Non-sorted circle occurrence

A study of landscape positions where non-sorted circles form

A.J. (Anne) Hoek van Dijke
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Table of contents

1 Introduction 2
   1.1 Introduction to non-sorted circle forming processes 2
   1.2 Purpose and research questions 4

2 Methods 5
   2.1 Study area 5
   2.2 Materials and methods
      2.2.1 Fieldwork 5
      2.2.2 DEM analysis 6
      2.2.3 Data analysis 7

3 Results 9
   3.1 Fieldwork 9
   3.2 DEM analysis 10
   3.3 Activity analysis 12

4 Discussion 14
   4.1 What are characteristics of non-sorted landforms in the Abisko area? 14
   4.2 On what landscape position are non-sorted circles present and absent? 14
   4.3 How does the activity of non-sorted circles change with landscape properties? 16
   4.4 What are the effects of a changing climate? 16

5 Conclusions 19

Bibliography 20

Appendix A 23
Abstract

Non-sorted circles are common frost features in periglacial environments. They play an important role in the storage of soil carbon and vegetation, nutrient and hydrology pattern. Global climate change is expected to alter non-sorted circle occurrence and the activity, however the direction and magnitude of the changes is still unclear. The purpose of this study was to determine landscape characteristics that drive non-sorted circle occurrence and activity. First field work was conducted in Abisko, northern Sweden, and second analysis were done using a Digital Elevation Model (DEM). In the field, characteristics of non-sorted circles were measured and analysed in relation to local altitude and slope. Using a DEM, the occurrence and activity of non-sorted circles was studied with respect to different landscape properties. This study shows that non-sorted circle occurrence is highest above the tree line, but limited at altitudes above 1000 m, where slopes are high and fine materials and soil moisture are limited. On a larger scale, concave topography increases non-sorted circle occurrence, but within the valleys, small ridges are favourable positions for non-sorted circle formation. Hypothesized is that non-sorted circles are favoured by high soil moisture and presence of fine materials, which is found in valley positions. A higher snow depth and longer snow cover in the lowest positions limits non-sorted circle formation. In the study area, few active circles were present. Under the current conditions, soil moisture is found to be the most important driver for non-sorted circle activity. The predicted higher precipitation for the 21st century could potentially increase activity, but higher air temperature and the effect it has on vegetation and active layer depth will decrease activity.
With the current changes in the global climate high northern latitude areas are expected and observed to warm more than other regions (Meehl et al., 2007). Air temperature warming is found to be correlated to warming of soils (Helama et al., 2011) and climate warming will therefore influence the permafrost and ice lens growth. Large amounts of carbon are stored in the arctic soils (Hugelius et al., 2014) and thickening of the active layers could facilitate the breakdown of soil organic matter and release large amounts of the greenhouse gasses methane and carbon dioxide (Davidson and Janssens, 2006; Mastepanoc et al., 2008; Schuur et al., 2015). Past cryoturbation (all movements of soil due to repeated freeze-thaw processes) led to the burial of the major part of this organic matter (Bockheim, 2007) and climate has a major influence on the activity of cryoturbation (Kaiser et al., 2007). Long-term cryoturbation can lead to the formation of patterned ground (Schaetzl and Thompson, 2015). Patterned ground is found in the form of circles, stripes, nets, polygons and steps and these forms may be sorted or non-sorted, where sorted forms are outlined by a coarse stony material (Allaby, 2004). Patterned ground is important in determining soil carbon and vegetation pattern and is important for the solute, heat and nutrient transport in the soil (Bockheim, 2007; Frost et al., 2013; Makoto and Klaminder, 2012). Because of the large potential of subarctic soils to store carbon and the influence that patterned ground has on soils and the subarctic ecosystem it is important to study the effect of climate warming on these subarctic ecosystems.

Non-sorted circles, which are also known as mud boils, frost boils, tundra craters or frost scars are a common form of patterned ground in areas where the July temperature is $2 - 12^\circ$C (Walker, 2003). Non-sorted circles show as round and convex non-vegetated areas. They are approximately 1 – 3 m in diameter and have little vegetation on them, but they are surrounded by vegetation (Daanen et al., 2008) (fig. 1.1). Non-sorted circles are found in locations with silty soils (Walker, 2003) and impeded drainage (Drew and Tedrow, 1962). On steeper slopes ($5 - 12^\circ$), non-sorted stripes may be found (Åkerman, 1980). Stripes are elongated non-vegetated areas, which are surrounded by vegetation (fig. 1.2). The vegetated area closely surrounding circles and stripes is in this study called the inter-circle zone, after Walker et al. (2004). The subduction zone is the area in between the circle and inter-circle area (fig. 1.3).

