final GLM model were also included. Used goodness-of-fit measures were log-likelihood for binary data and root-mean-square prediction error (RMSPE) for abundance data (Walsh & MacNally 2003). For every response variable there was generated 4096 regression models to find out the most meaningful predictors. In the end, the interest was focused on the independent contribution of specific predictor variable.
5 RESULTS

5.1 Predictor variables

In this study, a large number of predictors that are potentially important in modelling periglacial phenomena were calculated for each modelling square at the 25-ha resolution. The final array of predictors utilised in the modelling included 15 environmental factors and all five variable groups were represented (Table 14; see also Chapter 4.1.4). Mean altitude, mean slope angle, elevation-relief ratio and proportion of concave topography were selected from the group of pure topographical predictors. The maximum of topographical wetness index was omitted from the soil moisture variables, whereas mean and standard deviation of wetness index and water cover were taken into the analyses. The mean of minimum air temperature was excluded and relative solar radiation as well as aspect majority were selected from the climatological factors. Mean of shrub cover and mean of canopy cover were taken from the group of vegetation variables. Moreover, all soil variables were included into the final set of predictors.

Some of the selected variables were still rather highly correlated (Table 14). The highest bivariate correlations ($R_s > 0.6$) were between canopy cover and altitude ($R_s = -0.729$), peat and shrub cover ($R_s = 0.696$), glaciogenic deposit and peat ($R_s = -0.690$), concave topography and elevation-relief ratio ($R_s = -0.645$) as well as between mean of wetness index and concave topography ($R_s = 0.633$). Relative radiation and aspect majority correlated least with other variables.

5.2 Periglacial landforms in Báišduattar – Áilegas

Periglacial landforms are common geomorphological features in the study region and the diversity of the phenomena is rather considerable (Figs. 30 & 31). The mapped landforms were classified into six main groups (Table 15). Palsas and thermokarst ponds are the only features in the first group. Patterned ground is the largest group with six main landform classes, namely circles, polygons, nets, boulder depressions, steps and stripes. Circles have seven subclasses of which four represented non-sorted and three sorted features. In general, non-sorted circles are clearly more abundant than sorted features forming extensive fields in the central parts of the study area (Fig. 30). Sorted circles, however, have rather scattered distribution, although their occurrence is connected to the non-sorted circles and sorted nets.

Polygons and stripes include both non-sorted and sorted landforms, whereas nets are all sorted and steps non-sorted. In the generalised periglacial geomorphological map, sorted polygons are included in the class of sorted nets because polygons occur primarily in the same topographical locations as nets, mainly on the fell summits. Boulder depressions are common on the edges of mires, close to the occurrences of non-sorted and sorted circles. Sorted stripes are closely connected to the sorted solifluction sheets and therefore, only some separate stripe occurrences are indicated by symbols in Figure 30. Non-sorted stripes are spatially connected to the non-sorted circles and steps.

Slope phenomena include four landform groups, of which solifluction is the largest with eight feature types. Terraces, lobes, ploughing blocks and braking blocks are non-sorted and sheets, terraces, lobes and streams sorted solifluction landforms. Rapid slope phenomena and taluses have fairly limited distribution in the study area (Fig. 30). The distribution of non-sorted solifluction landforms is scattered at the whole study area scale. In addition, the different feature types are not spatially connected to each other or with any other periglacial landform types. The sorted solifluction landforms occur in similar regions, on fell slopes at high altitudes (Fig. 30).
Table 14. Correlation matrix of the environmental predictors used in the statistical analyses. Correlation coefficients and statistical significances were derived from the bivariate correlation procedure [Spearman’s rank correlation (*** = \( p < 0.001 \), ** = \( p < 0.01 \), * = \( p < 0.05 \), n.s. = not significant)].

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<tbody>
<tr>
<td>1 Mean altitude</td>
<td>***</td>
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<td>***</td>
<td>n.s.</td>
<td>n.s.</td>
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<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>2 Mean slope angle</td>
<td>0.266</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>n.s.</td>
<td>n.s.</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>n.s.</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>3 Elevation-relief ratio</td>
<td>0.124</td>
<td>0.106</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>n.s.</td>
<td>n.s.</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>n.s.</td>
<td>***</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>4 Concave topography</td>
<td>-0.196</td>
<td>-0.265</td>
<td>-0.645</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>n.s.</td>
<td>n.s.</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>n.s.</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>5 Mean wetness index</td>
<td>-0.225</td>
<td>-0.522</td>
<td>-0.371</td>
<td>0.633</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>n.s.</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>n.s.</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>6 Std of wetness index</td>
<td>-0.400</td>
<td>-0.385</td>
<td>-0.274</td>
<td>0.383</td>
<td>0.152</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>7 Water cover</td>
<td>-0.296</td>
<td>-0.287</td>
<td>-0.228</td>
<td>0.224</td>
<td>0.157</td>
<td>0.346</td>
<td>*</td>
<td>n.s.</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>8 Relative radiation</td>
<td>0.001</td>
<td>-0.056</td>
<td>0.015</td>
<td>0.025</td>
<td>0.107</td>
<td>-0.080</td>
<td>-0.050</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>9 Aspect majority</td>
<td>0.038</td>
<td>0.025</td>
<td>-0.024</td>
<td>0.033</td>
<td>0.004</td>
<td>-0.077</td>
<td>0.018</td>
<td>-0.114</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>*</td>
<td>*</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>10 Peat cover</td>
<td>-0.499</td>
<td>-0.501</td>
<td>-0.270</td>
<td>0.463</td>
<td>0.514</td>
<td>0.381</td>
<td>0.365</td>
<td>0.064</td>
<td>-0.007</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>11 Glaciogenic deposit cover</td>
<td>0.487</td>
<td>0.347</td>
<td>0.322</td>
<td>-0.441</td>
<td>-0.321</td>
<td>-0.544</td>
<td>-0.456</td>
<td>0.083</td>
<td>-0.017</td>
<td>-0.690</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>12 Sand and gravel cover</td>
<td>0.339</td>
<td>-0.010</td>
<td>-0.170</td>
<td>0.170</td>
<td>-0.047</td>
<td>0.438</td>
<td>0.233</td>
<td>-0.093</td>
<td>-0.003</td>
<td>0.072</td>
<td>-0.505</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>13 Rock terrain cover</td>
<td>0.225</td>
<td>0.211</td>
<td>0.008</td>
<td>-0.094</td>
<td>-0.164</td>
<td>-0.063</td>
<td>-0.044</td>
<td>-0.175</td>
<td>0.042</td>
<td>-0.204</td>
<td>-0.172</td>
<td>-0.050</td>
<td>***</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>14 Mean shrub cover</td>
<td>-0.492</td>
<td>-0.474</td>
<td>-0.219</td>
<td>0.367</td>
<td>0.507</td>
<td>0.304</td>
<td>0.242</td>
<td>0.111</td>
<td>0.049</td>
<td>0.696</td>
<td>-0.479</td>
<td>0.076</td>
<td>-0.234</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>15 Mean canopy cover</td>
<td>-0.729</td>
<td>0.057</td>
<td>-0.035</td>
<td>0.040</td>
<td>-0.035</td>
<td>0.172</td>
<td>0.163</td>
<td>0.007</td>
<td>0.012</td>
<td>0.243</td>
<td>-0.234</td>
<td>0.217</td>
<td>-0.169</td>
<td>0.264</td>
<td></td>
</tr>
</tbody>
</table>
Block fields and tors are the only frost weathering features mapped from the study area. The block fields are present at fairly high altitudes but not frequently on fell summits where tors are abundant. The group of nival phenomena includes snow accumulation hollows and stone pavements, which are common in the bottoms of glaciofluvial channels. The last landform class, aeolian features, includes sand dunes and deflation landforms. Dunes occur mainly in the southeastern corner east of the Luopmošjågotkkku esker where also deflations are common, although deflations can be found from different parts of the study area (Fig. 30). In addition to the features listed in Table 15, few lakeshore and fluvial landforms were observed but they are not treated here because their periglacial nature is unclear.

In the Báišduattar – Áilegas area, the most common periglacial landforms, if calculated by occupied modelling squares, were earth hummocks (n = 1636) and peat pounus (n = 702), sorted nets (n = 631), sorted sheets (n = 431) and deflations (n = 295). The rarest features were slushflow tracks (n = 4), braking blocks (n = 4), non-sorted lobes (n = 10), ploughing blocks (n = 15) and stone pavements (n = 15), respectively. Snow accumulation hollows were mapped only during the summer 2002 because their interpretation from the landscape was shown to be rather difficult and the results unreliable. Therefore, the total number of the snow accumulation features was not determined.

The number of different periglacial landform types in the 25-ha squares varied from zero to nine (Fig. 31). A total of 247 (9.9%) squares were without any periglacial features and 2253 (90.1%) sites were occupied by at least one landform type. Two types were observed from 671 squares and this class was the largest. Over six landform types were observed only from 58 (2.3%) squares.

Hereafter the focus will be on the periglacial landforms utilised in the statistical analyses (see Chapter 4.1.2). A general morphological and distributional description of the modelled features as well as topographical characteristics of the active landform squares is provided subsequently. A total of 2272 squares of 25-ha were used in the statistical analyses, whereas 128 squares were excluded based on the modelling square selection (Chapter 4.1.2) and due to the deficiency in the biotope data.

5.2.1 Palsas

Palsas and palsa mires represent four different morphological types: (1) string-form palsas, (2) hummocky palsas, (3) conical (i.e. dome-shaped) palsas and (4) palsa complexes. String-form palsas are generally one metre high, 1–2 m wide and often 10–30 m long tor-tuous ridges but features can be several tens of metres long (Fig. 32). Hummocky palsas are circular or longitudinal from one to 1.5 m high and up to three metres in diameter. Dome-shaped palsas are from one to four metres high and generally some tens of metres in diameter (Fig. 33). Most of the dome-shaped palsas have fissures at their surfaces and some of the steepest edges have collapsed due to block erosion (Fig. 33). Dome-shaped palsas and thermokarst ponds (Fig. 4) are frequently found in palsa complexes (Fig. 2). Palsa complexes have different morphological types of palsas at different development stages. However, only few examples of recently formed palsas were detected from the study area. All palsas were determined to be active.

The whole distribution of palsas can be seen in Appendix 1. The largest palsas, from ca. six hectares to 21 ha, are found from the mires of Biesjeaggi, south of Girjeeana, Bihtoš-Per jeaggi, Luopmošjohjeaggi and Vanadanjeaggi. The total cover of the palsas is about 227 ha in the study area. Topographical characteristics of present palsa squares in relation to absent sites are presented in Table 16 and Figure 34A. The mean altitude and mean slope angle differed significantly between the two groups (p < 0.001 in Mann-Whitney U-test).
5.2.2 Convex non-sorted circles

Convex non-sorted circles are from one to four metres in diameter and ca. five to 60 cm high convex or flat-centered mineral soil hummocks (Figs. 6 & 35). The shape of the circle can be elongated or step-like on gentle slopes, and they may transform to non-sorted steps on slopes of more than three degrees (cf. Chapter 2.2.3). The surface of the circle can be characterised by small non-sorted or sorted polygons (Fig. 36). The inter-circle sections are usually covered by 10–40 cm high vegetation but some are moderately sorted (Fig. 35). Hence, convex non-sorted circles can evolve to sorted patterned features (sorted circles or nets) on level ground if the sorting proceeds. Almost all circles were unvegetated and thus active. Inactive features were found only from a few sites (Table 15).

Convex non-sorted circles are common in the northeast part of the study area where they form extensive pattern fields (Appendix 2). The largest continuous areas are situated in the valleys near the fells of Guivi, Leaksågođoaivi and Suophonäsi. The sizes of the mapped feature areas range from ca. 100 m² to 30 ha. The total cover of the active convex non-sorted circles is about 320 ha. Topographical characteristics of active landform squares are presented in Figure 34B and Table 16. The mean altitude and mean slope angle differed significantly between the occupied and unoccupied squares (p < 0.001 in Mann-Whitney U-test).

5.2.3 Stony earth circles

Stony earth circles’ diameters range from ca. 0.1 to 1.5 m (Fig. 37). The shape of the circle varies from circular to elongate. On fairly steep slopes, circles may transform to non-sorted stripes (Chapter 2.2.3). If two circles coalesce, they can form sandglass-like features. Only active unvegetated bare-ground circles were de-
Figure 31. Number of different periglacial landform types in the study area at 25-ha resolution. The vertical interval of contours is 20 m (© National Land Survey of Finland, Licence number 49/MYY/06).
Table 15. Periglacial landforms and their prevalence in the Báišduattar – Áilegas area at the 25-ha modelling resolution (¬ = not observed, x = observed but not determined).

<table>
<thead>
<tr>
<th>Main division</th>
<th>Periglacial landforms</th>
<th>Present squares, active (%)</th>
<th>Present squares, inactive (%)</th>
<th>Present squares, total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permafrost and thermokarst</td>
<td>Permafrost and thermokarst</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermokarst ponds</td>
<td>Chapter 5.2.1</td>
<td>134 (5.4%)</td>
<td>¬</td>
<td>134 (5.4%)</td>
</tr>
<tr>
<td>Thermokarst ponds</td>
<td></td>
<td>38 (1.5%)</td>
<td>63 (2.5%)</td>
<td>69 (2.8%)</td>
</tr>
<tr>
<td>Patterned ground</td>
<td>Circles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convex non-sorted circles</td>
<td></td>
<td>221 (8.8%)</td>
<td>14 (0.6%)</td>
<td>229 (9.2%)</td>
</tr>
<tr>
<td>Stony earth circles</td>
<td></td>
<td>245 (9.8%)</td>
<td>¬</td>
<td>245 (9.8%)</td>
</tr>
<tr>
<td>Earth hummocks</td>
<td>1609 (64.4%)</td>
<td>238 (9.5%)</td>
<td>1636 (65.4%)</td>
<td></td>
</tr>
<tr>
<td>Peat pounus</td>
<td>692 (27.7%)</td>
<td>25 (1.0%)</td>
<td>702 (28.1%)</td>
<td></td>
</tr>
<tr>
<td>Sorted stone circles</td>
<td>62 (2.5%)</td>
<td>21 (0.8%)</td>
<td>81 (3.2%)</td>
<td></td>
</tr>
<tr>
<td>Stone pits</td>
<td>247 (9.9%)</td>
<td>5 (0.2%)</td>
<td>252 (10.1%)</td>
<td></td>
</tr>
<tr>
<td>Debris islands</td>
<td>28 (1.1%)</td>
<td>11 (0.4%)</td>
<td>39 (1.5%)</td>
<td></td>
</tr>
<tr>
<td>Polygons</td>
<td>Non-sorted polygons</td>
<td>9 (0.4%)</td>
<td>9 (0.4%)</td>
<td>18 (0.7%)</td>
</tr>
<tr>
<td>Sorted polygons</td>
<td>3 (0.1%)</td>
<td>48 (1.9%)</td>
<td>51 (2.0%)</td>
<td></td>
</tr>
<tr>
<td>Nets</td>
<td>Sorted nets</td>
<td>188 (7.5%)</td>
<td>499 (20.0%)</td>
<td>631 (25.2%)</td>
</tr>
<tr>
<td>Boulder depressions</td>
<td>9 (0.4%)</td>
<td>68 (2.7%)</td>
<td>77 (3.0%)</td>
<td></td>
</tr>
<tr>
<td>Steps</td>
<td>Non-sorted steps</td>
<td>111 (4.4%)</td>
<td>¬</td>
<td>111 (4.4%)</td>
</tr>
<tr>
<td>Slope phenomena</td>
<td>Debris flow slopes</td>
<td>17 (0.7%)</td>
<td>¬</td>
<td>17 (0.7%)</td>
</tr>
<tr>
<td>Slushflow tracks</td>
<td>x</td>
<td>x</td>
<td>4 (0.2%)</td>
<td></td>
</tr>
<tr>
<td>Solifluction features</td>
<td>Non-sorted terraces</td>
<td>267 (10.7%)</td>
<td>10 (0.4%)</td>
<td>275 (11.0%)</td>
</tr>
<tr>
<td>Non-sorted lobes</td>
<td>9 (0.4%)</td>
<td>1 (0.0%)</td>
<td>10 (0.4%)</td>
<td></td>
</tr>
<tr>
<td>Ploughing blocks</td>
<td>9 (0.4%)</td>
<td>6 (0.2%)</td>
<td>15 (0.6%)</td>
<td></td>
</tr>
<tr>
<td>Braking blocks</td>
<td>2 (0.1%)</td>
<td>2 (0.1%)</td>
<td>4 (0.2%)</td>
<td></td>
</tr>
<tr>
<td>Sorted sheets (2 subtypes, see Chapter 5.2.10)</td>
<td>418 (16.7%)</td>
<td>39 (1.6%)</td>
<td>431 (17.2%)</td>
<td></td>
</tr>
<tr>
<td>Sorted terraces</td>
<td>x</td>
<td>x</td>
<td>74 (3.0%)</td>
<td></td>
</tr>
<tr>
<td>Sorted lobes</td>
<td>x</td>
<td>x</td>
<td>68 (2.7%)</td>
<td></td>
</tr>
<tr>
<td>Sorted streams</td>
<td>236 (9.4%)</td>
<td>14 (0.6%)</td>
<td>244 (9.8%)</td>
<td></td>
</tr>
<tr>
<td>Talus slopes</td>
<td>12 (0.5%)</td>
<td>7 (0.3%)</td>
<td>19 (0.8%)</td>
<td></td>
</tr>
<tr>
<td>Frost weathering</td>
<td>Block fields</td>
<td>¬</td>
<td>34 (1.4%)</td>
<td>34 (1.4%)</td>
</tr>
<tr>
<td>Tors</td>
<td>x</td>
<td>x</td>
<td>127 (5.1%)</td>
<td></td>
</tr>
<tr>
<td>Nival phenomena</td>
<td>Snow accumulation hollows</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Stone pavements</td>
<td>x</td>
<td>x</td>
<td>15 (0.6%)</td>
<td></td>
</tr>
<tr>
<td>Aeolian phenomena</td>
<td>Sand dunes (parabolic, transverse and longitudinal)</td>
<td>¬</td>
<td>99 (4.0%)</td>
<td>99 (4.0%)</td>
</tr>
<tr>
<td>Deflations (2 subtypes, see Chapter 5.2.12)</td>
<td>295 (11.8%)</td>
<td>295 (11.8%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The distribution of stony earth circles is relatively dispersed in the study area but some clusters can be found from southeast, around Áilegas fell and in the wide zone east of Uhc-Áhkovárás fell (Appendix 3). Only the location of the features was mapped because of their scattered distribution. Topographical characteristics of stony earth circle squares are presented in Figure 34C and Table 16. Based on the Mann-Whitney U-test, the altitude ($p = 0.160$) and slope angle ($p = 0.476$) of the present and absent sites did not differ significantly.

### 5.2.4 Earth hummocks

Earth hummocks’ heights range from $ca.$ 0.1 to 0.9 m and diameter from 0.2 m up to 1.5 m

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**Figure 32.** String-form palsa in Luopmošjohjeaggi mire (69°23'7''N, 26°10'26''E / 290 m a.s.l. / 22nd of August 2003). The ridge is $ca.$ one metre high, two metres wide and some tens of metres long.

**Figure 33.** Ca. 2–3 m high dome-shaped palsas in Vanadanjeaggi mire (69°33'58''N, 26°15'6''E / 365 m a.s.l. / 9th of July 2002). Note the block erosion on the sides of these mature palsas.
Table 16. Topographical characteristics of the active landform occurrences in relation to absent sites. The analyses were performed with 2272 25-ha squares and 128 squares were excluded. Statistical significances ($p$) of the differences between present and absent squares were derived from the Mann-Whitney U-test ($** *= p < 0.001$, ** $p < 0.01$, * $p < 0.05$, n.s. $= $ not significant) and are illustrated in the present square columns only.

<table>
<thead>
<tr>
<th>Periglacial landform</th>
<th>Present</th>
<th>Absent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Altitude (m a.s.l.)</td>
<td>Slope angle (°)</td>
</tr>
<tr>
<td></td>
<td>mean ± std</td>
<td>mean ± std</td>
</tr>
<tr>
<td>Palsa</td>
<td>338 ± 32***</td>
<td>1.6 ± 1.0***</td>
</tr>
<tr>
<td>Convex non-sorted circle</td>
<td>421 ± 42***</td>
<td>3.5 ± 1.5***</td>
</tr>
<tr>
<td>Stony earth circle</td>
<td>382 ± 41 n.s.</td>
<td>4.4 ± 2.1 n.s.</td>
</tr>
<tr>
<td>Earth hummock</td>
<td>361 ± 45***</td>
<td>4.0 ± 2.2***</td>
</tr>
<tr>
<td>Peat pounu</td>
<td>348 ± 38***</td>
<td>3.0 ± 1.7***</td>
</tr>
<tr>
<td>Stone pit</td>
<td>354 ± 45***</td>
<td>2.9 ± 1.7***</td>
</tr>
<tr>
<td>Sorted net</td>
<td>390 ± 53**</td>
<td>3.4 ± 1.8***</td>
</tr>
<tr>
<td>Sorted stripe</td>
<td>467 ± 54***</td>
<td>7.3 ± 2.2***</td>
</tr>
<tr>
<td>Non-sorted terrace</td>
<td>407 ± 55***</td>
<td>5.3 ± 2.3***</td>
</tr>
<tr>
<td>Sorted sheet</td>
<td>447 ± 60***</td>
<td>7.3 ± 2.5***</td>
</tr>
<tr>
<td>Sorted stream</td>
<td>462 ± 55***</td>
<td>7.6 ± 2.3***</td>
</tr>
<tr>
<td>Deflation</td>
<td>371 ± 42 n.s.</td>
<td>4.0 ± 1.9**</td>
</tr>
</tbody>
</table>

(Fig. 38). Small features are often silty mineral soil, whereas large hummocks have peat cover on mineral soil core. The surface of the hummock is usually characterised by vegetation cover. Cryoturbated internal structures were found in excavations performed in the valleys of Leaksägoahti and northwest of Ruohtr fell. Active earth hummocks have relatively sparse vegetation cover and they can have cracked or mudboil-like summits, whereas mosses cover inactive hummocks (Fig. 26D).

Earth hummocks are prevalent periglacial landforms in the Báisduattar – Áilegas area (Appendix 4; Table 15). The largest continuous feature areas are located in Girjeeana region, east of Uhc-Áhkovárás fell, south of Gaska-
Results

Biesvári fell, around Viercágálmara fell as well as southwest and southeast of Geatgie-
las fell. The sizes of the mapped areas range from ca. 100 m² to several square kilometres. The total cover of earth hummocks is ca. 70 km². Topographical characteristics of active earth hummock squares in relation to absent sites are presented in Figure 39A and Table 16. The mean altitude and mean slope angle differed significantly between the two groups (p < 0.001 in Mann-Whitney U-test).

Figure 35. Convex non-sorted circles on a gentle slope west of Ráššoaivi fell (69°38'29"N, 26°16'23"E / 495 m a.s.l. / 12th of August 2002). The circles are from 10 cm to 30 cm high and their diameter ranges from one to three metres.

Figure 36. Convex non-sorted circle with small partly vegetated (mainly Calluna vulgaris) non-sorted polygons on the surface (69°30'37"N, 26°28'57"E / 410 m a.s.l. / 30th of July 2002). The circle is ca. two metres in diameter and the cracks are from five to 20 cm wide.
5.2.5 Peat pounus

Peat pounus are from ca. 0.2 m to 1.2 m high vegetated hummocks (Fig. 40). Pounus diameter ranges from ca. 0.3 m up to two metres and their shape is mostly circular but features can be elongated. The largest pounus are often located in thin peat deposits or on mire edges. Most of the features were active (Table 15). Inactive pounus are characterised by dry peat and are often partly destroyed.

The general distribution of pounus is presented in Appendix 5. The largest feature fields are found from Čulloveijeaggi mire,
Bieszjeaggi mire, south and southwest of Girjjeana, southwest of Njávgoaivi fell and from Luopmošjohjjeaggi mire. The sizes of the mapped feature areas range from ca. 100 m² to 243 ha and the total cover of the peat pounus is 1931 ha. Topographical characteristics of active peat pounu occurrences are presented in Figure 39B and Table 16. The mean altitude and mean slope angle differed significantly between the present and absent sites ($p < 0.001$ in Mann-Whitney U-test).

5.2.6 Stone pits

Stone pits’ diameters range from 0.3 to two metres and their depth is generally less than one metre (Fig. 41). The material of the features is stone or block-sized (0.1–1 m). Stone pits are more or less circular but if they coalesce, the shape of the pit can be more complex. Most of the mapped features were active and only few inactive features were detected (Table 15). Inactive stone pits were covered by vegetation, usually mosses.

Stone pits are fairly common and quite

Figure 39. Mean altitude and mean slope angle of the present and absent (A) earth hummock, (B) peat pounu and (C) stone pit squares. Only active landform occurrences were used in the analyses.

Figure 40. Peat pounus in the western part of Čullovejeaggi mire (69°35'21''N, 26°13'10''E / 365 m a.s.l. / 16th of July 2004). The hummocks are from 40 cm to 80 cm high.
sporadically distributed despite some feature concentrations existing (Appendix 6). Stone pits can form relative continuous fields where the distances between the features are 1–5 m. However, more often their distribution is quite random and the distances vary from a few metres to several tens of metres. Due to the scattered distribution, only the location of the features was documented. Topographical characteristics of active present stone pit squares are presented in Figure 39C and Table 16. The mean altitude and mean slope angle differed significantly between the present and absent squares ($p < 0.001$ in Mann-Whitney U-test).

5.2.7 Sorted nets

The size of the sorted nets (i.e. the diameter of the pattern centre) can range from less than one metre to more than five metres and the stony border from 0.1 m to two metres (Fig. 42). However, the average centre size is ca. two metres. Generally the borders consist of 10–40 cm stones but blocks up to 1.5 m in diameter may be present in thin soil sites or in large features. On level ground, slope angle less than two degrees, the shape of the stony mesh resemble polygonal but on gentle slopes (2–6°) it is clearly elongated. Most of the sorted nets are moderately or poorly sorted. However, optimal conditions can create well sorted features. The active nets are partly or totally without vegetation cover, whereas inactive features have lichen on stones and dense vegetation cover in the centres (Fig. 43). Sorted nets can be found from different parts of the study area (Appendix 7). The largest areas, which are inactive, are in the fell regions of Áílegas, Njávgoaivi – Suohpášoaivi and Guovdoaivi – Gamoai. The largest active feature areas were in Leakšagoahti valley, northwest of Biesjeaggi mire, south of Gamoai fell and northwest of Leakšagoađoaivi fell, respectively. In general, the sizes of the mapped fields ranged from ca. 100 m² to over 100 ha. However, the largest active net field was only 2.3 ha. In addition, despite over 270 active areas were found their total cover was only 28 ha. Topographical characteristics of active sorted net squares in relation to absent sites are presented in Figure 44A and Table 16. The topographical properties differed significantly between the two groups ($p < 0.01$ in Mann-Whitney U-test).
Sorted stripes are 0.2–2 m wide and from a few metres to tens of metres long features (Fig. 45). The width of the non-sorted inter-stripe area is often several times wider than the sorted parts ranging from to ten metres. Sizes of the stones in the sorted sections are generally from five to 40 cm in diameter but boulders up to one metre can be found from a few sites. Material of the stripes is usually quite rounded but some stripes can be formed of angular stones and blocks. The most active stripes were without vegetation cover (Fig. 46). However, usually even the active stripes were partly covered by vegetation; stones with

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5.2.8 Sorted stripes
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Figure 42. Active sorted net in a temporary ponding depression (69°34'52"N, 26°13'23"E / 375 m a.s.l. / 16th of August 2002). The mesh width ranges from 40 cm to one metre.

Figure 43. Inactive sorted net from the summit of Räššoaivi fell (69°38'15"N, 26°16'12"E / 515 m a.s.l. / 12th of August 2002). The diameter of the vegetated centre is ca. 1.5 m.
lichen and non-sorted parts by low heath vegetation (see Fig. 45).

Most of the sorted stripes occur in three fell regions, namely Áilegas in southwest, Njávägoiví – Suhpášoaivi area and around Guivi in the northeast (Appendix 8). In Áilegas, stripes are abundant on the slopes of fells north and southwest of Davimušalaš fell. The largest fields in the second area are on the slopes of Njávägoiví and Geavvogoašoaivvit fells. In the northeast, largest stripe fields can be found from the fells of Guovdoaivi, Guivi, west of Guivi and Ráššoaivi. Moreover, Ahkovárrí fell has several smaller feature occurrences. The total area of the sorted stripes could not be determined because only the locations of the features were recorded due their scattered distribution. In general, the stripe areas are quite small, usually less than one hectare. Topographical characteristics of active sorted stripe squares are presented in Figure 44B and Table 16. The mean altitude and mean slope angle differed significantly between occurrence and non-occurrence sites ($p < 0.001$ in Mann-Whitney U-test).

Figure 44. Mean altitude and mean slope angle of the present and absent (A) sorted net, (B) sorted stripe and (C) non-sorted solifluction terrace squares. Only active landform occurrences were used in the analyses.

Figure 45. C. 0.5 m wide active sorted stripes on the slope of Njávägoiví fell (69°29’34”N, 26°19’24”E / 545 m a.s.l. / 11th of July 2004).
Non-sorted solifluction terraces are 0.2–0.8 m high and up to a few tens of metres wide features with steep frontal riser (Figs. 26C & 47). The surface gradient of the feature was often measured to be less than five degrees despite the fact that the slope above the terrace could be up to 30º. The frontal riser of the feature can be discontinuous hummock-like (Fig. 47). The active non-sorted solifluction terraces have moderate vegetation cover and steeper frontal margin than the inactive due to constant soil movement by solifluction.

Non-sorted terraces are quite common features in the study area (Appendix 9; Table 15). Most of the terraces are situated in northern and eastern parts of the study area. However, smaller occurrences can be found from the fell areas of Áilegas and north of Gaska-Biesvári. The total cover of the non-sorted terraces could not be measured because only the locations of the features were determined in the field. Topographical characteristics of active present non-sorted solifluction terraces are presented in Figure 44C and Table 16. The mean altitude and mean slope angle differed significantly between the present and absent sites ($p < 0.001$ in Mann-Whitney U-test).

Sorted solifluction sheets are often transversal over 50 m wide slope features (Fig. 11). They consist of coarse material, stones, boulders and blocks. The size of the material ranges from 0.2 to one metre but blocks up to two metres in diameter can exist. Sheets can be divided to two subgroups; boulder sheets and block sheets. In the boulder sheets, the material is fairly rounded, whereas more angular blocks with rather sharp edges characterise the second type. Despite that material differences between the types occur, all sheets were grouped together. Both active and inactive features were identified from the study area (Fig. 48; Table 15).

The distribution of sorted solifluction sheets is presented in Appendix 10. The largest sheet areas, up to 70 ha, are found from the fell regions of Áilegas, Guovdoaivi
Results

– Gamoaivi, Ráššoaivi, Áhkovárrri, Njávgoaivi – Suhpášoaivi and Suobbatoaivi. The extensive features are commonly boulder sheets or mixed types where smaller blocky areas are present. The largest block sheets can be found from slopes of Uch-Áhkováráš fell, southwest of Guovdoaivi fell and northeast of Ruohtrir fell. The total cover of the sorted solifluction sheets is 1116 ha. Topographical characteristics of active present landform squares in relation to absent sites are presented in Figure 49A and Table 16. The mean altitude and mean slope angle differed significantly between the two groups ($p < 0.001$ in Mann-Whitney U-test).

Figure 47. Non-sorted solifluction terrace on the foot of 28° steep slope (69°37‘20”N, 26°21‘40”E / 455 m a.s.l. / 20th of June 2002). The terraces frontal riser is 35 cm high and it is partly hummocky-like.

Figure 48. Active sorted solifluction sheet with rather angular material and frontal soil embankment of ca. 40 cm high (69°28‘18”N, 26°1‘29”E / 400 m a.s.l. / 17th of July 2003).
5.2.11 Sorted solifluction streams

Sorted solifluction streams are ca. 3–20 m wide and generally from ten to several tens of metres long features (Fig. 50). The size of the stones range generally from 10 cm to 50 cm in diameter but boulders up to one metre can occur in some features. Material is often quite rounded but angular stones and blocks can be present. In addition, some features with more angular material occur in the study area. The active features material was only partly lichen covered, whereas inactive features had fairly dense lichen and moss cover on the stones and blocks.

The sorted solifluction streams have a quite similar distribution to the stripes and sheets (Appendix 11). Most of the sorted streams occur in the fell areas of Áilegas, Guovdoaivi – Gamoäivi, Räššoaivi, Åkkoavári, Njávgoaivi – Suohpåšoaivi, Suobbatoaivi and Stuorra Biesvárrí, where also the largest features can be found. The cover of the sorted streams could not be defined because only the locations of the features were mapped in the field. Topographical characteristics of active present feature squares are presented in Figure 49B and Table 16. The mean altitude and mean slope angle differed significantly between the occupied and unoccupied squares (p < 0.001 in Mann-Whitney U-test).

5.2.12 Deflations

The diameter of the deflation features range from two metres to some tens of metres and depth from a few centimetres to ca. three metres. Two main types of deflations were identified from the study area, deflation surfaces (Fig. 51) and deflation depressions i.e. blow-outs (Fig. 17). Deflation surfaces occur on glacial and glaciofluvial soils and landform, whereas depressions can only be found from aeolian deposits. Wind erosion surfaces were also observed from peaty areas, mainly from palsas (Fig. 4). Deflation surfaces are usually distinctively smaller than depressions, just from few centimetres to 20 cm deep and often less than 10 m in diameter. Only active deflation features were mapped. In this study, both the identified deflation landform types, surfaces and depressions, were combined together to ensure a sufficient number of observations in the statistical analyses.

Deflations are quite common landforms in the study area (Appendix 12; Table 15). They are most abundant in the areas southeast and east of Leakšagoadoaivi fell, on the Goike-Sitnogophi esker, east and south of Ulláváráš fell, on the marginal areas of Luopmošjáguotkku esker and generally in the southeast. Features over 50 m in diameter can be found east of Leakšagoadoaivi fell and southeast of Luopmošjáguotkku esker. However, usu-
ally deflations are quite small-sized and their distribution is scattered. Therefore, only the locations were documented. Topographical characteristics of present deflation sites are presented in Figure 49C and Table 16. According to Mann-Whitney U-test, the occurrence squares mean slope angle differed significantly ($p = 0.001$) from the absent sites values but mean altitude did not ($p = 0.082$).

5.3 Distribution and abundance models

5.3.1 Palsas

The final modelling data included 2272 squares of which 134 (5.9%) were occupied by palsas. In univariate analyses, the largest change in deviance was caused by water cover, mean slope angle, mean of shrub cover as well as peat...
and rock terrain cover (Fig. 52). The results of the final distribution model are presented in Table 17. The probability of palsa occurrence increased with increasing peat and water cover and decreasing mean slope angle. The response curve of water cover was humped, i.e. highest probability occurred at the intermediate values. The shapes of the separately fitted response curves of the variables in the final model are illustrated in Figure 53. The final model explained ca. 52 % of the variation in palsa distribution (Table 18).

In model evaluation, the Kappa value of 0.565 was obtained \( (SE = 0.064, p < 0.0001) \), which indicated a relatively good discrimination capability of the model. The used optimised cut off value was 0.32. The AUC value was 0.950 \( (SE = 0.018, p < 0.0001) \), which indicates an excellent discrimination ability between occupied and unoccupied squares. However, there occurred unsuccessfully predicted squares that can be seen from the Figure 54. For example, two modelling squares west of the Áilegas fell had very low probabilities \((0.00026 \text{ and } 0.00025)\) but were present squares (omission error) and the square in the Leåšagoahti valley had high probability \(0.84\) but was unoccupied (commission error). Ten commission error squares were visited to gain further information of the prediction errors and from eight of the sites palsas were found.

Based on the hierarchical partitioning, the autocovariate was the strongest predictor, whereas other spatial variables explained less than one percent of the variation in the data (Fig. 55). The most important environmental factors were peat cover, mean slope angle, mean of topographical wetness index, shrub cover, mean altitude and proportion of concave topography. Peat and slope angle were important factors in both GLM and hierarchical partitioning approaches but the effect of water cover declined substantially in HP.

Of the 134 present palsa squares 111 were used in the abundance modelling. The cover of the palsas ranged from 0.01 ha to 9.58 ha in the modelling squares. Mean of shrub cover, elevation-relief ratio, standard deviation of topographical wetness index, mean altitude and mean slope angle increased the residual deviance most in univariate analysis (Fig. 56). The variables and coefficients of the final abundance model are presented in the Table 19. The cover of the palsas increased when peat cover increased and mean of shrub cover decrease. According to residual plots, the as-

![Figure 52. Results of the univariate analyses for palsa distribution. The change in deviance is presented as absolute value because the results of the calculations were negative (see Chapter 4.2.1).](image)

Table 17. Variables, coefficients, standard errors (SE), z- and p-values of the final model for palsa distribution.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>z</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.550</td>
<td>0.566</td>
<td>-2.739</td>
<td>0.0062</td>
</tr>
<tr>
<td>Peat cover</td>
<td>1.744*10^{-3}</td>
<td>2.463*10^{-4}</td>
<td>7.081</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>-1.060</td>
<td>0.185</td>
<td>-5.742</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Water cover</td>
<td>1.334*10^{-2}</td>
<td>3.158*10^{-3}</td>
<td>4.224</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Water cover^2</td>
<td>-1.338*10^{-5}</td>
<td>3.630*10^{-6}</td>
<td>-3.686</td>
<td>0.0002</td>
</tr>
</tbody>
</table>
assumption of normal errors was appropriate despite that a few possible outliers were present (Fig. 57). The final abundance model explained 37% of the variation in the data (Table 18).

Spearman’s rank correlation coefficient (R_s) for the evaluation data was 0.2739 (p < 0.0001) which was substantially less than for the calibration data (R_s = 0.6470, p < 0.0001). Autocovariate for palsa abundance explained 5.4% and x-coordinate 1.1% of the variance in the data (Fig. 58). Peat cover, mean of topographical wetness index, mean slope angle, water cover and proportion of concave topography were independently the most influential environmental correlates. Peat cover was the most important factor in both statistical approaches but the effect of the shrub cover decreased drastically in the hierarchical partitioning analysis.

Table 18. Deviance information and degrees of freedom (D.f.) of the final distribution (D) and abundance (A) models.

<table>
<thead>
<tr>
<th>Calibration data</th>
<th>Null deviance</th>
<th>Residual deviance</th>
<th>Change in deviance</th>
<th>Change in deviance (%)</th>
<th>D.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palsa D</td>
<td>651.73</td>
<td>310.91</td>
<td>340.82</td>
<td>52.3</td>
<td>1585</td>
</tr>
<tr>
<td>Palsa A</td>
<td>29.315</td>
<td>18.440</td>
<td>10.875</td>
<td>37.1</td>
<td>75</td>
</tr>
<tr>
<td>Convex non-sorted circle D</td>
<td>1033.76</td>
<td>683.97</td>
<td>349.79</td>
<td>33.8</td>
<td>1584</td>
</tr>
<tr>
<td>Convex non-sorted circle A</td>
<td>93.254</td>
<td>56.908</td>
<td>36.346</td>
<td>39.0</td>
<td>151</td>
</tr>
<tr>
<td>Stony earth circle D</td>
<td>1094</td>
<td>1010.4</td>
<td>83.6</td>
<td>7.6</td>
<td>1584</td>
</tr>
<tr>
<td>Earth hummock D</td>
<td>2001.2</td>
<td>1060.4</td>
<td>940.8</td>
<td>47.0</td>
<td>1582</td>
</tr>
<tr>
<td>Earth hummock A</td>
<td>671.92</td>
<td>323.24</td>
<td>348.68</td>
<td>51.9</td>
<td>1026</td>
</tr>
<tr>
<td>Peat pounu D</td>
<td>1928.8</td>
<td>1024.3</td>
<td>904.5</td>
<td>46.9</td>
<td>1578</td>
</tr>
<tr>
<td>Peat pounu A</td>
<td>303.91</td>
<td>160.33</td>
<td>143.58</td>
<td>47.2</td>
<td>426</td>
</tr>
<tr>
<td>Stone pit D</td>
<td>1055.6</td>
<td>856.9</td>
<td>198.7</td>
<td>18.8</td>
<td>1584</td>
</tr>
<tr>
<td>Sorted net D</td>
<td>933.55</td>
<td>801.42</td>
<td>132.13</td>
<td>14.2</td>
<td>1584</td>
</tr>
<tr>
<td>Sorted stripe D</td>
<td>904.93</td>
<td>509.21</td>
<td>395.72</td>
<td>43.7</td>
<td>1586</td>
</tr>
<tr>
<td>Non-sorted solifluction terrace D</td>
<td>1131.3</td>
<td>1017.2</td>
<td>114.1</td>
<td>10.1</td>
<td>1586</td>
</tr>
<tr>
<td>Sorted solifluction sheet D</td>
<td>1467.65</td>
<td>584.96</td>
<td>882.69</td>
<td>60.1</td>
<td>1582</td>
</tr>
<tr>
<td>Sorted solifluction sheet A</td>
<td>226.13</td>
<td>123.03</td>
<td>103.1</td>
<td>45.6</td>
<td>278</td>
</tr>
<tr>
<td>Sorted solifluction stream D</td>
<td>1024.95</td>
<td>561.24</td>
<td>463.71</td>
<td>45.2</td>
<td>1587</td>
</tr>
<tr>
<td>Deflation D</td>
<td>1210.72</td>
<td>962.36</td>
<td>248.36</td>
<td>20.5</td>
<td>1583</td>
</tr>
</tbody>
</table>

Figure 53. Relationship between palsas and environmental variables. The predicted probability of palsas is derived from the logistic regression model relating each predictor separately to the response variable.
Results

Figure 54. Observed and predicted distribution of palsas in the whole modelling area. The probabilities of palsa occurrence were calculated for the whole modelling area with a calibrated logistic regression model at 25-ha resolution. This palsa model is an example where the Kappa measure (0.565) indicated a good, and the area under the curve (AUC) value (0.950) an excellent, discrimination ability of the model.

Figure 55. Results of the hierarchical partitioning analyses for palsa distribution. The partitioning approach included nine environmental and three spatial variables. The independent contribution of the predictor is given as a percentage of the total variance (Chapter 4.2.3).
Table 19. Variables, coefficients, standard errors (SE), t- and p-values of the final model for palsa abundance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.817</td>
<td>0.138</td>
<td>-5.930</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Peat cover</td>
<td>8.365*10^{-4}</td>
<td>1.288*10^{-4}</td>
<td>6.494</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean shrub cover</td>
<td>-3.253*10^{-2}</td>
<td>9.119*10^{-3}</td>
<td>-3.568</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Figure 56. Results of the univariate analyses for palsa abundance (for more details see Fig. 52).

Figure 57. Evaluation of the final calibration model for the palsa abundance with regression residuals: (A) residuals vs fitted values and (B) normal Q–Q plot. Residuals should not show systematic patterns in figure (A) and residuals should be approximately normally distributed i.e. they should form rather straight line in figure (B).

Figure 58. Results of the hierarchical partitioning analyses for palsa abundance (for more details see Fig. 55).

5.3.2 Convex non-sorted circles

The number of present convex non-sorted circle squares used in the modelling was 221 (9.7%), whereas 2051 squares were unoccupied. According to univariate analyses mean altitude, mean slope angle, relative solar radiation, mean of canopy cover as well as mean of topographical wetness index were the most important variables for the circle distribution (Fig. 59). It is notable that the effect of mean altitude was over threefold compared to the second most important variable, mean slope angle. The results of the binary GLM are pre-
The probability of convex non-sorted circles occurrence increased when the proportion of concave topography as well as mean altitude increased and mean slope angle and relative radiation decreased. The response curve of mean altitude expressed a non-linear association between the distribution of convex non-sorted circles and altitude, and the shape of the curve is demonstrated in Figure 60. The final model explained 33.8% of the deviance change in the data (Table 18).

The evaluation measures calculated with the evaluation data indicated good discrimination ability of the logistic regression model. The Kappa value was 0.482 (SE = 0.056, $p < 0.001$) and AUC of ROC plot was 0.879 (SE = 0.023, $p < 0.0001$). The Kappa measure was calculated with cut off value of 0.31. The calibration model was utilised to predict the occurrence of convex non-sorted circle for the whole modelling area and the results are presented in Figure 61. Most of the present squares with low predicted probability (<0.2) were outside the core distribution area, namely in the western and southern parts of the Báisduattar – Áilegas area, and almost all absent squares with high predicted probability (>0.6) were in the northeast and east. Seventeen of the commission error squares were visited and six of them were found to contain convex non-sorted circles.

The autocovariate variable explained 8.3% of the variance in the data, which is over two-fold more than the most important environmental variable, namely mean of canopy cover (Fig. 62). Furthermore, the $y$-coordinate explained 3.1% and $x$-coordinate 1.7% of the variance in the data. In addition to mean of canopy cover, the most influential environmental variables were mean altitude, mean of topographical wetness index, mean slope angle and proportion of concave topography. Mean of canopy cover and mean of topographical wetness index were not in the final distribution model. Furthermore, the independent contribution of relative radiation was very low in HP despite the variable was highly significant in the distribution model.

Abundance modelling of convex non-sorted circles was conducted with 221 present squares. The cover of the feature ranged from 0.01 ha to 13.49 ha in the modelling squares. Mean altitude, mean of topographical wetness index, mean slope angle, aspect majority and standard deviation of wetness index had the greatest effect on the deviance change in univariate analyses (Fig. 63). The difference be-

Table 20. Variables, coefficients, standard errors (SE), $z$- and $p$-values of the final model for convex non-sorted circle distribution.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>$z$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>43.11</td>
<td>7.296</td>
<td>-5.908</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>-0.692</td>
<td>7.908*10^{-2}</td>
<td>-8.748</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Concave topography</td>
<td>7.095*10^{-2}</td>
<td>9.985*10^{-3}</td>
<td>7.105</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>0.209</td>
<td>3.313*10^{-2}</td>
<td>6.297</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude$^2$</td>
<td>-2.115*10^{-4}</td>
<td>3.896*10^{-5}</td>
<td>-5.431</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Relative radiation</td>
<td>-0.113</td>
<td>3.009*10^{-2}</td>
<td>-3.745</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Figure 59. Results of the univariate analyses for convex non-sorted circle distribution (for more details see Fig. 52).
Figure 60. Relationship between the convex non-sorted circle occurrence and mean altitude (for more details see Fig. 53).

Figure 61. Observed and predicted distribution of convex non-sorted circles in the whole modelling area (for more details see Fig. 54). The model is an example where the Kappa measure (0.482) indicated rather good, and the area under the curve (AUC) value (0.879) good, discrimination ability of the final model.

Figure 62. Results of the hierarchical partitioning analyses for convex non-sorted circle distribution (for more details see Fig. 55).
between mean altitude and the second most important variable was even more striking than in the distribution data; the effect of mean altitude was over four-fold compared to the moisture index.

The results of the GLM showed that the abundance of convex non-sorted circles increased when mean altitude as well as mean of topographical wetness index increased and mean slope angle decreased (Table 21). The assumption of normal errors was adequate because residuals were distributed relatively evenly and, above all, they were normally distributed (Fig. 64). The only discernible pattern in the residuals is caused by the landform classification system. Pattern areas, which were mapped by single points, can be detected from the residual plot (Fig. 64). The final abundance model explained 39% of the deviance change in the data (Table 18).

In the model evaluation, the Spearman’s rank correlation coefficient was 0.650 \( (p < 0.0001) \) that was even better than for the calibration data \( (R_s = 0.633, p < 0.0001) \). Autocovariate had the greatest effect on the response (Fig. 65). In addition, both coordinate variables explained over three percent of the variance in the response data. Four environmental variables, namely mean of topographical wetness index, mean altitude, proportion of concave topography and mean slope angle, explained over two percent and all other environmental predictors explained over one percent of the variance in the data. Therefore, all variables in the final GLM model were also important according to HP.

### 5.3.3 Stony earth circles

A total of 243 (10.7%) stony earth circle squares were used in the modelling. Mean altitude, mean of topographical wetness index, mean of canopy cover, relative solar radiation, proportion of concave topography and mean of shrub cover caused the largest changed in deviance in univariate analyses (Fig. 66). The variables and coefficients of the final logistic regression model for feature distribution are presented in Table 22. The probability of feature occurrence increased with increasing glacigenic deposit cover as well as mean altitude and decreasing mean of topographical wetness index and mean of canopy cover. The humped response curve of mean altitude is displayed in Figure 67. It is notable that the final model explained only 7.6% of the variation in the stony earth circle data (Table 18).

Cohen’s Kappa statistic for evaluation data indicated poor discrimination power of the model \( (\kappa = 0.254, SE = 0.053, p < 0.0001, \text{cut off value} = 0.20) \). The area under the curve measure was 0.735 \( (SE = 0.033, p < 0.0001) \) that indicated a rather good performance of the model. However, the evaluation value was
fairly close to the limit of poor model. The relatively poor discrimination ability of the model can also be detected from the prediction map (Fig. 68). However, the prediction accuracy of the model was slightly better than indicated by Kappa measure in the core distribution areas because all of the five visited absent squares with relatively high (> 0.2) predicted probability of occurrence contained stony earth circles.

In hierarchical partitioning, the autocovariate explained ca. 16.9% of the variance in the data, which was over four-fold more than the most important environmental variable, namely cover of glacigenic deposit (Fig. 69). Mean of shrub cover, topographical wetness index and canopy cover were the next most important environmental correlates. The results of the two statistical approaches differed partly; mean of shrub cover was not in the GLM model and the independent effect of mean altitude on the feature distribution was low in HP analysis.

5.3.4 Earth hummocks

The distribution modelling of active earth hummocks was performed with 1553 (68.4%) present squares. Mean of shrub cover, peat
Table 22. Variables, coefficients, standard errors (SE), z- and p-values of the final model for stony earth circle distribution.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>z</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-11.59</td>
<td>5.056</td>
<td>-2.293</td>
<td>0.0219</td>
</tr>
<tr>
<td>Glacigenic deposit cover</td>
<td>7.330*10^{-4}</td>
<td>1.787*10^{-4}</td>
<td>4.102</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean wetness index</td>
<td>-0.474</td>
<td>0.125</td>
<td>-3.799</td>
<td>0.0001</td>
</tr>
<tr>
<td>Mean canopy cover</td>
<td>-5.228*10^{-2}</td>
<td>1.388*10^{-2}</td>
<td>-3.768</td>
<td>0.0002</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>7.568*10^{-2}</td>
<td>2.496*10^{-2}</td>
<td>3.032</td>
<td>0.0024</td>
</tr>
<tr>
<td>Mean altitude^2</td>
<td>-1.077*10^{-4}</td>
<td>3.156*10^{-5}</td>
<td>-3.413</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Results

The discrimination power of the model was good (κ = 0.637, SE = 0.032, p < 0.0001) or excellent (AUC = 0.920, SE = 0.011, p < 0.0001) depending on the utilised evaluation measure. The optimal Kappa statistic was obtained with cut of value of 0.56. According to the field checking, the distribution model was even better than indicated by the evaluation values because five of the ten absent squares with high predicted probability (> 0.8) were present squares. In general, unsuccessful predictions were distributed relatively randomly in the modelling area (Fig. 72). However, most of the commission errors were in or near the core distribution area, whereas omission errors (predicted probability < 0.2) were in the distributional margins i.e. in fell regions.

Based on hierarchical partitioning, autocovariate was the best explanatory variable (Fig. 73). Seven of the nine environmental predictors explained over one percent of the variance in the response data, namely mean of shrub cover, peat cover, mean altitude, mean of topographical wetness index, proportion of concave topography, standard deviation of topographical wetness index and mean slope angle. Thus, all five variables of the final distribution model were among the six most influential factors in the partitioning routine.

Abundance modelling was performed with 1478 active present squares. The cover of the earth hummocks ranged from 0.01 ha to 25 ha in the data, i.e. some of the squares were fully occupied by earth hummocks. Univariate analyses indicated that mean of shrub cover is a superior correlate for earth hummock abun-
Results

Figure 68. Observed and predicted distribution of stony earth circle in the whole modelling area (for more details see Fig. 54). Stony earth circle model is an example where the Kappa measure (0.254) indicated poor, and the area under the curve (AUC) value (0.735) fairly good, discrimination ability of the model.

Figure 69. Results of the hierarchical partitioning analyses for stony earth circle distribution (for more details see Fig. 55).
Results

dance (Fig. 74). Other potentially important but clearly less effective factors are peat cover, mean slope angle, mean altitude, water cover and the mean as well as standard deviation of topographical wetness index.

The results of the final abundance model showed that the abundance of earth hummocks increased when mean of shrub cover, peat cover and mean of topographical wetness index increased and mean slope angle, mean altitude and water cover decreased (Table 24). The effect of shrub and peat cover was non-linear as in the distribution model. The assumption of normal errors was fairly proper but, again, the grid approach and the features size classification system caused some minor trend in the residual plot. Six predictors of the final model explained ca. 52% of the deviance change in the data (Table 18).

Spearman’s rank correlation coefficient for the evaluation data set was 0.722 (p < 0.0001) that indicated a relatively high prediction ability. According to the hierarchical partitioning, autocovariate had the highest explanation power but the distinction with the most important environmental factor, shrub cover, was in fact negligible (Fig. 75). In addition, peat cover, mean of topographical wetness

Table 23. Variables, coefficients, standard errors (SE), z- and p-values of the final model for earth hummock distribution.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>z</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-7.209</td>
<td>1.452</td>
<td>-4.966</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Peat cover</td>
<td>1.211*10^-2</td>
<td>1.672*10^-3</td>
<td>7.241</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Peat cover^2</td>
<td>-5.550*10^-6</td>
<td>7.216*10^-7</td>
<td>-7.692</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean wetness index</td>
<td>0.865</td>
<td>0.122</td>
<td>7.121</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean shrub cover</td>
<td>0.258</td>
<td>3.697*10^-2</td>
<td>6.988</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean shrub cover^2</td>
<td>-6.727*10^-3</td>
<td>3.966*10^-3</td>
<td>-3.966</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>-1.097*10^-2</td>
<td>1.578*10^-3</td>
<td>-6.954</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Std of wetness index</td>
<td>1.066</td>
<td>0.202</td>
<td>5.273</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Figure 70. Results of the univariate analyses for earth hummock distribution (for more details see Fig. 52).

Figure 71. Relationship between earth hummocks and environmental variables (for more details see Fig. 53).
Figure 72. Observed and predicted distribution of earth hummock in the whole modelling area (for more details see Fig. 54).

Figure 73. Results of the hierarchical partitioning analyses for earth hummock distribution (for more details see Fig. 55).

Figure 74. Results of the univariate analyses for earth hummock abundance (for more details see Fig. 52).
index, mean slope angle, glacigenic deposit, proportion of concave topography and mean altitude were the most influential factors in the partitioning routine. The water cover variable was significant in the final GLM model but its independent effect on the response was fairly marginal in HP, ca. 0.5%.

### 5.3.5 Peat pounus

Active peat pounus were located from 678 (29.8%) modelling squares. According to univariate analyses, mean slope angle, water cover, peat cover, mean of shrub cover, proportion of concave topography, standard deviation of topographical wetness index and mean of canopy cover have the greatest effect on the feature distribution (Fig. 76). Moreover, mean altitude, relative solar radiation and mean of topographical wetness index stand out from the rest of the variables. The set of the predictors in the final logistic regression model was diverse, including eight correlates. The probability of peat pounu occurrence increased when the cover of peat, water and shrub as well as standard deviation of topographical wetness index, mean of canopy cover and proportion of concave topography increased and mean slope angle and proportion of relative radiation decreased (Table 25). Three of the predictors were non-linearly associated with the response, namely peat and water cover as well as relative solar radiation. The shape of the response curve of peat cover, mean slope angle and shrub cover is shown in Figure 77. The final model explained ca. 47% of the deviance change in the pounu data (Table 18).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.207</td>
<td>0.330</td>
<td>-3.659</td>
<td>0.0003</td>
</tr>
<tr>
<td>Mean shrub cover</td>
<td>6.765*10^{-2}</td>
<td>6.464*10^{-3}</td>
<td>10.467</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean shrub cover(^2)</td>
<td>-1.281*10^{-3}</td>
<td>2.138*10^{-4}</td>
<td>-5.993</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Peat cover</td>
<td>1.031*10^{-3}</td>
<td>1.053*10^{-4}</td>
<td>9.790</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Peat cover(^2)</td>
<td>-5.182*10^{-7}</td>
<td>5.541*10^{-8}</td>
<td>-9.351</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>-5.988*10^{-2}</td>
<td>9.240*10^{-3}</td>
<td>-6.480</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean wetness index</td>
<td>0.158</td>
<td>2.982*10^{-2}</td>
<td>5.298</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>-1.506*10^{-3}</td>
<td>4.234*10^{-4}</td>
<td>-3.556</td>
<td>0.0004</td>
</tr>
<tr>
<td>Water cover</td>
<td>-3.590*10^{-3}</td>
<td>1.026*10^{-3}</td>
<td>-3.500</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Figure 75. Results of the hierarchical partitioning analyses for earth hummock abundance (for more details see Fig. 55).

Figure 76. Results of the univariate analyses for peat pounu distribution (for more details see Fig. 52).
The Kappa value was 0.641 (SE = 0.032, \( p < 0.001 \)) and AUC of ROC plot was 0.913 (SE = 0.012, \( p < 0.0001 \)). Therefore, the discrimination ability of the distribution model was good or excellent depending on the utilised evaluation approach. The \( \kappa \) measure was calculated with the cut off value of 0.41. The probability map of peat pounu occurrence for the whole modelling area is presented in Figure 78. Most of the present squares with low pounu probability (< 0.1) were in the eastern, and absent squares with high probability (> 0.8) were in the southern, part of the study area and around the Áitečohkka fell. Twelve of the commission error squares were visited and all of them were found to contain peat pounus.

In HP analysis, the autocovariate and peat cover explained about the same amount of variance of the response data (Fig. 79). The other most influential environmental factors were mean of shrub cover, mean slope angle, proportion of concave topography and mean as well as standard deviation of topographical wetness index. Explanation power of water cover, relative solar radiation and mean of canopy cover was distinctively less than one percent despite that they were in the final GLM model.

Abundance modelling was conducted with 615 present pounu squares. The cover of the feature ranged from 0.01 ha to 22.9 ha in the modelling squares. Mean slope angle had the greatest effect on pounu abundance in univari-

Table 25. Variables, coefficients, standard errors (SE), \( z \)- and \( p \)-values of the final model for peat pounu distribution.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>( z )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>88.35</td>
<td>25.41</td>
<td>3.477</td>
<td>0.0005</td>
</tr>
<tr>
<td>Peat cover</td>
<td>4.698*10^{-3}</td>
<td>4.705*10^{-4}</td>
<td>9.985</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Peat cover(^2)</td>
<td>-1.635*10^{-6}</td>
<td>2.488*10^{-7}</td>
<td>-6.572</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>-0.430</td>
<td>6.450*10^{-2}</td>
<td>-6.665</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Std of wetness index</td>
<td>0.999</td>
<td>0.221</td>
<td>4.524</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean canopy cover</td>
<td>3.845*10^{-2}</td>
<td>9.321*10^{-3}</td>
<td>4.125</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Water cover</td>
<td>5.723*10^{-3}</td>
<td>1.398*10^{-3}</td>
<td>4.093</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Water cover(^2)</td>
<td>-2.818*10^{-6}</td>
<td>7.679*10^{-7}</td>
<td>-3.669</td>
<td>0.0002</td>
</tr>
<tr>
<td>Concave topography</td>
<td>3.685*10^{-2}</td>
<td>9.497*10^{-3}</td>
<td>3.880</td>
<td>0.0001</td>
</tr>
<tr>
<td>Relative radiation</td>
<td>-2.315</td>
<td>0.6279</td>
<td>-3.687</td>
<td>0.0002</td>
</tr>
<tr>
<td>Relative radiation(^2)</td>
<td>1.423*10^{-2}</td>
<td>3.874*10^{-3}</td>
<td>3.674</td>
<td>0.0002</td>
</tr>
<tr>
<td>Mean shrub cover</td>
<td>4.253*10^{-2}</td>
<td>1.175*10^{-2}</td>
<td>3.620</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Figure 77. Relationship between peat pounu distribution and environmental variables (for more details see Fig. 53).
Figure 78. Observed and predicted distribution of peat pounus in the whole modelling area (for more details see Fig. 54).

Figure 79. Results of the hierarchical partitioning analyses for peat pounu distribution (for more details see Fig. 55).

Figure 80. Results of the univariate analyses for peat pounu abundance (for more details see Fig. 52).
ate analyses and the deviance change ability of the other variables was over two-fold less (Fig. 80). It is notable that peat was in tenth position and such variables as sand and gravel, rock terrain and relative solar radiation were more influential. The results of the final model are presented in Table 26. The pounu abundance increased when peat cover increased and mean slope angle as well as elevation-relief ratio decreased in the modelling square. The non-linear association between pounus and slope angle is demonstrated in Figure 81. The final abundance model explained 47.2% of the variation in the data (Table 18).

The residuals of the calibrated model had a slight trend and their distribution was only fairly close to normal. However, the calibration model was accepted because: (1) the utilised transformation gave the best result, (2) the model’s ability to predict pounu abundance with evaluation data was good ($R^2 = 0.715$, $p < 0.0001$), (3) the model was rather robust ($R^2$ of calibration model was 0.689) and (4) the results of the GLM model concorded fairly well with the outcomes of HP analyses (Fig. 82). The peat cover explained 6.7%, mean slope angle 3.4%, whereas elevation-relief ratio explained only 0.5% of the variation in the data. Other notable correlates were mean of topographical wetness index, mean of shrub cover and proportion of concave topography. Finally, it is worth of noting that, for the first time in this study, the environmental variable explained more than the autocovariate; however, the difference was not great.

Table 26. Variables, coefficients, standard errors (SE), t- and $p$-values of the final model for peat pounu abundance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>t</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.544</td>
<td>0.204</td>
<td>2.662</td>
<td>0.0081</td>
</tr>
<tr>
<td>Peat cover</td>
<td>6.695*10^{-4}</td>
<td>5.750*10^{-5}</td>
<td>11.643</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>-0.377</td>
<td>6.297*10^{-2}</td>
<td>-5.987</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle$^2$</td>
<td>1.444*10^{-2}</td>
<td>6.836*10^{-3}</td>
<td>4.600</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Elevation-relief ratio</td>
<td>-1.007</td>
<td>0.284</td>
<td>-3.549</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

Figure 81. Relationship between peat pounu abundance and mean slope angle (for more details see Fig. 53).

Figure 82. Results of the hierarchical partitioning analyses for peat pounu abundance (for more details see Fig. 55).
of the deviance change in the data (Table 18). Kappa value of the evaluation data was 0.318 (SE = 0.047, \( p < 0.0001 \), cut off value = 0.19) indicating fairly poor discrimination ability of the model. Instead, area under the curve (AUC) measure of 0.806 (SE = 0.024, \( p < 0.0001 \)) indicated rather good model performance. Predicted probabilities of stone pit occurrence for the whole modelling area are visualised in Figure 85. Present squares have, in general, higher predicted probabilities than absent squares, which concords well with the threshold independent evaluation measure. When the probabilities are truncated back to binary form, the worse modelling performance is revealed. However, based on field evaluation the distribution model is still better than indicated by Kappa measure because 13 of the 19 absent squares with relatively high predicted probability (> 0.3) were occupied by stone pits.

In hierarchical partitioning, the autocovariate variable explained independently at 4.1% of the variation in the response data (Fig. 86). Eight of the environmental predictors explained more than one percent of the variance, namely mean slope angle, mean of shrub cover, mean of topographical wetness index, peat cover, standard deviation of topographical wetness index, proportion of concave topography, mean altitude and moraine cover.

**5.3.6 Stone pits**

Of the 2272 modelling squares 247 (10.9%) were found to contain active stone pits. According to univariate analyses, standard deviation of topographical wetness index, mean slope angle, mean of shrub cover, mean of topographical wetness index, as well as sand and gravel cover have the greatest effect on stone pit occurrence (Fig. 83). Based on logistic regression, the distribution of features is determined by mean slope angle, mean of shrub cover, standard deviation of topographical wetness index and moraine cover (Table 27). The shape of the response curve of glacigenic deposit and slope angle are exhibited in Figure 84. The final model explained at 19%
Figure 85. Observed and predicted distribution of stone pits in the whole modelling area (for more details see Fig. 54).

Table 27. Variables, coefficients, standard errors (SE), z- and p-values of the final model for stone pit distribution.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>z</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-5.209</td>
<td>0.939</td>
<td>-5.548</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>-0.393</td>
<td>6.669*10^{-2}</td>
<td>-5.885</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean shrub cover</td>
<td>5.796*10^{-2}</td>
<td>1.067*10^{-2}</td>
<td>5.431</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Std of wetness index</td>
<td>1.004</td>
<td>0.264</td>
<td>3.796</td>
<td>0.0001</td>
</tr>
<tr>
<td>Glacigenic deposit cover</td>
<td>2.011*10^{-3}</td>
<td>5.702*10^{-4}</td>
<td>3.527</td>
<td>0.0004</td>
</tr>
<tr>
<td>Glacigenic deposit cover^2</td>
<td>-6.478*10^{-7}</td>
<td>1.920*10^{-7}</td>
<td>-3.375</td>
<td>0.0007</td>
</tr>
</tbody>
</table>
Results

Slope and shrub variables were important predictors based on both approaches but the standard deviation of topographical wetness index and glacigenic deposit were clearly less effective in HP than in GLM.

5.3.7 Sorted nets

The number of present active sorted net squares used in the modelling was 185 (8.1%). Standard deviation of topographical wetness index, mean altitude, peat cover and mean of topographical wetness index changed most the deviance in univariate analyses (Fig. 87). The same set of correlates was in the final logistic regression model (Table 28). The probability of finding sorted net from the modelling square increased when the standard deviation and mean of topographical wetness index, mean altitude as well as peat cover increased.

The humped shape of the response curve of peat cover is illustrated in Figure 88. The final model explained ca. 14% of the deviance change in the data (Table 18).

In model evaluation, a Kappa measure of 0.170 (SE = 0.053, \( p < 0.0001 \), cut off value = 0.18) and an AUC value of 0.722 (SE = 0.035, \( p < 0.0001 \)) were obtained. The \( \kappa \) measure indicated poor model performance and concorded well with the low proportion of explained deviance of the calibration model. The fairly poor prediction ability of the model can also be seen in Figure 89. Once again, the threshold-independent measure indicated a better discrimination capability of the distribution model than the threshold-dependent approach. However, the AUC value was relatively close to the limit of poor model; the difference was less then the amount of one standard error. Despite that the evaluation results indicated insufficient prediction ability of the model, it can be used to detect new feature areas because six of the seventeen commis-

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>( z )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-21.92</td>
<td>2.062</td>
<td>-10.632</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Std of wetness index</td>
<td>1.753</td>
<td>0.252</td>
<td>6.945</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean wetness index</td>
<td>0.968</td>
<td>0.143</td>
<td>6.790</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>1.276\times10^{-2}</td>
<td>2.128\times10^{-3}</td>
<td>5.997</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Peat cover</td>
<td>1.860\times10^{-3}</td>
<td>6.058\times10^{-4}</td>
<td>3.070</td>
<td>0.0021</td>
</tr>
<tr>
<td>Peat cover(^2)</td>
<td>-1.318\times10^{-6}</td>
<td>3.725\times10^{-7}</td>
<td>-3.537</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

Table 28. Variables, coefficients, standard errors (SE), \( z \)- and \( p \)-values of the final model for sorted net distribution.
sion error sites (predicted probability > 0.3) were found to contain small fields of sorted nets.

Based on the HP, the autocovariate had the highest contribution in the sorted net occurrence (Fig. 90). Independently the most influential environmental factors were proportion of concave topography, mean of topographical wetness index, mean slope angle and standard deviation of topographical wetness index. In addition, water cover, mean altitude, peat cover and glacigenic deposit cover explained over one percent of the variation in the sorted net data. The differences between GLM and HP results were quite clear because only the

Figure 88. Relationship between sorted nets and peat cover (for more details see Fig. 53).

Figure 89. Observed and predicted distribution of sorted nets in the whole modelling area (for more details see Fig. 54).
wetness index variables were among the most important factors in partitioning.

### 5.3.8 Sorted stripes

The total number of the present active stone stripe squares used in the modelling was 185 (8.1%). Mean slope angle and mean altitude were distinctively the most influential predictors in univariate analyses (Fig. 91) and these factors were the only variables in the final distribution model as well (Table 29). The probability of feature presence increased when mean altitude and mean slope angle increased. The shape of the response curve of altitude was s-shaped and slope angle humped (Fig. 92). The final distribution model explained ca. 44% of the deviance change in the response data (Table 18).

According to the evaluation, the prediction ability of the model was good based on the Kappa value ($\kappa \pm SE = 0.437 \pm 0.068, p < 0.0001$, cut off value = 0.32) and excellent based on the area under the curve measure ($\text{AUC} \pm \text{SE} = 0.937 \pm 0.012, p < 0.0001$). The good success of the model can also be seen in the prediction map (Fig. 93). Nevertheless, over thirty of the present squares had low predicted probability (less than 0.1) and twenty of the squares with fairly high probability (> 0.6) were absent squares. However, in the field checking, the model was shown to be slightly better because three of the commission error squares (predicted probability > 0.8) were actually present sites.

Mean altitude explained 6.1% of the variation in the sorted stripe data and was independently measured as the most important variable in hierarchical partitioning (Fig. 94). However, the explanation power of the autocovariate was fairly close to the proportion of mean altitude. Moreover, the $y$-coordinate explained slightly over one percent of the variance. Mean slope angle, mean of shrub cover, standard deviation of topographical wetness index, glacigenic deposit cover and proportion of concave topography had clearly less expla-

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>$z$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-18.98</td>
<td>1.439</td>
<td>-13.188</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>$2.375 \times 10^{-2}$</td>
<td>$2.196 \times 10^{-3}$</td>
<td>10.811</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>1.763</td>
<td>0.286</td>
<td>6.165</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle$^2$</td>
<td>$-9.656 \times 10^{-2}$</td>
<td>$1.870 \times 10^{-2}$</td>
<td>-5.165</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
Results

Figure 92. Relationship between sorted stripes and mean altitude and mean slope angle (for more details see Fig. 53).

Figure 93. Observed and predicted distribution of sorted stripes in the whole modelling area (for more details see Fig. 54).
nation power than mean altitude, but still over one percent. GLM and HP gave similar results because altitude and slope angle were the most important predictors in both approaches.

### 5.3.9 Non-sorted solifluction terraces

Altogether 266 (11.7%) of the 2272 modelling squares were found to contain active non-sorted terraces. In univariate analyses, standard deviation of topographical wetness index, mean slope angle, mean altitude, mean of topographical wetness index and relative solar radiation were the most important correlates for distribution (Fig. 95). The final logistic regression model included three predictors (Table 30). The probability of feature occurrence increased with increasing standard deviation of topographical wetness index as well as mean altitude and decreasing peat cover. All variables were linearly associated with the response. The final model explained 10.1% of the variation in distribution of non-sorted solifluction terraces (Table 18).

In model evaluation, a Kappa measure of 0.047 (SE = 0.043, \( p = 0.204 \), cut off value = 0.26) indicated very poor discrimination ability of the model. The area under the curve of ROC plot (0.725, SE = 0.026, \( p < 0.0001 \)) denoted a better prediction power than the \( \kappa \) value, but it was still almost poor. The rather low prediction capability of the distribution model and the difference between the Kappa and AUC values can also be seen in Figure 96. However, by means of the extrapolated calibration model, it was possible to discover a few new feature sites because four of the eleven visited commission error squares were present sites.

The autocovariate explained 10.5% and \( x \)-coordinate 1.7% of the variance in the non-sorted solifluction data in hierarchical partitioning (Fig. 97). Peat cover, mean altitude, mean slope angle and standard deviation of topographical wetness index were the most important environmental factors but clearly less effective than the autocovariate. In the

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>z</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-8.588</td>
<td>1.049</td>
<td>-8.191</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Std of wetness index</td>
<td>1.335</td>
<td>0.222</td>
<td>6.026</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>8.734*10^{-3}</td>
<td>1.593*10^{-3}</td>
<td>5.484</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Peat cover</td>
<td>-2.352*10^{-3}</td>
<td>4.480*10^{-4}</td>
<td>-5.249</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Table 30. Variables, coefficients, standard errors (SE), z- and \( p \)-values of the final model for non-sorted solifluction terrace distribution.
end, the results of the GLM and HP were fairly similar despite that slight differences occurred (Table 30 & Fig. 97).

### 5.3.10 Sorted solifluction sheets

The number of active present feature squares used in the modelling was 404 (17.8%). The univariate analyses exhibited the overwhelming effect of mean slope angle and mean altitude on sorted sheet occurrence (Fig. 98). These topographical parameters were also the most important predictors in the final logistic model with a positive sign (Table 31). Other predictors in the model were aspect majority, mean of canopy cover and proportion of concave topography that all had a negative effect on the sheet occurrence. The affect of concave topography on the feature probability was non-linear. In Figure 99 are displayed the response curves of slope angle, altitude and canopy cover. The final model explained 60.1% of the deviance change in the sheet data (Table 18).

The evaluation measures indicated very good and excellent discrimination ability of the logistic regression model. The Kappa
Results

Figure 97. Results of the hierarchical partitioning analyses for non-sorted solifluction terrace distribution (for more details see Fig. 55).

Figure 98. Results of the univariate analyses for sorted solifluction sheet distribution (for more details see Fig. 52).

Table 31. Variables, coefficients, standard errors (SE), z- and p-values of the final model for sorted solifluction sheet distribution.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>z</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-7.887</td>
<td>2.585</td>
<td>-3.051</td>
<td>0.0023</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>0.934</td>
<td>6.753*10^-2</td>
<td>13.833</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>3.001*10^-2</td>
<td>3.134*10^-3</td>
<td>9.576</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Aspect majority</td>
<td>-5.557*10^-3</td>
<td>1.106*10^-3</td>
<td>-5.025</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean canopy cover</td>
<td>-0.103</td>
<td>2.515*10^-2</td>
<td>-4.094</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Elevation-relief ratio</td>
<td>-6.037</td>
<td>1.500</td>
<td>-4.025</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Concave topography</td>
<td>-0.276</td>
<td>7.643*10^-2</td>
<td>-3.608</td>
<td>0.0003</td>
</tr>
<tr>
<td>Concave topography^2</td>
<td>2.675*10^-3</td>
<td>7.472*10^-4</td>
<td>3.580</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Results

value was 0.636 (SE = 0.039, p < 0.0001) and AUC of ROC plot was 0.943 (SE = 0.009, p < 0.0001). The best Kappa measure was obtained with the cut off value of 0.44. Most of the present squares with low feature probability (< 0.2) were in the margins of larger sheet fields, and almost all absent squares with very high probability (> 0.8) were in the northeast and east (Fig. 100). Eight of the commission error sites were visited, but none of them were found to contain sorted sheets.

The results of the HP denoted the importance of the mean altitude, mean slope angle, mean of shrub cover, mean of canopy cover

Figure 99. Relationship between sorted solifluction sheets and environmental variables (for more details see Fig. 53).
and glacigenic deposition cover from the set of environmental predictors (Fig. 101). In addition, autocovariate variable explained 7.8% and $y$-coordinate 1.1% of the variation in the response data. Thus, the altitude and slope angle were the most important environmental predictors in both statistical approaches.

Abundance modelling of sorted sheets was conducted with all 404 present squares. The cover of the feature ranged from 0.01 ha to 16.06 ha in the modelling squares. Mean altitude, mean slope angle, aspect majority and relative solar radiation had the greatest effect on the deviance change in univariate analyses (Fig. 102) but the proportion of explained deviance decreased rapidly between the three most effective predictors. The results of the generalized linear model showed that the cover of sorted sheets increased when mean altitude as well as mean slope angle increased and relative radiation at first decreased but then increased (Table 32). The final abundance model explained ca. 46% of the deviance change in the data (Table 18).

The assumption of normal errors was correct because residuals of the model were randomly distributed when they were plotted against fitted values. Furthermore, distri-
Results

The distribution of the residuals was close to normal. The Spearman’s rank correlation coefficient for the calibration data was 0.650 ($p < 0.0001$) and for the evaluation data 0.539 ($p < 0.0001$). Thus, some level of degradation of prediction power occurred when the calibration model was evaluated. Based on hierarchical partitioning, the autocovariate was the best explanatory variable (Fig. 103). Four of the environmental variables explained over one percent of the variation, namely mean altitude, mean slope angle, standard deviation of topographical wetness index and mean of shrub cover. Therefore, mean altitude and mean slope angle were the most important determinants in both approaches but the effect of relative radiation decreased substantially in HP.

5.3.11 Sorted solifluction streams

A total of 233 (10.3%) modelling squares were found to contain active sorted streams. Mean altitude, mean slope angle and elevation-relief ratio caused the largest change in deviance in univariate analyses (Fig. 104). The rest of the variables affected clearly less than the above mentioned. The variables and coefficients of the final logistic regression model for feature distribution are presented in Table 33. The probability of feature occurrence increased with increasing mean altitude and mean slope angle.

Table 32. Variables, coefficients, standard errors (SE), t- and $p$-values of the final model for sorted solifluction sheet abundance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>$t$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>13.45</td>
<td>5.170</td>
<td>2.602</td>
<td>0.0098</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>8.4287*10^{-3}</td>
<td>6.693*10^{-4}</td>
<td>12.593</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>0.103</td>
<td>1.976*10^{-2}</td>
<td>5.198</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Relative radiation</td>
<td>-0.426</td>
<td>0.127</td>
<td>-3.358</td>
<td>0.0009</td>
</tr>
<tr>
<td>Relative radiation$^2$</td>
<td>2.715*10^{-3}</td>
<td>7.859*10^{-4}</td>
<td>3.455</td>
<td>0.0006</td>
</tr>
</tbody>
</table>
angle. Response curves of mean altitude and mean slope are illustrated in Figure 105. The final model explained ca. 45% of the deviance change in the response data (Table 18).

Cohen’s Kappa statistic for evaluation data indicated good discrimination power of the model ($\kappa = 0.565, SE = 0.052, p < 0.0001$, cut off value $= 0.31$). The area under the curve measure was 0.951 ($SE = 0.009, p < 0.0001$) which indicated an excellent performance of the model. The good prediction ability of the model can also be seen from Figure 106. Most of the present sites with low predicted probability ($< 0.1$) were on the edges and absent sites with high probability ($> 0.8$) in the core distribution area. Five of the seven commission error squares were found to be present sites in the field evaluation.

According to the hierarchical partitioning, the most effective environmental predictors were mean altitude, mean slope angle, mean of canopy cover, mean of shrub cover, mean of topographical wetness index and glacigenic deposit cover (Fig. 107). The mean altitude explained slightly more of the variation in the data than autocovariate. In general, the results of the GLM and HP approaches were similar.

5.3.12 Deflations

A total of 290 (12.8%) of the 2272 modelling squares were found to contain deflations. According to univariate analyses mean of canopy cover, mean altitude, standard deviation of topographical wetness index, sand and gravel cover as well as mean of shrub cover were the most important variables for the deflation distribution (Fig. 108). It is notable that the canopy cover and mean altitude changed the deviance much more than the other variables. The results of the GLM are presented in Table 34. The probability of finding deflations in a modelling square increased when the proportion of sand and gravel as well as mean altitude increased and mean of canopy and

![Figure 104](image)

Figure 104. Results of the univariate analyses for sorted solifluxion stream distribution (for more details see Fig. 52).

![Figure 105](image)

Figure 105. Relationship between the sorted solifluxion stream occurrence and mean altitude and mean slope angle (for more details see Fig. 53).
shrub cover decreased. The response curves of sand and gravel and mean altitude were humped expressing the non-linear association between the distribution of features and predictors. The shapes of the response curves are illustrated in Figure 109. The final distribution model explained 20.5% of the deviance in the data (Table 18).

The evaluation measures indicated a fairly good discrimination ability of the distribution model. The Kappa value was 0.446 (SE = 0.053, \( p < 0.0001 \)) and AUC of ROC plot was

---

Table 33. Variables, coefficients, standard errors (SE), \( z \)- and \( p \)-values of the final model for sorted solifluction stream distribution.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>( z )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>16.24</td>
<td>-1.042</td>
<td>-15.59</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean altitude</td>
<td>2.723*10^{-2}</td>
<td>2.130*10^{-3}</td>
<td>12.78</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean slope angle</td>
<td>0.472</td>
<td>4.618*10^{-2}</td>
<td>10.22</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

---

Figure 106. Observed and predicted distribution of sorted solifluction streams in the whole modelling area (for more details see Fig. 54).
0.812 (SE = 0.028, \( p < 0.0001 \)). The optimal \( \kappa \) measure was obtained with cut off value of 0.31. The predictions calculated for the whole modelling area are presented in Figure 110. Many of the present squares with low feature probability (< 0.1) occurred on the fells or fell slopes and most of the absent squares with rather high probability (> 0.3) were in the valleys. Nineteen of the commission error squares were visited, and thirteen of them were found to contain deflations.

The autocovariate explained 11.6% of the variance in the response data that was over two-fold more than the most important environmental variable, sand and gravel cover (Fig. 111). In addition, \( x \)-coordinate explained 1.6% of the variance indicating a slight geographical trend in the response data. The other most influential environmental predictors were standard deviation of topographical wetness index, glacigenic deposit cover and canopy cover. The results of the GLM and HP had notable differences. Mean altitude and mean of shrub cover were independently measured clearly less important than standard deviation of topographical wetness index and moraine cover, which were excluded from the final distribution model.

### 5.3.13 Modelling results: a summary

The modelling results are summarised in Tables 35 and 36, and Figures 112 and 113. In distribution modelling, the amount of explained deviance varied from 7.6% (stony earth circles) to ca. 60% (sorted solifluction sheets). In abundance modelling, values ranged from
Results

Figure 109. Relationship between deflations and sandy soils and altitude (for more details see Fig. 53).

Figure 110. Observed and predicted distribution of deflations in the whole modelling area (for more details see Fig. 54).
In model evaluation, the kappa values ranged from 0.047 (non-sorted solifluction terraces) to 0.641 (peat pounus) and AUC measures from 0.722 (sorted nets) to 0.951 (sorted solifluction streams). In the abundance modelling, earth hummock and peat pounus models obtained the best prediction ability ($R_s > 0.7$). The number of the predictors varied from two to eight (distribution model of peat pounus) in the final GLMs. In addition, models included commonly at least one non-linear factor.

Table 35. Summary of the model performances of the distribution models. Kappa and area under the curve (AUC) values are for evaluation data [italic = good prediction ability, bold = excellent prediction ability (Landis & Koch 1977: 165; Swets 1988: 1292)].

<table>
<thead>
<tr>
<th>Landform</th>
<th>Change in deviance (%)</th>
<th>Kappa (eval)</th>
<th>AUC (eval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palsa</td>
<td>52.3</td>
<td>0.565</td>
<td>0.950</td>
</tr>
<tr>
<td>Convex non-sorted circle</td>
<td>33.8</td>
<td>0.482</td>
<td>0.879</td>
</tr>
<tr>
<td>Stony earth circle</td>
<td>7.6</td>
<td>0.254</td>
<td>0.735</td>
</tr>
<tr>
<td>Earth hummock</td>
<td>47.0</td>
<td>0.637</td>
<td>0.920</td>
</tr>
<tr>
<td>Peat pounu</td>
<td>46.9</td>
<td>0.641</td>
<td>0.913</td>
</tr>
<tr>
<td>Stone pit</td>
<td>18.8</td>
<td>0.318</td>
<td>0.806</td>
</tr>
<tr>
<td>Sorted net</td>
<td>14.2</td>
<td>0.170</td>
<td>0.722</td>
</tr>
<tr>
<td>Sorted stripes</td>
<td>43.7</td>
<td>0.437</td>
<td>0.937</td>
</tr>
<tr>
<td>Non-sorted solifluction terrace</td>
<td>10.1</td>
<td>0.047</td>
<td>0.725</td>
</tr>
<tr>
<td>Sorted solifluction sheet</td>
<td>60.1</td>
<td>0.636</td>
<td>0.943</td>
</tr>
<tr>
<td>Sorted solifluction streams</td>
<td>45.2</td>
<td>0.565</td>
<td>0.951</td>
</tr>
<tr>
<td>Deflation</td>
<td>20.5</td>
<td>0.446</td>
<td>0.812</td>
</tr>
</tbody>
</table>

Table 36. Summary of the model performances of the abundance models. Spearman’s rank correlation coefficients ($R_s$) are for calibration (cal) and evaluation (eval) data.

<table>
<thead>
<tr>
<th>Landform</th>
<th>Change in deviance (%)</th>
<th>$R_s$ (cal)</th>
<th>$R_s$ (eval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palsa</td>
<td>37.1</td>
<td>0.647</td>
<td>0.274</td>
</tr>
<tr>
<td>Convex non-sorted circle</td>
<td>39.0</td>
<td>0.633</td>
<td>0.650</td>
</tr>
<tr>
<td>Earth hummock</td>
<td>51.9</td>
<td>0.757</td>
<td>0.722</td>
</tr>
<tr>
<td>Peat pounu</td>
<td>47.2</td>
<td>0.689</td>
<td>0.715</td>
</tr>
<tr>
<td>Sorted solifluction sheet</td>
<td>45.6</td>
<td>0.650</td>
<td>0.539</td>
</tr>
</tbody>
</table>
**Results**

Figure 112. Summary of the environmental factors of the final distribution models. The direction of the effect is indicated with signs (+ = positive correlate, − = negative correlate, + − = non-linear correlate with a humped response curve, − + = non-linear correlate with a downward humped response curve).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Mean altitude</th>
<th>Mean slope angle</th>
<th>Elevation-ratio</th>
<th>Concave topography</th>
<th>Mean wetness index</th>
<th>Std of wetness index</th>
<th>Water cover</th>
<th>Aspect majority</th>
<th>Peat cover</th>
<th>Glaciogenic deposit cover</th>
<th>Sand and gravel cover</th>
<th>Rock terrain cover</th>
<th>Mean shrub cover</th>
<th>Mean canopy cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palsa</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convex non-sorted circle</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td></td>
<td>+</td>
<td></td>
<td>-</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stony earth circle</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth hummock</td>
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<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat pounu</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone pit</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td></td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorted net</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorted stripe</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td></td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-sorted solifluction terrace</td>
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<td>Sorted solifluction sheet</td>
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<td>Deflation</td>
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Figure 113. Summary of the environmental factors of the final abundance models (for more details see Figure 112).
6 DISCUSSION

6.1 Periglacial landforms: prevalence, distribution, activity and morphology

In northernmost Finnish Lapland, periglacial phenomena are common close or above the treeline. However, the frequencies of the features and diversity of the types vary spatially (e.g. Piironen 1969, 1972; Seppälä 1982b, 1987, 1993b, 1997b; Kejonen 1997; Hjort & Seppälä 2003; Luoto & Hjort 2004, 2005). In the study area, the prevalence of the periglacial landforms varied from 0.2% to 65.4% at the 25-ha resolution. The most abundant features were earth hummocks, peat pounus, sorted nets and sorted solifluction sheets. The specific environmental requirements and fairly continental climate of the study region are probably the main reasons for the small number of slope features such as slushflow tracks, ploughing and braking blocks, non-sorted solifluction lobes and taluses (e.g. Rapp 1986; Pissart 1993). Moreover, the low activity of certain processes may cause the rarity of, for example, non-sorted and sorted polygons, snow accumulation hollows and stone pavements. In general, the prevalence differences between different landform types were quite expected if compared to other subarctic regions (cf. Lundqvist 1962; Harris C. 1982; Jahn & Siedlecki 1982; Meier 1987, 1991; Niessen et al. 1992).

The environmental conditions of the studied area have promoted the formation of different cryoturbation and peat accumulation based non-sorted features (e.g. van Vliet-Lanoë and Seppälä 2002). For example, earth hummocks and peat pounus covered over 15% of the study area. Also the sorted landforms were rather common periglacial features. For instance, the total cover of sorted nets and solifluction sheets was over 24 km² (4%). However, the abundance of the sorted features describes mainly the former conditions and periglacial processes rather than the present circumstances in northernmost Finland (see Kejonen 1997; Luoto & Hjort 2004).

The diversity of the periglacial landforms varied spatially although some clumped patterns could be identified from the study area. Analysis squares without periglacial features were commonly characterised by fairly low slope angles and dry soils. However, the vegetation types and densities as well as altitudes can vary considerable between the non-occurrence sites. Squares with only one landform type were commonly occupied by the extensive fields of earth hummocks, peat pounus, palsa or inactive sorted nets. Considerably many of the modelling squares included two to four different landform types, which is mainly caused by the presence of feature continuums (Figs. 30 & 114; see also Karte 1979: 146; Ballantyne & Harris 1994: 205–209). The most common sequences were: (1) earth hummock – stone pit – peat pounu – palsa, (2) sorted stripe – sorted solifluction stream – sorted solifluction sheet, (3) sorted polygon/circle – sorted net – sorted stripe and (4) non-sorted step – convex non-sorted circle – earth hummock/active sorted net (cf. Piironen 1969; Seppälä 1982b; van Vliet-Lanoë & Seppälä 2002). The sites with highly variable environmental conditions often had more than four types of periglacial landforms. Commonly, these squares included upper fell areas with sorted patterned ground and slope landforms as well as valleys with non-sorted circles and solifluction features.

The activity of periglacial landforms changes temporally as well as spatially and it is fairly challenging to classify features to discrete active/inactive classes (e.g. Goldthwait 1976; Matthews et al. 1998; Haugland 2004; also see below). The activity classification method used in this study was rather suggestive and it probably emphasized the number of the active landforms because the classification was only used to separate clearly inactive landform occurrences from at least partly active features. Therefore, field measurements of the processes should be performed to draw
more detailed conclusions of the activity of the periglacial features in the region (cf. Kejonen 1994; Seppälä 2005c). Nonetheless, based on the mapping results, it can be seen that northern Finnish Lapland is a transitional zone between active continuous permafrost regions and stabilized relict feature areas (cf. Jahn & Siedlecki 1982). In general, the sensitive subarctic regions are key areas when addressing the potential consequences of climate change on periglacial phenomena (e.g. Zuidhoff 2002; Luoto et al. 2004b; Walker et al. 2004). For example, future environmental changes could affect the activity of landforms and processes in a few decades, especially on small-sized and permafrost-related features (e.g. Ballantyne & Matthews 1982, 1983; van Vliet-Lanoë et al. 1993; Nelson 2003; Fronzek et al. 2005). However, to utilise the modelling approach presented in this study to explore the effects of climate change on phenomena occurrence direct environmental determinants should be included in the set of predictors and the causality of these factors should be studied in more detail.

Palsas are clearly the most studied and most accurately described periglacial landforms in northern Finland (e.g. Auer 1924, Ruuhijärvi 1960, 1962; Salmi 1970, 1972, Seppälä 1976b, 1983, 1986, 1994b, 2003a; Luoto & Seppälä 2002a; Rönkkö & Seppälä 2003). In general, the palsas in the study area resembled those described in the literature (e.g. Ahman 1977; Seppälä 1988; Zuidhoff & Kolstrup 2005) although some differences existed. For example, string-form palsas were smaller and had no

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**Figure 114.** Schematic cross-section summarising the study results. Profile (A): the main topographical, soil and vegetation characteristics of the study area. Profile (B): the occurrence of the modelled periglacial landform types and other geomorphological features.
specific orientation compared to mire inclination (cf. Salmi 1972: 130; Åhman 1977: 41). In addition, small rather ambiguous humped features were distinguished from classical conical palsas into the class of hummocky palsas. From the different morphological types (Åhman 1977: 38–42), palsa plateaus and distinct esker palsas could not be found in the study region despite that some large tortuous ridge-features were detected.

The activity determination of the palsas was rather problematic because most of the landforms are at mature stage and obviously degrading (see Figs. 3 & 33; cf. Ruuhijärvi 1962; Zuidhoff & Kolstrup 2000; Luoto et al. 2004b). Moreover, the permanency of the frozen ground found from some of the stringform and hummocky palsas was difficult to determine. The presence of permafrost should be determined in the end of the thaw season (Seppälä 1976b, 1983) but this was not possible due to the large research area. Furthermore, the core may be frozen for several years or decades but thaw during a rainy summer (Seppälä, personal communication). Thus, the distinction between real palsas and large peat pounus can be difficult without several year-round measurements (e.g. Lundqvist 1969: 213–214). In addition, Seppälä (1998) has argued that some of the peat pounus are permafrost features. Nevertheless, all palsas were defined to be active and indicators of sporadic permafrost and thereby fulfilled the activity requirement for the modelling (cf. Lundqvist 1962: 73).

In Finland, studies on non-sorted circles have focused on earth and peat hummocks (e.g. Salmi 1972; Seppälä 1998, 2005c; Luoto & Seppälä 2002b; van Vliet-Lanoë & Seppälä 2002) and observations on non-sorted circles of other kinds are rather limited (Seppälä, personal communication). Due to the morphological and distributional differences, it was presumably that slightly different processes governed the distribution of the features. Hence, the convex non-sorted circles were classified into a separate group and a descriptive term was applied. The new term was used to avoid the confusion of these landforms with the other non-sorted circles. Nevertheless, the terminological vagueness of the different non-sorted circles complicated the comparison between the features described in the literature and circles found from the study area (e.g. Shilts 1978; Harris 1998; Overduin et al. 2003; Ping et al. 2003; Walker et al. 2004). In addition, the morphological distinction of the convex non-sorted circles from other patterned ground was occasionally difficult in the field. For example, if sorting was present, the landform resembled poorly sorted nets (Fig. 35; cf. Mooers & Glaser 1989: 429; also see Walker et al. 2004: 172).

The morphological and distributional characteristics of stony earth circles have not been studied in Finnish Lapland. In the study area, the stony earth circles resembled convex non-sorted circles, but features were (1) on average smaller, (2) flat without raised centres and (3) had scattered appearance and formed rarely continuous pattern fields (Williams 1959; Rissing & Thorn 1985; Wilson & Sellier 1995; cf. Chapter 5.2.2). Nonetheless, some continuous fields were found, for example from northeast of Suohpášoaivi fell and east of Guovdoaivi fell.

Earth, turf and peat hummocks are often combined in Finnish literature (e.g. Salmi 1972; van Vliet-Lanoë & Seppälä 2002; Seppälä 2005c). However, based on the field observations, it was presumable that slightly different environmental factors determine the distribution of mineral and peat hummocks (see also Lundqvist 1969: 210–211). Thus, the mineral soil cored features and pure peat hummocks were classified to separate groups. Both classical earth hummocks (e.g. Schunke & Zoltai 1988) and thin peat mounds (Raup 1965; van Vliet-Lanoë & Seppälä 2002) were combined under the earth hummock term for practical reasons (Lundqvist 1969: 210–211; Niessen et al. 1992: 194; cf. Grab 2005: 140).

Due to the relatively continuous vegeta-
tion cover, the activity determination of the earth hummocks was in several circumstances rather challenging. For example, large pattern fields were located in the forested areas where the snowcover can be rather thick, over one metre, which reduces the intensity of frost processes (e.g. Clark et al. 1985: 213). However, using quite detailed observations of the vegetation cover, frost heaving and general soil disturbance the activity of the earth hummock areas, even in the mountain birch forests, was determined (see also Jahn & Siedlecki 1982: 43; van Vliet-Lanoë & Seppälä 2002: 187; Seppälä 2005c: 175).

Peat pounus are probably the most studied patterned ground in Finnish Lapland (Ruhijärvi 1960: 220–222; Salmi 1972; Seppälä 1998; Luoto & Seppälä 2002b; Seppälä 2005c). Morphologically, peat pounus are rather similar to earth hummocks (Chapter 5.2.4; van Vliet-Lanoë & Seppälä 2002). However, in this study, the pounus were separated from earth hummocks because of the material difference; peat pounus are formed of organic material and they lack of mineral core (Lundqvist 1969: 212; cf. van Vliet-Lanoë & Seppälä 2002). Furthermore, the large peat pounus (> 70 cm high) often have a perennially frozen core (e.g. Salmi 1972: 124; Luoto & Seppälä 2002b: 129), whereas permafrost in mineral soil features is rather exceptional in Finnish Lapland (Seppälä 1997b: 91–93). The activity determination of the features was slightly more straightforward than for the earth hummocks because of the material difference; peat pounus are formed of organic material and they lack of mineral core (Lundqvist 1969: 212; cf. van Vliet-Lanoë & Seppälä 2002). Furthermore, the large peat pounus (> 70 cm high) often have a perennially frozen core (e.g. Salmi 1972: 124; Luoto & Seppälä 2002b: 129), whereas permafrost in mineral soil features is rather exceptional in Finnish Lapland (Seppälä 1997b: 91–93). The activity determination of the features was slightly more straightforward than for the earth hummocks because of the surficial characteristics of the active and inactive pounus differed more clearly. In addition, it was possible to use the observations of the frozen cores in the classification (see also van Vliet-Lanoë & Seppälä 2002: 187; Seppälä 2005c: 175).

Stone pits are small sorted circles that have mainly been described from Sweden (e.g. Lundqvist 1962: 21–24). The features have been mentioned in Finnish literature (e.g. Aartolahti 1969: 17; Piirala 1972: 133; Seppälä 1982b: 237, 1987: 48), but their environmental properties have not been studied in detail. In general, the stone pits mapped from the study area resembled those described by Lundqvist (1962: 21–24) and differed clearly from Washburn’s (1979: 129, Fig. 5.13) stone pits.

Sorted patterned ground features are rather common in northern Finland (e.g. Piirala 1969, 1972; Seppälä 1982b, 1987; Tabuchi & Hara 1992; Hirvas et al. 2005; Luoto & Hjort 2005). However, most of the observations have been made of sorted circles and polygons, or at least the features have been termed so (see Chapter 2.2.3; Lundqvist 1962: 29; Ballantyne & Harris 1994: 195). In this study, if the patterns were not clearly circular or polygonal the feature was determined to be sorted net (Washburn 1956: 830). Therefore, most of the landforms on gentle slopes with elongated mesh patterns were classified to the net and not to the circle or polygon class. In general, the morphology and size of the nets vary considerably in the study area (cf. Washburn 1969: 163; Ballantyne & Matthews 1982: 345; Coxon 1988: 83–84).

The mapping of the activity of the sorted nets was a rather straightforward task. However, the abundance of the nets and the reactivation of the old landforms may have led to some misinterpretations. The oldest sorted nets were probably formed in severe climate conditions close to the retreating ice edge during the deglaciation (Luoto & Hjort 2004: 334; Chapter 3.6; cf. Cook-Talbot 1991: 138; Matthews et al. 1998: 161–162; Haugland 2004: 299). Nowadays, these inactive pattern fields are more abundant than active feature areas. Thus, despite that the sorted nets are very common landforms, the cover of the active nets did not vary enough between the modelling squares for abundance modelling. For example, over 60% of the present modelling squares had active features less than 0.1 ha and only four squares had landform cover more than one hectare.

Sorted stripes are fairly abundant patterned ground in Finnish Lapland (Piirala 1969, 1972; Seppälä 1972b; Kejonen 1979; Söderman 1980; Hirvas et al. 2005). In the study area, the landforms resembled sorted streams and had rather similar distribution in the landscape (Appendices 8 & 11). In addition, the formative processes of stripes, frost heaving of stones from ground moraine, solifluction
and eluviation of fines (see Washburn 1956: 857–859, 1969: 185–188), are also possible mechanisms for the sorted streams genesis (cf. Clapperton 1975: 212–216). Despite the morphological and distributional similarities feature types were separated because stripes belongs to the patterned ground and streams are considered to be solifluction landforms (e.g. Washburn 1947: 87). The activity classification of the sorted stripes was rather challenging. Most of the stripes were probably formed during or shortly after the deglaciation but have reactivated under colder and moister conditions after climatic optimum (Kejonen 1994: 54; Chapter 3.6; cf. Ballantyne 1984: 314). However, if the feature, recently formed or ancient, had some sign of current activity, it was classified into the active class.

Hult (1887) and Helaakoski (1912) were probably the first who described solifluction phenomena in Finland. Afterwards, processes and landforms have been studied for example by Ohlson (1964), Piirola (1969), Kejonen (1979), Seppälä (1979b), Söderman (1980), van Vliet-Lanoë et al. (1993) and Matthews et al. (2005). The non-sorted solifluction terraces have been described from different parts of Finnish Lapland (e.g. Kejonen 1979: 10; Hirvas et al. 2005) but their distributional characteristics have not been studied in detail. The features in the Báišduattar – Áilegas area resemble those described in the literature (e.g. Söderman 1980: 126; Ballantyne & Harris 1994: 205–206; cf. Lundqvist 1962: 51–53). However, the terraces were generally rather small with frontal riser less than 50 cm high (cf. Jahn & Siedlecki 1982: 36–37). Due to the landforms small size, only their locations were mapped and distribution modelled. The non-sorted terraces were divided into active and inactive based on the observations of vegetation characteristics and morphology of the features (e.g. Ballantyne & Harris 1994: 213). In addition, the overall picture of the activity of solifluction features and their appearance was obtained from the studies of Kejonen (1979), Söderman (1980) as well as Jahn and Siedlecki (1982). Still, the activity determination of the non-sorted terraces was rather difficult and some misinterpretations probably exist in the data.

Sorted solifluction sheets have been recognised from northern Finnish Lapland, but they have often been termed as block slopes (Piirola 1969: 19, 1972: 133; Kejonen 1979: 9–10). In this study, all solifluction formed block and boulder slopes, ancient or present, were included into the class of sorted solifluction sheets (cf. Ballantyne & Harris 1994: 209–210). The transverse nature of the landforms in the landscape is probably due to large-scale step-like slope topography that is caused by bedrock schistosity (Mikkola 1932: 32–33). These large-scale risers are generally steeper than adjacent steps.

The activity determination of the sorted sheets was rather troublesome because of the features’ age. All sorted sheets were most probably formed before ca. 8600 BP and stabilized during the milder phase when forests covered the area (Eronen 1979; Kultti 2004). After the climatic optimum ca. 4000 BP, many of the sheets have reactivated and are active under the present climatic conditions (Kejonen 1994; cf. Ballantyne 1984: 325). Moreover, the activity determination was in some places complicated by two facts. Firstly, the whole sheet can be in a uniform movement despite the stones and blocks being covered by lichen (active but seem to be inactive). Secondly, lichen cover can be incomplete because of snow accumulation (nivation) processes and wind deflation (inactive but seem to be active). Both of these facts can give a false impression of the activity of the landform. However, detailed field observations were used to ensure the correctness of the classification. In addition, the field measurements of Kejonen (1994) and the appearance of frontal soil embankments (e.g. Fig. 48) gave further confidence about the activity or inactivity of a specific sheet (see also Jahn & Siedlecki 1982: 36).

Studies on sorted solifluction streams are quite limited despite the fact that sorted slope features are rather common in Finnish Lapland (Piirola 1969, 1972; Seppälä 1972b, 1982b; Kejonen 1979, 1994; Söderman 1980). In general, the material and possible formative...
processes of the sorted streams resembled the material and probable formation mechanisms of the sorted stripes and sheets in the study area (cf. Clapperton 1975: 212–214). Furthermore, there was a morphological continuum between the sorted streams and largest stripes (e.g. Washburn 1969: Fig. 114). Therefore, the earlier discussion on the origin and activity of sorted solifluction landforms also holds here (see also Tyurin 1983: 1284).

Deflations can be found from different parts of Finnish Lapland where late glacial and early Holocene sand dunes are abundant (e.g. Tanner 1915; Ohlson 1964; Seppälä 1971, 1974, 1982, 1993a, 1995b; Tikkanen & Heikkinen 1995; Käyhkö et al. 1999; Käyhkö et al. 1999; Kotilainen 2004). In addition to the sandy soil areas and moraine hummocks, wind has also eroded peat deposits on the fell summits (e.g. Seppälä 1972b; Luoto & Seppälä 2000) and palsas (e.g. Seppälä 2003a) in the study area.

6.2 Environmental factors affecting periglacial landform occurrence

6.2.1 Palsas

In Báišduattar – Áilegas, palsas were common on level peaty areas where the small ponds were abundant. However, if the water cover exceeded a certain threshold in the 25-ha grid cell, ca. 5 ha when the water variable was fitted separately, the probability of the feature occurrence decreased displaying a humped relationship. Not surprisingly, peat cover was the most important factor in the distribution model of palsas (cf. Luoto & Seppälä 2002a) because the palsa formation and preservation is dependent on the organic material that enables frost formation during the winter and protects the permafrost core from thawing during the summer (e.g. Brown 1970: 176; Åhman 1977: 129–130; Seppälä 1988: 268–269; Zuidhoff & Kolstrup 2005: 49).

The slope angle was a strong negative correlate for the palsa occurrence. The probability was very low when the mean slope angle was over ca. three degrees, because palsas occurred on flat areas (Lundqvist 1969: 208), in moist and flat-bottomed valleys that have commonly been bottoms of paleolakes, i.e. ice-dammed lakes (see Chapter 3.3). Furthermore, the slope variable is comparable to the proportion of flat topography (see Luoto & Seppälä 2002a: 23) that was excluded from the final set of predictors based on the correlation analysis (R, of mean slope angle and proportion of flat topography was −0.849).

The inclusion of water cover with a humped response curve was partly contradictory because a water body as an energy store is a negative factor for palsa preservation (e.g. Matthews et al. 1997: 120; Sollid & Sørbel 1998: 288). However, Luoto and Seppälä (2002a) also derived a water variable in their distribution model of palsas. They explained the positive association of palsas and water bodies with the exposure of open mire areas to strong winds and moisture availability (Luoto & Seppälä 2002a: 25). However, the presence of water variable can also indicate the occurrence of thermokarst ponds that are abundant in large palsa mires, especially in palsa complexes (cf. Luoto & Seppälä 2003).

Univariate analyses emphasized that shrub cover and rock terrain affect the palsa distribution. Despite that shrub cover was not in the final logistic regression model, it could have an important negative effect on the palsa formation because dense shrub cover enables considerable snow accumulation. The thick snow layer would avert the deep frost formation and thus prevent permafrost growth (e.g. Goodrich 1982; Seppälä 1982a, 1994b). However, if the palsa has formed, the denser shrub cover may not cause the degradation of the palsa (cf. Rönkkö & Seppälä 2003: 999; Seppälä 2003b; Zuidhoff & Kolstrup 2005: 58). The importance of rock terrain is slightly peculiar. Naturally, there occurs a negative correlation between palsa distribution and rock terrain but this association was rather weak and it was emphasized due to the utilised univariate approach in this study (see Crawley 1993: 192).
The model included three geomorphologically realistic factors that explained over half of the deviance change in the data. Thus, the distribution model for palsas was quite robust despite that the response was rather strongly spatially autocorrelated. In addition, the field checking revealed that the model was even better than expressed by the evaluation measures (cf. Bustamante & Seoane 2004). However, despite the good assessment results, there occurred prediction errors that can be caused by six main reasons.

First, the peat cover of the site was too thin for palsa formation. Second, the mire is too wet for palsa preservation. Third, palsas could form on a relative small mire, if the peat layer was thick enough and the mire was open to the wind effect. Fourth, the set of the used predictor variables was not complete, if we take into account all the important causal factors for palsa formation and preservation (e.g. Seppälä 1986: 141–145, 1988: 268–270). The solution for the previous problems could be the utilisation of more causal correlates, for example a variable describing the thickness of the peat layer. In general, the problems concerning the use of direct determinants such as snow-cover and temperature in spatial palsa models are discussed in Luoto and Seppälä (2002a: 25–26). Fifth, despite that the palsa data was based on detailed photo interpretation as well as extensive field mapping, there can be minor deficiencies in the response data (see Chapter 6.1; cf. Brown 1970: 178). Sixth, the grid approach can cause some problems in the detection of the key variables (see Chapter 6.3.3).

Hierarchical partitioning showed that the soil moisture, shrub cover, altitude and concave topography were potentially important variables that were not in the final distribution model. The association between palsas and shrub cover was already discussed and the effect of altitude is treated below. The topographical wetness index as an indicator of the soil moisture and location of streams could be an important positive or negative factor for the palsas (Brown 1970: 176; Seppälä 1986: 142; Luoto & Seppälä 2002a: 20, 2003: 25). The concave areas are accumulation sites for cold air, soil moisture and snow. Therefore, the effect of this topographical curvature variable is contradictory.

The abundance of palsas was determined by two already discussed factors, namely peat and shrub cover. Instead, the difference between the results of the final abundance model and the univariate analyses needs further notation. The minor importance of the peat in the univariate approach is probably attributed to the correlation of the variable with the shrub cover, mean altitude and slope angle (Table 14). However, the slope variable was not in the abundance model because peat and shrub cover are probably suppressing it, i.e. the predictors are strongly intercorrelated. The negative association of palsas with altitude can be explained by climatological and biological factors. During the winters, the valleys and lower altitudes can be colder due to temperature inversion and cold air drainage (Harris S.A. 1982b; Fig 28C; Chapter 3.6). Moreover, the drier soil conditions at higher altitudes are unsuitable for peat and palsa formation (e.g. Seppälä 1986: 142; cf. Luoto & Seppälä 2002a: 25). The association between the palsa abundance and elevation-relief ratio, as well as standard deviation of topographical wetness index, has to be viewed at a 25-ha grid resolution. The high values of moisture variability and the low values of elevation-relief ratio describe concave valleys that are potential sites for peat accumulation and palsa formation.

The final abundance model included two realistic predictors that explained rather well the deviance change of the response. Still, the prediction ability of the abundance model was relatively poor because the calibration model could not predict the palsa cover satisfactorily with the evaluation data. The failure can be attributed to two reasons: (1) the modelling square selection or (2) a lack of important causal factors from the final model. In the first case, the selection procedure neglected modelling squares with substantial palsa cover because these squares also had abundant water cover. By removing these hot spots of palsas valuable information was lost for the model building. However, the criterion for omitting
abundant water cover squares was justified in the modelling process (cf. Chapter 4.1.2). In the second case, the inclusion of variables representing soil moisture, slope angle, water cover and concave topography should be explored in more detail because the presence of spatial autocorrelation indicates that some causal factor is missing from the model (see Chapter 6.3).

The differences between the distribution and abundance models were expected because they address different aspects of the same phenomena. In distribution modelling, the whole study area was utilised in the analyses, squares with and without palsas, whereas the abundance modelling was focused on the present squares only. The peat cover was the only common but also the most important correlate for palsa distribution and abundance. The mean slope angle was not in the abundance model because present squares had rather uniform topography, whereas slope angle was an important discriminator in the distribution modelling. The same holds for the water cover as well but the exclusion of the water variable from the abundance model can also be due to the procedure of modelling squares selection. The shrub cover was not a proper discriminator but it was an important factor in the prediction of palsa abundance.

6.2.2 Convex non-sorted circles

In the study area, convex non-sorted circles were common in rather flat-bottomed valleys at relatively high altitudes (cf. Hodgson & Young 2001: 320–323). To be more precise, the circles were often situated in large cirque-like bedrock valleys that are relatively common in the study region (Kaitanen 1969: 46). Based on literature (e.g. Washburn 1969: 108, 118; Overduin et al. 2003: 869), non-sorted circles occur on level ground and, therefore, the negative effect of the slope angle on the probability of the feature occurrence was expected. Moreover, the concave sites are accumulation areas for a fine-grained soil material and moisture that are, in general, crucial determinants for the formation of non-sorted circle (e.g. Washburn 1969: 111; Schunke & Zoltai 1988: 235, 239–240). The concave areas are also accumulation sites for wind-drifted snow, which have a negative effect on the soil freezing, respectively. However, the raised centres of the circles enable deeper frost formation into the features than into the vegetated inter-circle boundary sustaining the soil particle motion (cf. Overduin et al. 2003: 870–872; Walker et al. 2004: 182).

The altitude had a clear non-linear effect on the probability of landform occurrence, and this concorded with the observations made in the field. The convex non-sorted circles occurred at high altitudes above the treeline but still in the valleys, which are favourable sites for frost processes, for example cryoturbation, to act (e.g. van Vliet-Lanoë 1988a, 1991). In addition, the direct solar radiation was demonstrated to be an important discriminator between the occupied and unoccupied modelling squares. The radiation differences may cause variability in the soil moisture and vegetation density that can initiate circle genesis (e.g. Shunke & Zoltai 1988: 240; Walker et al. 2004: 183–185).

According to the univariate analyses, the canopy cover and topographical wetness index were potentially important correlates of the convex non-sorted circle distribution. Both of the variables were realistic factors, as stated earlier. However, these variables were not in the final GLM model probably because of the intercorrelation of explanatory variables; the canopy cover correlates with altitude ($R_s = -0.729$) and the wetness index with concave topography ($R_s = 0.633$).

The variables in the final distribution model were rather plausible albeit strong spatial autocorrelation and trend was present in the response data. In addition, based on the evaluation measures, the distribution model was good in discriminating between the occupied and unoccupied sites. Nonetheless, there occurred prediction errors which were mainly caused by (1) the lack of important causal factors from the final model, (2) deficiencies in the mapping and (3) due to the grid ap-
proach (see Chapter 6.3.3). Firstly, the utility of vegetation and soil variables could improve the model performance (see also below). For example, the glaciofluvial activity could have washed the fines away from the glasigenic deposits generating unsuitable soils for the non-sorted circles to form (Shunke & Zoltai 1988: 235). Furthermore, many of the topographically proper sites were covered by peaty soil or rather dense shrub cover, factors that prevent the circle formation. Secondly, the fact that ca. 35% of the absent sites with high predicted probability were actually present squares indicated the possibility to build better model if all, even the smallest feature fields, could be observed. The large convex non-sorted circle areas are detectable from aerial photographs but the smallest fields, less than 30 m in diameter, were difficult to interpret by remote sensing data and the discovery of the least active landforms was troublesome even in the field.

Hierarchical partitioning analysis revealed the potential importance of the canopy cover and wetness index. These variables were not in the final distribution model but their importance was highlighted by the univariate analyses as well. The canopy cover and soil moisture could be more causal environmental correlates for the presence of convex non-sorted circles than the mean altitude and proportion of concave topography (cf. Hodgson & Young 2001: 321–323).

The abundance model was able to predict the cover of the convex non-sorted circles fairly well despite that the response data was spatially autocorrelated and had a strong trend toward northeast. In addition, according to the evaluation, the model was robust (cf. Chapter 6.2.1). The most important landscape scale factors were the altitude, soil moisture and slope angle (e.g. Washburn 1956: 841–842; Overduin et al. 2003: 870–872). The same variables were the most influential also in the univariate analyses. Moreover, the proportion of concave topography, slope direction and moisture variability could potentially affect the circle abundance. The slope direction as a surrogate for solar radiation could reflect the local climatological differences of a site (e.g. Geiger 1965: 417–418) and it could be a meaningful correlate. The standard deviation of wetness index describes valleys that are potential sites for the convex non-sorted circles (see above).

The set of the most important environmental factors for the circle distribution and abundance was strikingly similar. The surrogates for topography, climate and soil moisture were present in both GLM models. The only significant difference between the models was the effect of canopy cover. The tree cover could be a meaningful discriminator between the present and absent sites but it does not have an effect on the cover of the convex non-sorted circles because the feature fields occur mainly in the treeless regions.

### 6.2.3 Stony earth circles

Based on the literature, stony earth circles commonly occur in exposed, snow-free sites in the subarctic and on the alpine tundra where the vegetation cover is sparse (e.g. Williams 1959: 13; Williams & Smith 1989: 163–164; cf. Ping et al. 2003). According to the distribution model presented in this study, the stony earth circles occurred in dry and sparsely vegetated moraine soils at relatively high altitudes. Hence, despite that the prediction performance and explanation power of the model were relatively poor, the environmental determinants in the final GLM model concord well with the previously made observations.

More precisely, the stony earth circles were common in open mountain birch forests and on the alpine heaths where the undergrowth was relatively scant (cf. Rissing & Thorn 1985: 154). The defoliated and poorly recovered birch forest region in the southeast was one of the core distribution areas of the stony earth circles (cf. Chapter 3.8). The relationship between the circles and tree cover was also illustrated by the non-linear effect of altitude on the feature occurrence. The highest probability was at the treeline, at ca. 400 m a.s.l. In this zone, the sparse vegetation cover enables deflation and accelerates short-term freeze-thaw cycles (Williams 1959: 3, 5; Rissing & Thorn
The sites of stony earth circles were, based on the topographical location, relatively dry. However, the glacigenic deposits with wide grain-size distribution and relatively good moisture holding capacity often fulfilled the moisture requirement for the frost activity (Goldthwait 1976: 30). In addition to the variables already in the distribution model, univariate analyses pointed out the possible importance of the solar radiation and proportion of concave topography. Despite that these predictors represent the vegetation and soil moisture distribution in the area neither of the variables has, in general, a direct connection to the feature distribution (e.g. Williams 1959).

The prediction ability of the model was rather poor and several reasons for the failure can be proposed. The stony earth circles are quite small and sporadically distributed non-sorted patterned ground (cf. Overduin et al. 2003: 869). The scattered appearance impeded their mapping and complicated the building of a comprehensive response data set for the analyses. In addition, the very strong spatial autocorrelation indicated a lack of causal factors from the final distribution model. For example, hierarchical partitioning analyses revealed a moderate independent importance of the shrub cover variable. In the end, the scale difference between the formative mechanisms and utilised environmental variables (Williams 1959: 12–13) and unpredictable factors, such as vegetation destruction by reindeer herding and direct human activities (Lundqvist 1969: 211). The negative association between hummocks and altitude can be attributed to two main reasons (cf. Grab 2005: 150). Firstly, the lower altitudes are accumulation areas for moisture, fine-grained soil material and cold air (cf. Chapter 6.2.2). Secondly, many of the low altitude valleys with abundant earth hummock cover have been bottoms of paleolakes, i.e. ice-dammed lakes during the deglaciation stage (Appendix 4: van Vliet-Lanoë & Seppälä 2002: 189–191). These silty soils are very frost susceptible and thus ideal areas for the formation of earth hummocks (Shilts 1978; Tarnocai & Zoltai 1978: 592; Schunke & Zoltai 1988: 239; van Vliet-Lanoë 1988a: 92).

The variables in the final distribution mod-
el covered relatively well the set of important landscape scale factors for the earth hummock occurrence albeit the response data was spatially autocorrelated (cf. Schunke & Zoltai 1988; van Vliet-Lanoë & Seppälä 2002). Moreover, the model was able to explain almost half of the deviance change in the hummock data. Therefore, the very good prediction ability of the model was expected. However, the inclusion of soil factors could even further improve the prediction performance of the model.

The HP analysis revealed the possible importance of concave topography and slope angle. The proportion of concave topography was positively (cf. Grab 1997: 443–444) and mean slope angle negatively associated with the earth hummock distribution in the earlier stages of the model building, but these variables were omitted from the final model probably due to the intercorrelation. For instance, slope is one of the factors controlling the earth hummock distribution in the landscape (van Vliet-Lanoë & Seppälä 2002: 189) but the explanation power of slope was taken by the wetness index, peat cover as well as shrub cover (see Table 14).

The abundance of earth hummocks was determined by the soil properties and topographical factors. Hence, rather the same set of predictors had an effect on the feature distribution and abundance. However, some minor differences existed between the models. The abundance model included the slope angle and water cover variables and the excluded standard deviation of topographical wetness index factor. For example, the inclusion of the slope was understandable because extensive earth hummock fields occur in flat areas (Mackay & Mackay 1976: 889; Jahn & Siedlecki 1982: 41).

The final abundance model was rather good, regardless of the presence of spatial autocorrelation, because the model explained over 50% of the deviance change in the response data and it predicted the earth hummock cover fairly well. In addition, the model was relatively robust despite that six explanatory variables were present (cf. Crawley 1993: 211). However, the inclusion of high quality soil data could even further improve the prediction ability of the model (Schunke & Zoltai 1988: 239).

### 6.2.5 Peat pounus

Based on the logistic regression model presented in this study, the active peat pounus were common in moist relatively flat-bottomed valleys where the peat and shrub cover was high (cf. Salmi 1972: 124–129; van Vliet-Lanoë & Seppälä 2002: 189–190). Moreover, the feature fields gained generally less solar radiation and were more often covered by mountain birch forests than unoccupied sites. Smaller peat pounu occurrences were relatively abundant in the cirque-like valleys but at lower altitudes than the convex non-sorted circles (Chapter 6.2.2) and earth hummocks (Chapter 6.2.4).

The final model for the peat pounus included eight environmental predictors. The large array of correlates can be attributed to the intermediate location of the peat pounus in the landscape, spatially between the earth hummocks and palsas, and heterogeneity of the environmental conditions of the present sites (cf. van Vliet-Lanoë & Seppälä 2002: 190). The largest mires and thickest peat deposits were occupied by palsas and most of the mire edges were covered by mineral-cored mounds. Therefore, the distribution of pounus could not be explicitly determined by the utilised set of predictors, at least not at the 25-ha modelling resolution. However, despite that the model had a high number of predictors, almost all of the variables were explainable with distinct physical connection to the pounu distribution.

Organic material is a basic requirement for peat pounu formation (e.g. Salmi 1972: 124; Seppälä 1998) and the humped response curve is due to the presence of palsas in extensive mires (Fig. 77). Flatness, concavity, shadiness, moderate vegetation cover and soil moisture are all positive factors for peat accumulation and pounu development (van Vliet-Lanoë & Seppälä 2002: 187–190). For example, concavity promotes cold air ponding and deep frost...
formation in the pounu hummocks (Seppälä 1998: 369–371; cf. Chapter 6.2.2). At first, the water cover can be seen as a negligible predictor but small ponds are often indicators of mires and relatively high ground water level (cf. van Vliet-Lanoë & Seppälä 2002: 190). Thus, only the inclusion of the canopy cover into the final model was rather difficult to explain because pounus had no causal connection to the mountain birch forests (see also Luoto & Seppälä 2002: 129). However, the pounus were often located at relatively low elevations and the altitude variable was rather highly correlated with the canopy cover (see Table 14).

The distribution model for peat pounus was quite robust because even the Kappa measure indicated almost excellent prediction performance, and the model was able to explain over 46% of the deviance change. In addition, based on the field evaluation, the model could predict the present squares correctly despite that the pounus were not previously observed because all visited high probability absent squares were actually present sites. However, even though the model had a high ability to distinguish between occupied and unoccupied squares, some prediction errors occurred as well. Most of the incorrectly predicted squares were present sites with low predicted probability (omission error) (see Chapters 4.2.3 & 6.3.3). Altogether, to build even better distribution models for pounus, the number of the predictors should be reduced (e.g. Crawley 1993: 188, 211) and the role of the wetness index as well as mean altitude explored.

The prediction ability and explanation power of the abundance model were good and the included predictors were quite realistic despite the presence of autocorrelation in the response data. Peat cover had a positive, and slope angle as well as elevation-relief ratio a negative, effect on the pounu cover. However, when the effect of slope was examined separately, the upward curvature of the response curve of the slope variable increased when the slope angle surpassed a certain threshold (ca. seven degrees). The shape of the curve can probably be attributed to the presence of small pounu fields in the bottoms of steep-sided valleys and in the breaks on otherwise relatively steep slopes (cf. van Vliet-Lanoë & Seppälä 2002: 189–190).

The differences between the results of the abundance model and univariate analyses were considerable. The slope angle was important in both approaches but the peat cover and elevation-relief ratio were distinctively less meaningful in the univariate analyses. The latter approach indicated connection between landform abundance and water cover, sand and gravel, soil moisture, rock terrain, concave topography and canopy cover variables. In theory, sand and gravel as well as rock cover are negatively correlated to the pounu abundance but the association was rather weak in the study area (cf. Chapter 6.2.1). The rest of the predictors may have a stronger relation to the response despite that the variables were not in the final model. In addition, hierarchical partitioning displayed the potential importance of the shrub cover (van Vliet-Lanoë & Seppälä 2002: 187–190).

Rather clear differences between the variables in the final distribution and abundance models occurred (see Chapter 6.2.1). The only shared predictors were peat cover and slope angle, which were important both in discriminating between occupied and unoccupied sites but also in determining the feature cover. The shrub, water and tree cover, proportion of concave topography, standard deviation of wetness index and direct solar radiation were proper discriminators, whereas elevation-relief ratio compiled the set of important cover predictors.

6.2.6 Stone pits

Active stone pits were often found from moist and flat valley floors where the ground was covered by shrubs and glacigenic deposits were fairly abundant. The slope angle was the most important landscape scale factor with a negative effect on the feature occurrence (e.g. Lundqvist 1962: 22). The importance of flat topography was also highlighted by the shape of the response curve. The predicted prob-
ability decreased drastically when slope angle increased (Fig. 84). The shrub cover had an indirect connection to stone pit distribution because features occurred in areas of abundant shrub cover despite that the stone pits do not require dense vegetation to form (e.g. Lundqvist 1949: 336).

Topographically the features were found from valleys where the ground water level was close to the ground surface (Aartolahti 1969: 17). The presence of ground water and its fluctuations enabled wash out of fines from the frost-sorted stony pits (Seppälä 1987: 48). Addition to the requirements for the stone pit formation, the soil has to be rather rich in stones and boulders (e.g. Lundqvist 1949: 336; see Chapter 3.3; cf. Kessler & Werner 2003: Fig. 3). However, the squares with the highest probabilities were those where the moraine cover was at the intermediate values. This is explained by the presence of peat in the feature squares. The peat does not have direct connection to the stone pits but features occur in thin peat areas, on the edges of mires (see Seppälä 1987: 48). In addition, according to univariate analyses, soil moisture and sorted material could be potential variables in distribution modelling. The association of stone pits and soil moisture is understandable, as discussed above, but the connection to sand and gravel is without a clear foundation.

The discrimination ability of the model was quite good, if we take into account the field checking results where almost 70% of the absent squares with relatively high predicted probability were present sites. However, as the evaluation measures indicated, numerous incorrectly predicted squares existed. Based on the visual analyses of the prediction map and field observations, four main reasons for the errors could be proposed. First, the small size and the fairly scattered distribution of the stone pits caused deficiencies in the response data (cf. Aartolahti 1969: 17), but this holds only for the unvisited sites. Second, the soil material was in some sites probably too dry and the ground water level too deep in the ground for the landform genesis. Third, small-scale topographical variability may prevent the feature formation. Fourth, the presence of spatial autocorrelation and minor trend in the response data indicated that some important determinants could be missing from the final distribution model. For example, the soil moisture indicators, such as topographical wetness index, proportion of concave topography and peat cover might improve the discrimination power of the model (see above).

### 6.2.7 Sorted nets

In the Bǎǐduàttar – Áilegas area, the active sorted nets were more common in valleys at relatively high altitudes where soil moisture was present. Based on the logistic regression model, the standard deviation of topographical wetness index was the most important predictor for feature distribution. In general, this variable cannot be seen as the most important correlate for sorted net occurrence (e.g. Washburn 1969: 164). However, the valleys are potential sites for nets, if other environmental conditions are favourable for frost sorting processes (see e.g. Corte 1966: 237; Kling 1998: 444; Matsuoka et al. 2003: 75).

Indicator of soil moisture and surrogate for climate conditions were in the model but one crucial determinant, namely soil material (i.e. moraine cover), was not in the final model (cf. Goldthwait: 1976: 30). Instead, the peat cover was included into the distribution model with a humped response curve (Fig. 88). Nonetheless, based on the field observations, a logical explanation for this exists. The net fields were often located close to the mires in thin peat areas where soil moisture was abundant and proper material for sorting was present (Washburn 1969: 164; Hodgson & Young 2001: 320).

The factors in the distribution model were mostly explainable but still the prediction ability of the model was, at the most, moderate. It is difficult to find unambiguous causes for the prediction errors but four potential reasons are proposed. First and probably the most important reason could be the scale difference between the causal factors and utilised
environmental variables. For example, the importance of small-scale determinants for patterned ground can be seen from the study of Matthews et al. (1998). The second potential reason for prediction errors could be the heterogeneity of the sorted nets and formative processes (Washburn 1970: 440–441). Morphology of the patterns can vary notably between the different net fields and some of them can be still evolving toward sorted circles or polygons (e.g. Washburn 1969: 165; Ballantyne & Matthews 1982: 344–345; Ballantyne & Harris 1994: 93). This may cause problems in the modelling because, according to Kling (1998), sorted circles and polygons occur in different locations in the landscape and the primary formative factors are different. However, based on the field observations, this was a minor problem in the Báišduattar – Áilegas area and the findings of Kling (1998) may not hold in all regions and every circumstance.

The third reason for the errors could be the small size of the active pattern fields that led to mapping difficulties (cf. Kling 1998: 444). Finally, the presence of spatial autocorrelation and trend in the sorted net data indicated a lack of direct factors from the final model. For example, the concave topography, slope angle and till cover could be more causal correlates (Washburn 1969: 164, 167, 173; Goldthwait 1976: 30; van Vliet-Lanoë 1988b: 1009–1012; Kling 1998: 450; Matsuoka et al. 2003: 75). However, the final distribution model was better than indicated by evaluation measures because new sorted net sites were found with the extrapolated calibration model.

6.2.8 Sorted stripes

Most of the active sorted stripes occurred on relatively steep slopes above 440 m a.s.l. in the study area. The inclusion of slope variable into the model was axiomatic but the non-linear nature was not. Based on the field measurements and literature (e.g. Washburn 1969: 181; Walters 1983: 1351; Hall 1994: 121), sorted stripes do not occur on very gentle slopes with gradients less than ca. three degrees. Equally, when the average slope angle was over ca. 10° the site was occupied by sorted solifluction sheets (Chapter 6.2.10), streams (Chapter 6.2.11) or talus formations (Goldthwait 1976: Fig. 4; Ballantyne 1984: Fig. 6). Besides the slope gradient, the altitude is a good determinant of slope activity in Finnish Lapland (Seppälä 1993b: 60). The higher altitudes, generally areas above 400 m a.s.l., are treeless heaths with low vegetation cover, which enables solifluction processes to act (e.g. Benedict 1976: 60).

Altitude and slope angle were the most important factors also in the univariate analyses. The other notable predictors in the univariate analyses, namely canopy cover, slope aspect, concave topography and shrub cover were all possible and realistic correlates despite that they were excluded from the final GLM model (Washburn 1969: 179; Pissart 1993: 212–213; Matsuoka 2001: 127, 130). In the earlier steps of the model building, the mean of canopy cover, aspect majority, proportion of concave topography and mean of shrub cover were all negative factors for the occurrence of stripes. Based on the predictors above, sorted stripes can be found from rather sparsely vegetated convex slopes, which are often orientated to the eastern sector (cf. Ballantyne 1984: Fig. 7). Nowadays, the slope aspect has a minor importance to the genesis of the features but when the stripes were formed, strong northwestern winds transported snow (i.e. soil moisture) to eastern and south-eastern slopes (Seppälä 1993b: 272). However, strong winds, especially during winters, blowing from the northwest may affect the distribution of active sorted stripes in the study area at present (cf. Hall 1994: 122; Holness 2001: 80). The formation of new stripes on the fell slopes is mostly prevented by the lack of soil moisture and due to too dense vegetation cover (e.g. Åkerman 1993: 247). Therefore, the recently formed features can only be found from special locations, such as moist valley floors (Fig. 46). However, these stripes cannot be detected with the built distribution model because local small-scale factors dominate their formation (e.g. Muir 1983; Werner & Hallet 1993).

The distribution model for sorted stripes
was robust. Firstly, the model could with only two factors explain a notable amount of the deviance change and, secondly, accurately discriminate between the occupied and unoccupied sites regardless of the spatial autocorrelation and slight trend in the response data. However, several prediction errors could also be identified. More than half of the incorrectly predicted squares were absent sites with high predicted probability. Most of the commission error squares were non-occurrence sites without any specific reason but some of the squares were occupied by other sorted solifluction features. Moreover, some of the stripe occurrences were not previously detected in the field. The omission errors were mainly attributed to the simplicity of the model; altitude and slope angle could not encompass all the potential factors determining the occurrence of stripes (Washburn 1956: 857–859). For example, many landforms on the slopes of large glacial melt water channels remained unidentified by the distribution model.

Based on the field observations and HP analysis, the inclusion of topographical factors such as the standard deviation of topographical wetness index and proportion of convex topography should be considered. In addition, the vegetation and soil variables could improve the prediction ability of the model (e.g. Lundqvist 1962: 55; Washburn 1969: 179; Benedict 1976: 61–62). However, the robustness and simplicity of the constructed model indicated good extrapolation potential of the model (cf. Crawley 1993: 188, 211).

### 6.2.9 Non-sorted solifluction terraces

According to the distribution model, the non-sorted terraces were frequently found from valleys at high altitudes where the peat cover was poor or absent. If we take into account the important determinants for solifluction features (e.g. Washburn 1979: 198–204; Åkerman 1993: 247; Pissart 1993: 212–213; Matsuoka 2005: 41), all three variables in the model were rather deficient factors despite the fact that the altitude is connected to process activity (Seppälä 1993b: 60) and the standard deviation of wetness index describes topographically the potential occurrence areas (Ballantyne and Harris 1994: 115, 205–206).

The absence of causal correlates led to poor explanation power and prediction ability of the model (see Fig. 96). On the other hand, soil moisture variability, altitude and peat cover were among the four most important variables in the hierarchical partitioning where the effect of spatial autocorrelation and geographical trend was controlled by including spatial variables. This denotes the distinct association between the features and included predictors at a landscape scale despite the fact that variables are not direct determinants of the occurrence of solifluction terraces (e.g. Benedict 1976: 61–63; Matsuoka 2001: 127–128). In general, the inclusion of more direct factors such as slope angle and soil moisture could improve the model performance (e.g. Washburn 1999: 175). However, the wetness index is not a suitable surrogate for soil moisture on slopes. Instead, information of the perennial or late laying snow patches could help to model the distribution of the non-sorted solifluction terraces. As noticed in the field and by many researchers, snow distribution, especially late laying snow patches, are spatially connected to solifluction phenomena (e.g. Williams 1959: 5; Ulfstedt 1993: 220).

In spite of all, the main reason for the model failure can probably be attributed to the size and scattered occurrence of the features. Non-sorted solifluction terraces are small periglacial features, which are distributed fairly randomly at a landscape scale. Nevertheless, the occurrences of the features were strictly controlled by topography on a local scale in the study area. For instance, based on the field observations, glaciofluvial melt water channels were the most common occurrence sites. Therefore, to improve the prediction power of the model more specific topographical correlates should be added to the set of predictors. For example, variables describing the length or number of the melt water channels and foot slope areas should be considered. The effect of local
topography exceeded even the influence of soil material because the non-sorted solifluction terraces were as common in poorly sorted sand and gravel areas as in moraine soils (cf. Harris et al. 1995; Chapter 3.3).

6.2.10 Sorted solifluction sheets

Based on the distribution model, active sorted sheets were common at high altitudes, on convex southeast and northeast slopes (cf. Chapter 6.2.8). When the slope angle and altitude were related separately to the occurrence of sheets, the most abrupt rise in the feature probability occurred when the mean slope angle increased from five to 13° (cf. Ballantyne 1984: Fig. 6; Åkerman 1993: 231) and mean altitude from 400 m to 530 m a.s.l. The most important predictors, slope angle and altitude, were rather self-evident landscape scale correlates (Piirola 1969: 32; Francou & Bertran 1997: 382; Matuoka 2001: 127–128) although they have been effective in different periods. Slope gradient was the important factor when the sheets were formed, whereas altitude determines the distribution of the active landforms nowadays (Seppälä 1993b: 60).

Topographically the fell slopes can be divided into two main sections; upper convex slopes and lower concave slopes. The convex slopes are areas for accelerated soil motion and thus the most probable places for sorted solifluction landforms, as indicated by the distribution model (cf. Karte 1979: 146; Ballantyne 1984: Fig. 7, Fig. 9; Ballantyne & Harris 1994: 205). Instead, concave slopes are sites of decelerated material movement and thus more probable areas for non-sorted slope features (e.g. Washburn 1947: 87; cf. Chapter 6.2.9). The inclusion of the elevation-relief ratio variable with a negative sign is more difficult to justify. However, this predictor may complete the final set of determinants and act as a proper discriminator for some of the modelling squares without true causality.

The distribution model was robust albeit the data was clearly spatially autocorrelated and the model included six variables, of which one predictor was without causal connection to the response (see above). The good prediction performance is seen to be caused by the strong association between the sorted sheets and slope angle as well as altitude. However, despite that the model was an excellent discriminator, it could not be use to detect new landform sites. This is explained with the good accuracy of the response data, which is due to large size of the sheets. Therefore, five other reasons are proposed for the causes of prediction errors.

First, the topography of the site was unsuitable for the sheets. For example, small-scale variability caused by the melt water channels broke the unity of the slope, or the slopes were too gentle. The second reason, inability of the utilised predictors to capture the effect of small-scaled topographical variability, is related to the previous one. Third, small frost creep features that are not true sorted solifluction sheets (cf. Kejonen 1979: 11) occupied some of the high probability sites. Fourth, some of the predicted sites were areas of bedrock outcrops with thin moraine cover. In some places, the sheet material can originally be from bedrock but more often thin soil sites are unsuitable for solifluction phenomena (e.g. Åkerman 1993: 247). The potential importance of the soil material emerged also in the hierarchical partitioning. The fifth and final reason was the grid approach (see Chapter 6.3.3). Moreover, to improve the prediction ability of the distribution model, the role of shrub cover should be explored because some of the absent high altitude fairly steep slopes were densely vegetated. The association between the sorted sheets and shrub cover was also shown in the HP analysis where the shrub variable was the most important predictor after altitude and slope angle. Also, the canopy cover could be a potential discriminator even though it correlates rather strongly with altitude (Table 14).

The cover of sorted sheets was determined by altitude, slope angle and relative solar radiation. In the abundance model, the altitude was more important than slope angle. This is because the active fields are more exten-
ative at higher fell areas than at lower altitudes with corresponding slope gradients due to more favourable conditions for frost activity (see above). According to the solar radiation variable, sorted sheets were abundant on the northern and southern slopes. The correlation of the sheets with northern slopes was understandable because these slopes receive less solar radiation and remain colder, moister and consequently more active. The occurrence of the sorted solifluction sheets on the southern slope sector was more difficult to explain, although the association could be attributed to the moisture distribution during the genesis of the landforms (see Chapter 6.2.8).

The abundance model was demonstrated to be quite robust in the model evaluation. However, the prediction ability of the model was better with building ($R_s = 0.650$) than testing data ($R_s = 0.539$). This rather substantial decrease could be due to the lack of some causal factor from the model, which was also indicated by the presence of clear spatial autocorrelation in the response data. According to HP, the standard deviation of topographical wetness index and mean of shrub cover variables explained independently part of the variance in the sheet data. From these predictors, the inclusion of the vegetation variable should be considered before the topographical surrogate (e.g. Pissart 1993: 212; Ulfstedt 1993: 223).

Based on the GLMs, a similar set of correlates determined the distribution and abundance of the sheets because altitude and slope angle were the most important factors in both models. In addition, the solar radiation variable is comparable to slope direction albeit that the predictors do not correlate strongly. However, the distribution model included three other variables which were not in the final abundance model. The canopy cover, elevation-relief ratio and proportion of concave topography were not proper determinants for sheet cover because landform fields occurred in treeless areas where these topographical conditions were quite coherent.

6.2.11 Sorted solifluction streams

In the study area, active sorted solifluction streams were common on the fell slopes at high altitudes (cf. Piironen 1969: 17, 1972: 13; Clapperton 1975: 212). The importance of the altitude and slope angle on sorted solifluction phenomena was already discussed in Chapters 6.2.8 and 6.2.10 and only one additional comment can be made concerning the difference between the distribution of sorted streams and stripes. According to Figure 105, the steepest rise in the probability of sorted stream presence was when altitude was over 410 m a.s.l. and slope angle was more than seven degrees. Thus, despite that the general distribution of the sorted streams resembled stripes occurrence, the response curves and field observations indicated a minor distributional difference between these two landform types. The stripes were more common at slightly higher altitudes on convex slopes where the mean gradient was less than on the middle parts of the slopes where the streams were more abundant (Clapperton 1975: 212; Fig. 114).

The variables in the final distribution model covered the most important landscape scale factors for the occurrence of sorted solifluction streams despite the fact that spatial autocorrelation was present in the response data (cf. Tyurin 1983: 1283; Harris et al. 1998: 127). Therefore, the good prediction ability of the model was expected. However, there still occurred prediction errors that can be explained with four causes. Firstly, all features were not detected in the field because five new occurrences were found with the prediction map. Secondly, the topographical or soil properties of the site have been unsuitable for the feature genesis. For example, glaciofluvial melt water channels broke the unity of the slope or the area was almost totally covered by bedrock. Thirdly, the site was occupied by some other landform, usually sorted solifluction sheet. Finally, the local circumstances have enabled the formation of the features despite that the mean environmental conditions, according to the model, were unfavourable.

Most of the sources of the prediction er-
rors could be removed with more accurate data (e.g. Chapter 6.3.2) or by including new explanatory variables into the model (Harris et al. 1998: 127). Hence, the effect of the canopy, shrub and moraine cover as well as soil moisture should be studied in more detail because the active sorted streams occurred in fairly dry and sparsely vegetated moraine soils above the treeline. On the other hand, the distribution model with only two predictors explained a substantial amount of the deviance change in the data and the insertion of a variable that would only slightly increase the explanation power of the model is unnecessary (e.g. Crawley 1993: 188, 211).

6.2.12 Deflations

According to the distribution model, deflations occurred most often at relatively high altitudes in sand and gravel soils where the vegetation cover was moderate or absent (cf. Seppälä 1971: 22–29, 1984: 39, 2004b: 145; Åkerman 1980: 111; Käyhkö et al. 1999: 435). Deflations were very common on glaciofluvial and aeolian landforms where the sparse vegetation cover could not resist the wind erosion (Seppälä 2004b: 146). However, the non-linear connection between the features and sandy soils has to be due to the modelling resolution. Most of the present squares were mostly but not totally covered with sand and gravel soil because of the linear appearance of the sorted deposits. Therefore, the response curve was humped with the highest probability of feature occurrence at rather intermediate values.

The negative association between the canopy cover and deflation was explained by the exposure of the open and sparse birch forest areas to stronger winds than densely forested regions (Seppälä 1993a: 274). However, the humped response curve of mean altitude indicated that the most probable sites were not the fell summits despite that the strongest winds and lowest vegetation cover occurred there. Instead, the valleys with eskers, sand dunes, palsas, kame- and moraine hummocks were the sites of wind erosion (e.g. Åkerman 1980: 253; Käyhkö et al. 1999: 435). These hummocky landforms were usually very sparsely vegetated and were, therefore, the sites with the greatest potential for deflation.

The effect of reindeer has to be taken into account when the causes of deflation are discussed (Seppälä 1984; Käyhkö & Pellikka 1994). As seen in the field, reindeer were often grazing in the windy places where the mosquitoes cause less harm. Consequently, the animals trample the vegetation and can inflict local soil erosion leaving small bare soil patches, which can be enlarged by wind action. Thus, some of the deflation surfaces were the result of the combined effect of wind and water erosion, as well as reindeer herding (Åkerman 1980: 253; Seppälä 1995b: 808–809).

The univariate analyses and distribution modelling gave fairly similar results. However, the sand and gravel variable was less important than the standard deviation of topographical wetness index in the univariate analyses. The inclusion of the later predictor into the model could be explained by the topographical location of the deflations, but as indirect factor; it would clearly be a less important correlate than the former variable. In addition, the standard deviation of wetness index variable correlates moderately with the mean altitude as well as the sand and gravel cover variables (Table 14).

The discrimination ability of the model was rather good, if we take into account the field checking results where ca. 68% of the absent squares with relatively high predicted probability were present sites. This deficiency in the response data clearly demonstrated the difficulty in mapping small and quite scattered deflations, although most of the features over five metres in diameter were detectable from the aerial photographs. However, some other causes for the predictions errors could also be identified. Firstly, many of the squares with abundant sand and gravel cover were without small-scale topographical variability, i.e. hummocks and ridges, or the sites were densely vegetated. For example, most of the esker ridges had a thick tree cover that efficiently prevented deflation (cf. Seppälä 2004b: 146). Secondly, the strong spatial autocorrelation in-
icated that some important explanatory variable was missing from the model. HP demonstrated the independent importance of the standard deviation of topographical wetness index and moraine cover. However, neither of these variables could be seen as a good additional discriminator between occupied and unoccupied deflation sites. Perhaps the lack of a predictor representing the hummocky topography could be one of the main reasons for the errors. For instance, the deflation surfaces were often present on the moraine landforms and the model could not predict these occurrences correctly. Moreover, the grid approach may have introduced an additional source of error (Chapter 6.3.3).

6.3 Data and methodological issues – advantages and shortcomings

In general, numerical techniques and GIS data have not been widely used to model geomorphological phenomena although a need for cost-efficient mapping approaches has emerged recently (e.g. Bocco et al. 2001; Gude et al. 2002; Walsh et al. 2003b; Gurney & Bartsch 2005). In this study, the employment of a spatial grid system with generalized linear modelling (GLM) and hierarchical partitioning (HP) proved to be a useful way to estimate the role of several potentially significant environmental predictors in determining the distribution and abundance of periglacial landforms. However, the utilisation of GIS data, a grid-based approach and statistical methods in the modelling of geographical phenomena included several problems (e.g. Luoto & Hjort in press). Accuracy (e.g. thematic and positional), completeness (areal coverage) and price are general GIS data problems (e.g. Burrough & McDonnell 2000: 220–221; Zhang & Goodchild 2002: 3–6). In addition, statistical techniques commonly have several data related requirements that can be violated. For example, non-normality, non-constant variance structure, spatial autocorrelation and intercorrelation of predictors are general features of the geographical data that may cause harm in statistical analyses (e.g. Sokal & Rohlf 1981: 459–460; McCullagh & Nelder 1989: 21–22). Furthermore, the causal factors of the studied phenomena may operate on a different scale than the utilised covariates (e.g. Luoto et al. 2001). Consequently, these data related problems and methodological constrains should be taken into account at the different stages of modelling in order to obtain reliable results and to make valid interpretations.

6.3.1 Periglacial landform data

The utilised periglacial landform database is rather unusual because of its high mapping intensity, fine-scale resolution, and because it consists of fairly precisely georeferenced sampling locales. Furthermore, the same geomorphologist performed all surveys so variation resulting from differences between observers does not exist. However, the response data also included inaccuracies and deficiencies. The utilised digital aerial photographs were ortho-rectified. Still, there occurred spatial discontinuity between neighbouring images. An additional inaccuracy was caused by the GPS positioning although the location errors are estimated to be usually less than 20 m in open mountain birch forests and better than 10 m in treeless alpine heaths (cf. Miettinen 2002: 43–54). Despite that these spatial inaccuracies do not generally cause serious problems in mesoscale analyses, they should be considered in the selection of the modelling resolution.

According to the field checking, rather many new previously unobserved landform sites were detected with extrapolated prediction maps (e.g. Chapter 5.3.5), which is at the same time a positive and negative issue. The new landform occurrences clearly demonstrated the great potential of the numerical approach to map periglacial features (cf. Bustamante & Seoane 2004). On the other hand, new observations revealed deficiencies in the response data set. The most significant problems occurred with small landform types (e.g. stony earth circles, stone pits etc.) that were dif-
difficult to map directly with remote sensing data and their observation was problematic even in the field (e.g. Chapter 5.3.6; Kling 1998: 444). In addition, all occurrences of the prevalent landform types, such as earth hummocks, were difficult to determine because of their wide size and distribution range. Additional problems were caused by activity (see Chapter 6.1) and landform type definition. Periglacial features often form continuums and it can be difficult to classify large landform fields to discrete areas. For example, some of the cryogenic features have a rather similar morphological appearance (e.g. earth hummocks and peat pounus) or complex genetic processes (e.g. sorted nets). Therefore, it is quite obvious that the large response database included some misinterpretations.

Spatial autocorrelation is a very general statistical property of geomorphological variables observed across geographic space (e.g. Legendre 1993). Phenomena or environmental variables are spatially autocorrelated if a measure made at one point can be predicted with a measure made at another location, and autocorrelation is positive when subjects close to each other are more alike than distant things (Goodchild 1986: 3). Spatial autocorrelation can hamper attempts to identify plausible relationships between geomorphological phenomena and environment correlates, because the use of statistical tests may be invalidated by a strong spatial structure (e.g. Diniz-Filho et al. 2003). For example, regression techniques assume that modelled events are independent, which is not true in the case of autocorrelated data (e.g. McCullagh & Nelder 1989: 21).

In general, there occur several possible means to manage spatially autocorrelated data (Guisan & Zimmermann 2000: 156). For example, we can simply add an autocovariate to the set of predictors, widen the sample distance beyond the distance of spatial autocorrelation or we can build an autoregressive model (e.g. Legendre 1993; Augustin et al. 1996; Lichstein et al. 2002). However, the introduction of an autocovariate can drop out some of the meaningful predictor(s) because environmental factors are often also autocorrelated. Hence, spatial variables were only used in hierarchical partitioning to detect the independent contribution of a specific predictor in this study (see Chapters 4.2.3 & 6.3.3).

The selection of a link function for the responses in the abundance modelling was problematic due to the highly skewed distributions. Several different functions were tested but none of them gave fair results. The test modelling showed that normalisation of the responses could produce an appropriate outcome. Therefore, despite that the transformation can complicate the results’ interpretation, the aim was to normalise the responses. The utilised Box-Cox transformation defines the optimal transformation (e.g. Dobson 2002: 109), but still the responses were not ideally normally distributed, which can cause vagueness in the models. An additional possible problem in the abundance modelling was caused by the classification system of the landforms because, in some cases, the landform fields mapped as points (0.04 or 0.16 ha) were detectable from the residual plots (e.g. Fig. 64). However, it was assumed that this did not, in general, bias the modelling results.

The prediction abilities of the distribution and abundance models (GLMs) were evaluated by data obtained from the split-sample approach (e.g. Guisan & Hofer 2003). Consequently, the data used in the model testing were spatially autocorrelated with the data used to build the models and it is possible to gain over-optimistic estimates for the predictive abilities of the models. Therefore, the utilisation of independent evaluation data would improve the reliability of the model predictions.

6.3.2 Predictor data

Key factors affecting periglacial landforms and processes occurrence are fairly well known (e.g. Washburn 1979: 10–17). However, to include these determinants in the spatial modelling is problematic due to three main reasons. Firstly, to generate spatial data layers of causal correlates we often need numerous field measurements, which are commonly laborious to
Spatially continuous information layers can be obtained by remote sensing but these techniques also pose some resolution, accuracy and price related disadvantages (e.g. Jensen 2000; cf. Klein 2004). Secondly, we can only perform point measurements of spatially variable environmental factors in the field. Thus, to build a continuous information layer, we have to use interpolation techniques. The resulting predictors are models that include a generally unknown amount of uncertainty. However, methods such as kriging, where the uncertainty can be presented may help to spatially assess the validity of the data (e.g. Cressie 1993). Thirdly, the data used in the creation of a spatial information layer can be inappropriate for the purpose. For example, the climatological variables interpolated based on measurements conducted at the standard screen heights may not describe the actual conditions at the ground surface level where the processes act. Moreover, the network of the meteorological stations is scattered in remote regions and the measurements may only represent the climatological conditions of specific topographical locations, for example valleys in mountainous regions (see Chapter 3.6; Seppälä & Hassinen 1997: 158). Because of the lack of empirical data, mesoscale approach and the issues discussed above, most of the environmental factors used in this study were indirect correlates of periglacial phenomena (cf. Guisan & Zimmermann 2000: 155).

Several of the predictors were calculated from the digital elevation model (DEM) (Chapter 4.1.3). In general, DEMs frequently contain systematic and non-systematic errors that are amplified when first (e.g. slope angle) and second-order (e.g. wetness index) derivatives are calculated (Zhang & Goodchild 2002: 93–94, 120). Therefore, the quality of the created DEMs has to be assessed (Florinsky 1998: 41–42; Etzelmüller 2000: 140). The absolute height accuracy of the created DEM could not be evaluated because detailed height measurements were not available from the study area. However, the lack of reference information does not cause serious problems because the relative accuracy of the DEM is more important than absolute accuracy in the spatial analyses and the relative accuracy of the DEM was rather good (cf. Oksanen & Jaakkola 2000: 9).

Topography is probably the most widely used surrogate of frost activity. A number of studies have related different topographical parameters to periglacial landforms and processes (e.g. Harris C. 1982; Ødegård et al. 1988; Kling 1996; Matthews et al. 1998; Luoto & Hjort 2004, 2005). Not surprisingly, the mean altitude-variable was selected in many models as a statistical significant predictor. However, while the use of altitude variables in studies of patterns of geomorphological features is widespread, it is also problematic. The altitudinal gradient represents surrogates for several environmental gradients that are often intercorrelated, making tests of hypothesis associated with these factors difficult and controversial. For example, altitude has traditionally been viewed as a surrogate for air temperature because temperature decreases 0.56–0.60°C/100 m (e.g. Geiger 1965). However, it should be noted that the ‘classic’ elevation gradient of periglacial features is obviously not caused by elevation per se. The elevation-dependence is ultimately caused by more causal edaphic factors such as frost intensity, soil properties and vegetation (Matthews et al. 1998). In other words, elevation is a surrogate for one or more factors that are more direct correlates to geomorphologic processes than elevation.

Soil moisture has been stated as one of the most important factors determining the distribution and activity of periglacial landforms (e.g. Ballantyne & Matthews 1982; van Vliet-Lanoë 1988a; Matthews et al. 1998). The direct factor representing moisture distribution could not be used in the modelling because empirical information was not available. Hence, the topographical wetness index was used in the analyses. Despite the indirect nature of the factor and possible DEM data related uncertainties, the wetness index is a greatly acknowledged and widely used surrogate of soil moisture distribution (e.g. Moore et al. 1991). The importance of the topographical wetness index was also highlighted in several distribution and abundance models in this study. However, the
spatial information of the springs could even further improve the possibilities to model the distribution of periglacial landforms on the fell slopes and foot of slopes because features, for example earth and peat hummocks, occurred commonly in the areas of ground water seepage.

Air temperature is a crucial environmental driver for frost processes although usually only indirect information, such as a model of solar radiation balance, is available for spatial analyses (e.g. Heggem et al. 2001). The radiation variable utilised in this study was a simplified surrogate of solar radiation but it was still a fairly good approximation of the relative radiation differences in the region. Moreover, an empirical model of air temperature was available but it was not included in the final set of predictors. The minimum temperature variable was highly correlated ($R_s = 0.927$) with mean altitude and could be seen as a more important determinant for frost processes than altitude. However, the minimum temperature model was based on, among others, mean altitude, and it was constructed with 34 measurements from which only five were in the present study area. Therefore, mean altitude was seen to be a more reliable explanatory variable and thus, it was chosen for the set of predictors.

The soil data was compiled from three different information sources because a fine-scale soil map was not available from the study area. The coarse-scaled Quaternary deposit map (Kujansuu 1981) was completed with information obtained from the biotope database and field observations. In general, the utilised soil data was estimated to be rather good but some possible sources of errors were detected. Firstly and most importantly, peat data may be insufficient because the peaty areas were determined based on mire vegetation (e.g. Eeronheimo 1996: 26). This could cause precariousness in several models where the peat variable was a critical factor. Nonetheless, the mire information layer of the topographical maps and field observations concord almost perfectly with the utilised peat data. Secondly, according to the field observations, the rock terrain layer of biotope data included some misinterpretations that were probably because of the difficulty to map areas with thin soil cover. Thirdly, sand and gravel areas were grouped together although the frost susceptibility of glaciofluvial, aeolian and fluvial deposits can vary considerably depending on the fine-grain content. Moreover, some amount of the unexplained variation in the landform, particularly cryoturbation-based feature data, could be caused by the lack of information on silty soils (e.g. Schunke & Zoltai 1988; van Vliet-Lanoë 1988a, 1991).

The vegetation data utilised in this study contained certain problems. The mountain birches under two metres high were included in the shrub class (Sihvo 2002: 43) and shrub cover was determined only when the canopy cover was less than 30% (Eeronheimo 1996: 11). Based on the field observations, the possible sources of errors were, however, quite minor because firstly the shrub cover decreased rapidly with increasing tree cover and, secondly, small mountain birches had a very scattered distribution.

In addition to the data related shortcomings, collinearity between predictor variables (i.e. multicollinearity) can cause harm in detecting environmental determinants (see MacNally 1996). For example, insignificant or indirect variable A can omit meaningful direct factor B and C from the model due to intercorrelation (e.g. MacNally 2002: 1398). Consequently, if we perform spatial statistical analysis, we should take into account the intercorrelation of the predictors to make reliable inferences (e.g. Helkkinen et al. 2004). In this study, the hierarchical partitioning approach was used to reveal the most likely causal variables that may have remained undetected by the GLMs (see the next chapter).

### 6.3.3 Statistical modelling

Statistical models are often static but processes in nature are dynamic, and do not usually fulfil the equilibrium assumption (Guisan & Zimmermann 2000: 153). However, periglacial processes are relatively sluggish, but above all,
most of the mature features are fairly stable in short time periods (in decades) and this enables statistical modelling of periglacial landforms. Statistical modelling of periglacial phenomena has gained more attention from the beginning of the 1990s although other computer-based spatial models have been constructed earlier (Nelson 1986; Jorgenson & Kreig 1988). The majority of the studies have concentrated on mapping and modelling permafrost distribution or indicators of permafrost (e.g. Keller 1992; Hoelzle & Haebler 1995; Leverington & Duguy 1997; Ettelmüller et al. 1998; Gruber & Hoelzle 2001; Hoelzle et al. 2001; Luoto & Seppälä 2002a; Luoto et al. 2004a; Lewkowicz & Ednie 2004; Heggem et al. 2005) and only few studies have focused on the other periglacial phenomena (e.g. Ettelmüller et al. 2001; Luoto & Hjort 2004, 2005; Hjort & Luoto 2005, 2006).

Generalized linear models constitute a more flexible family of methods than traditional least square regression techniques. GLMs handle non-linear relationships and different types of statistical distributions of geographical data types, such as discrete, categorial, ordinal and continuous data. Therefore, GLMs provide a useful modelling framework for testing the shapes of the response functions and significance of variables describing environmental gradients (e.g. Franklin 1995). However, the technique and data-related constrains should also be considered. For example, GLMs, which are based on standard regression theory, assume that all predictors are measured without error. However, the exact value of the variables at each grid square was not known in this study, which may introduce an additional source of error into the results (e.g. Clark & Hosking 1986: 317; Yee & Mitchell 1991). Furthermore, collinarity between predictors and spatial autocorrelation can hamper the detection of causal correlates by regression techniques because the presence of autocorrelation may inflate the degrees of freedom in the test of significance (Chapter 6.3.1; Legendre 1993; Diniz-Filho et al. 2003).

The predictors of the final GLMs could explain only part of the variation in the response data, from ca. eight to 60%. In general, the large amount of unexplained variation can be caused by insufficient explanatory data (e.g. indirect factors or poor quality of the predictors) or lack of causal factors from the final model (e.g. Chapters 6.2.7 & 6.2.9). However, most of the logistic models explained over 20% of the deviance change in the data that can be kept as a rather good result (e.g. Clark & Hosking 1986: 463). Another reason for the fairly high amount of unexplained variation can be in the GLM method itself. Sometimes GLMs are not flexible enough to capture the shape of the interactions between environmental correlates and responses (e.g. Guisan & Zimmermann 2000: 161). Even by adding higher polynomial terms (e.g. a cubic term), the approximation may still be inadequate. The solution to the detection of more complex responses could be the utilisation of non-parametric methods, such as classification tree analysis (CTA) and multiple adaptive regression splines (MARS) that allows a wider range of response curves to be modelled (e.g. Luoto & Hjort 2005). However, non-parametric techniques have generally very little statistical theory to support them and it is easy to over-fit and over-explain features of the data. In addition, non-parametric methods have been criticized because they can produce very complex model outputs that are difficult to interpret (e.g. Venables & Ripely 2002: 211). Thus, corresponding parametric functions may capture most of the same variation and have a more realistic explanation (Guisan & Zimmermann 2000: 158–165; cf. Luoto & Hjort 2005).

Traditional regression techniques may distort inferences about the relative importance of predictor variables. This is because these approaches do not take into account the inter-correlation of the predictors. The hierarchical partitioning (HP) method used in this study provides a separate measure of the amount of variation explained independently by two or more explanatory variables and, therefore, it helps to make better deductions of the important environmental determinants (MacNally 1996). However, there are two shortcomings in this approach. Firstly, HP does not produce
a model and, secondly, the importance of polynomial variables cannot be assessed. Consequently, HP is suitable method in exploring causal factors but not, for example, in predicting landform distributions. Moreover, computational power required for analysing large data set can be seen as a minor shortcoming too. Hence, due to the different advantages and disadvantages of the GLM and HP, both methods were used and the results compared in this study.

Many of the spatial modelling studies have utilised a grid-based approach (e.g. Kunin 1998; Rowbotham & Dudycha 1998; Luoto et al. 2002; Heikkinen et al. 2004; Ayalew & Yamagishi 2005). An advantage of the spatial grid system is the possibility to convert usually vacillating spatial variables to numeric form enabling statistical analysis and the possibility to utilise GIS data as a source of predictor variables. The spatial grid system has also been used in periglacial distribution studies (e.g. Keller 1992; Leverington & Duguay 1997; Etzelmüller et al. 2001; Luoto & Seppälä 2002a, Luoto et al. 2004a; Luoto & Hjort 2005). However, examples of abundance studies in periglacial themes are largely lacking (for exception see Luoto & Hjort 2004). The utilisation of the grid-based method at the 25-ha resolution also posed disadvantages. Firstly, the rather coarse modelling resolution caused the loss of information. Secondly, the approach classified, according to the average environmental conditions, unsuitable sites as present squares even if the feature cover was minor (0.01 ha). The first problem could be overcome by using a finer resolution, although this could introduce a new source of error (see Chapter 4.1.1; Hurlbert 1984; Luoto & Hjort in press). The second issue is of course not an error, but decreases the power of statistical model to detect the association between response and explanatory variables. This shortcoming could be removed by using a threshold to omit the squares with very low feature cover. However, this was not performed in this study because some of the real observations would then be removed.

In summary, novel statistical techniques combined with grid-based GIS data offers an efficient framework for analysing geomorphological phenomena. Numerical spatial modelling can be an extremely useful addition to the current range of techniques available to researchers to map and monitor different landforms and processes. However, once again, it should be noted that the data related problems and method-based weaknesses discussed in this chapter may bias the modelling results and the model outcomes should be interpreted critically.
In this study, periglacial landforms were mapped and analysed from an area of 600 km² in subarctic Finland in the zone of discontinuous permafrost. More precisely, the distribution and abundance of the active periglacial features were modelled in a grid-based system utilising statistical methods to explore the important landscape scale environmental correlates. Empirical data sets and multivariate techniques in combination with GIS data enabled the construction of models to study the relationship between specific landforms and environmental factors.

The periglacial landforms were mapped with aerial photographs and located with a GPS-device in the field. The field-mapping results were digitized in a vector format on ortho-rectified aerial photographs. Periglacial landforms were classified to six main groups: (1) permafrost and thermokarst, (2) patterned ground, (3) slope phenomena, (4) frost weathering, (5) nival phenomena and (6) aeolian phenomena. The whole study area was divided into equal-sized 25-ha squares. Using GIS-techniques, response variables indicating the landform presence/absence and abundance (i.e. cover) were produced in each modelling square.

Twenty-four explanatory variables, which are potentially important in modelling periglacial phenomena, were compiled for each grid square. The predictors were calculated from GIS data sets and models. The variables were classified into five groups based on the environmental factor that they reflected; namely topography, soil moisture, temperature and solar radiation, soil type and vegetation. In addition, a group of spatial variables was compiled to use in hierarchical partitioning for controlling the effect of spatial autocorrelation and geographical trend in the response data. The final set of environmental predictors for the statistical analyses was selected based on the correlation analysis (Spearman’s rank correlation coefficient < 0.75).

The final modelling data were randomly divided into model calibrating (70%) and evaluation (30%) sets. The random approach was used to ensure the similarity of model calibration and evaluation data. The statistical methods were generalized linear modelling (GLM) and hierarchical partitioning (HP). GLMs were used to produce distribution and abundance models and HP to reveal independently the most likely causal variables.

The analyses were performed in statistical software R. In GLMs, the variables were selected using a statistically focused backward elimination approach. The possibility of a non-linear relationship between the explanatory variable and response variable was examined by including quadratic terms of the predictors into the modelling. In the end, the prediction abilities of the GLMs were assessed with evaluation data and field observations. Moreover, the correspondence of the model variables to potential causal environmental factors was evaluated using literature and results of the HP analyses. The binary logistic regression models were assessed quantitatively by calculating Kappa (κ) and area under the curve (AUC) measures. Abundance models were evaluated quantitatively by calculating Spearman’s rank correlation coefficient (R) between the predicted and observed values. Furthermore, predictions of the distribution models were evaluated visually and empirically using both prediction maps and new field observations.

A total of 40 different periglacial landform types and subtypes were identified from the study area. The largest landform groups with over ten types were patterned ground and slope phenomena. The most common features were earth hummocks, peat pounus, sorted nets, sorted solifluction sheets and deflations. From the mapped periglacial landform types twelve were utilised in distribution modelling, namely palsas, convex non-sorted circles, stony earth circles, earth hummocks, peat pounus, stone pits, sorted nets, stone stripes, non-sorted solifluction terraces, sorted solifluction sheets, sorted solifluction streams and defla-
tions. Palsas, convex non-sorted circles, earth hummocks, peat pounus and sorted solifluction sheets were used in abundance modelling, respectively.

The potentially important environmental factors affecting periglacial landform distribution and abundance are summarised in Figures 115 and 116. In general, pure topographical factors often were the primary correlates in distribution and abundance modelling because they are summary surrogates for several crucial environmental determinants of periglacial processes, such as temperature and soil moisture distribution. In addition, soil property and vegetation predictors were commonly in the models. However, there emerged differences between the set of important predictors for the distribution and abundance modelling of the periglacial landforms. For example, canopy cover was rather crucial discriminator between occupied and unoccupied sites but it was not a meaningful factor in the abundances modelling.

Continuums of periglacial landforms were prevalent in the study area. At lower altitudes with gentle slope angles occurred earth hummock, stone pit, peat pounu and palsa sequences and at higher altitudes with steeper slopes sorted stripe, stream and sheet continuums were common. However, sorted solifluction features can be without specific order on the same fell slopes. In general, palsas were more abundant below the treeline, but they occurred also in regio alpina. More precisely, peat cover and thickness, flat topography, soil moisture and vegetation were important factors determining the palsa distribution and abundance on the landscape scale. Convex non-sorted circles often located at higher altitudes than the other non-sorted circles, although convex circles could be spatially connected to the earth hummocks and sorted nets. Important factors in predicting convex non-sorted circles occurrence were topographical and soil moisture variables.

The set of important factors in determining the stony earth circle presence was more versatile including soil property, vegetation and topographical predictors. Generally stony earth circles occurred in areas where other periglacial landforms were rather rare. Earth hummocks and peat pounus had a fairly similar distribution at the landscape level, although earth hummocks were more abundant and obtained wider range through topographical gradients. On a local scale, soil properties and vegetation characteristics of earth hummock and pounu fields differed slightly. Flatness, shrub cover and soil properties specified the distribution of stone pits. In proportion, topographical factors and soil material were important correlates for sorted net occurrence. Active stone pits and sorted nets occupied rather the same environments although stone pits were, in general, more common than nets. Slope angle and altitude were crucial factors for the presence of active sorted stripes, sorted solifluction sheets and sorted solifluction streams. The possible importance of the vegetation variables was common among the sorted slope features as well. Non-sorted solifluction terraces were more abundant at lower altitudes than sorted solifluction features where the local topography varied considerably. Deflations occurred commonly in sparsely vegetated sand and gravel areas but also on the glacigenic as well as peat landforms. Therefore, at least vegetation and soil type information should be used in the distribution modelling of erosional aeolian features.

Most of the GLMs obtained good or excellent prediction ability in the model evaluation although the explanation power as well as the number and validity of the predictors varied notably between the final models. The best distribution models were constructed with palsa, earth hummock, peat pounu, sorted solifluction sheet and sorted solifluction stream data. Stony earth circle, non-sorted solifluction terrace and sorted net models had deficiencies in the prediction ability. In abundance modelling, earth hummock and peat pounu models were demonstrated to be the best (R² > 0.7) and palsa model the worst.

The employment of a spatial grid system with generalized linear modelling and hierarchical partitioning proved to be a useful way to estimate the role of potentially important
environmental predictors in determining the occurrence of periglacial landforms. However, the utilised mapping and modelling approach included several data and method-based shortcomings, which may bias the model outcomes. The positional errors, interpretation difficulties and uncertainties, spatial autocorrelation, multicollinearity, the indirect nature of some predictors (non-causality), scale differences between the processes and utilised predictors (mesoscale resolution), difficulties of compiling causal correlates as well as analytical requirements and limitations are examples of the critical methodological issues that should be taken into account in the different stages of modelling.

Figure 115. Potentially important environmental factors affecting periglacial feature distribution in northernmost Finnish Lapland at a landscape scale. The factors were grouped into three classes based on the univariate analyses, final generalized linear models and HP analyses. In determining the relative importance, validity of the predictor was also taken into account (large black circle = predictor was important in GLM and HP, small black circle = predictor was important/rather important in GLM and/or HP, open small circle = predictor had some importance in GLM and/or HP). The direction of the effect is not presented because some of the factors can be positive or negative or non-linear correlates of the feature occurrence (e.g. Chapter 6.2.1).
Figure 116. Potentially important environmental factors affecting periglacial feature abundance in northernmost Finnish Lapland at a landscape scale (for more details see Fig. 115).
8 CONCLUSIONS

Periglacial landforms were common geomorphological features in the study area. The diversity and activity of the phenomena varied spatially. The most active areas occurred commonly above the treeline in the moist valleys and on the fell slopes. Morphologically, periglacial landforms resembled those described from other subarctic regions. The present environmental conditions of the study area have promoted the formation of different cryoturbation and peat accumulation based non-sorted features. Most of the sorted landforms were probably formed before the climatic optimum over 8000 years ago, although many of them are active under current climate.

The modelling approach presented in this study provided a versatile method of modeling the relationship between environmental correlates and periglacial landforms as well as predicting distributions and abundances of the features. Moreover, the results of the analyses concord well with the hypotheses of feature occurrence in subarctic Fennoscandia at the landscape scale. Conversely, it can be argued that the results of GLMs and HP only showed what is already known. However, the results of this study have to be seen in a larger context. Firstly, the predictive mapping of geomorphological landforms (and other geographical phenomenon too) in remote regions is important because distribution maps of a different kind are essential tools to landscape planners, conservation managers, engineers, scientists and teachers. For example, the spatial information of the cryogenic phenomena is needed to monitor the possible effects of environmental change on the human activity in polar regions.

Secondly, numerical approaches and GIS data can be used to synthesize interactions between different phenomena and environmental drivers in physical geography. For example, the occurrence of geomorphological landforms is commonly a result of several factors and the relative importance of the correlates can be difficult to determine a priori. In addition, geographical phenomena are typically complex systems, thus a multivariate approach is needed to explore the correlation structure of explanatory and response variables.

Thirdly, despite that many of the variables in the models were axiomatic, the shapes of the response curves were often not. By introducing second-order polynomial variables, it was possible to detect non-linear response functions of environmental factors. For example, the several quadratic response functions displayed that the suitable conditions for periglacial landforms are often not at the end of the environmental gradients, but rather at the intermediate values. To take even one step further, higher order polynomials could be used to detect more complex responses. In addition, thresholds and optimums of the factors could be determined to study the potential effects of climate change. However, in that case, the quality of the data should be higher and predictors direct factors of periglacial phenomena.

Fourthly, utilising simultaneously two or more approaches we can gain deeper insight into the process-environment relationships. For example, several cryogenic landforms probably have different genesis in different periglacial (e.g. seasonally frozen vs permafrost) regions and many of the processes are still poorly understood (e.g. Grab 2005: 145–149). By modelling the phenomena through environmental gradients, we can obtain new information of environmental drivers affecting landforms genesis.

Fifthly, despite that the periglacial landforms were spatially autocorrelated and predictors commonly intercorrelated, most of the predictors in the final models were realistic when compared to literature and observations in the field. Therefore, the potential problems and constrains of geographical data sets did not, at least in most cases, hamper the detection of key environmental factors (cf. Diniz-Filho et al. 2003). This gave confidence about the possibility to utilise landform and GIS data
in statistical analyses to identify important factors of geomorphological phenomena.

Finally, too often the evaluation of the statistical models is neglected despite that it is a crucial step in the numerical analyses. Models cannot be applied confidently without knowledge of their accuracy as well as the nature and source of the errors because the data related problems and method-based shortcomings may bias the modelling results. Hence, the assessment of the models, especially distribution models, was emphasised in this study. The utilisation of two different evaluation measures and field checking of the prediction maps gave not only a comprehensive view of the model performance but also valuable information of the prediction errors. Thus, model assessment techniques presented in this study can play an important role in future and it is highly recommended that spatial statistical models should be evaluated with different quantitative and qualitative approaches. However, the utilisation of independent evaluation data would improve the reliability of the model predictions, which is important if the models are extrapolated to other regions.

New information of, for example, occurrence of periglacial landforms in subarctic Finland, environmental factors, shapes of the responses and applicability of the GLMs in predicting geomorphological phenomena was gained in this study. However, there are still numerous unsolved problems and open questions that are related to data, scale and methodological issues. In future, the analyses should focus on periglacial process units to deepen the theoretical understanding of the affective factors. In addition, more physically causal environmental variables should be used to obtain better models for prediction, exploration and extrapolation purposes. A significant task is the compilation of valid and reliable explanatory variables, especially from the digital elevation models and remote sensing data and their combinations, applied to model soil moisture, ground temperatures and snow distribution in periglacial environments. In statistical modelling, we should study landform distributions on different scales because parameters and processes important at one scale are frequently not important or predictive at another scale, and information is often lost as data are converted to coarser scales of resolution. Furthermore, the analyses should be performed in different environments with different statistical approaches taking into account the spatiality and multivariate nature of the geographical variables.

In the end, the mapping approach presented in this study does not reduce the importance of the traditional research methods, for example the geomorphological field survey. On the contrary, it expands the possibility to study complex periglacial phenomena more efficiently. Thorn (1992: 3), Barsch (1993: 158–160) and Seppälä (1997a: 83) have proposed guidelines for periglacial research and several of the presented study problems could be analysed further with modern spatial mapping and modelling techniques. Cost-efficient and reliable surveying of extensive polar regions, determination of the interactions between processes and landforms as well as between phenomena and environmental conditions, and the estimation of future modification of the periglacial domain in the context of projected climate change are examples of forthcoming challenges in periglacial studies.
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