### 1.1 Introduction to non-sorted circle forming processes

Many different mechanisms have been proposed to be important in non-sorted circle formation. Van Vliet-Lanöe (1991) reviewed these mechanisms and concluded that differential frost heave is the main process in the formation of non-sorted circles, although other processes may help. Some important frost and slope related processes involved in the formation of non-sorted circles will be introduced first.

#### Ice Lens Formation and differential frost heave

Cooling of the surface can result in the formation of ice lenses in the soil. Water expands when it freezes and this transition of liquid to frozen water results in a volume expansion of approximately 9%, but larger heaving of soils is observed. Taber (1928) was the first to demonstrate that if water freezes, the surroundings get dryer and cryostatic suction pulls unfrozen water from below or the vegetated inter-circle area towards the freezing front. This water freezes onto the ice particles and thick ice lenses form. Because of a difference in insulation and wind chill, ice lens formation is larger on non-sorted circles than on the surrounding inter-circle areas (Romanovsky et al., 2008; Walker et al., 2004). The difference in heave between...
the circle and inter-circle area is called differential frost heave.

The formation of ice lenses requires (among others) repeated freeze-thaw cycles and water available for freezing. Impeded drainage, e.g. a permafrost or bedrock layer, increases water availability. A high capillary action and high water permeability allows water to move towards the freezing front. In silty soils, these conditions are met and therefore ice lenses preferably form in silty soils. Cold temperatures to allow for freezing are found in locations with little isolation; no plant cover, no organic matter and no thick isolating snow layer (Zhang, 2005).

**Vertical and radial movements in non-sorted circles**

The soil in non-sorted circles moves circulatory (fig. 1.3). The ice lenses heave the soil and during periods of thaw, the heaved soil in the centre moves to the sides by frost creep and erosion (e.g. Klaminder et al., 2014; Klaus, 2012). The open spaces formed by the melting ice lenses are filled up with soil from below. In the subduction zone soil is transported downwards (Klaminder et al., 2014). This subduction hypothesis is supported by evidence of buried organic material in the margins of non-sorted circles (Becher et al., 2013; Boike et al., 2008).

Vertical sorting of the soil takes place in non-sorted circles, because larger stones are brought to the surface faster than finer materials by frost pull and frost push (Derbyshire et al., 1979). For the first process, ice lenses form under stones, (because stones have a higher thermal diffusivity than the surrounding soil (Bowley and Burghardt, 1971)) and force the stones up. By frost pull, the soil above a stone is lifted during freezing and the stone is pulled up when the adfreeze force around it is greater than the forces holding it to its place (Kaplar, 1965). The vertical sorting and radial soil movement can lead to the formation of sorted circles, (a circle of fine material is bordered by stones), if the sorting takes place for longer periods (Hjort, 2006; Hopkins and Sigafoos, 1950; Nicholson, 1976; Van Vliet-Lanoë, 2014).

**Slope Processes**

On steeper slopes, non-sorted stripes are found which form by solifluction (King, 1971). The direction of the stripes reflects the direction of the greatest slope (Akerman, 1980; King, 1971). Different definitions of solifluction exist, the definition of the encyclopedia of geomorphology is used: "slow downslope movement of soil mass usually associated with freeze thaw cycles and frost heave" (Matsuoka, 2004, p. 984). Solifluction includes gelifluction and frost creep, where the first is a slow downslope flow of unfrozen earth on a frozen layer (permafrost) and the latter is the movement of individual particles which heave normal to the slope by frost heave and settle vertical when thawing (Hargitai and Johnson, 2014). Solifluction can operate on gradients as low as one degree and the annual rates of downslope movement vary between ca. 0.5 and 10 cm a⁻¹ (Matsuoka, 2004). Important factors that determine solifluction are climate (Matsuoka, 2004), soil moisture, slope gradient (increasing rates with inclination), grain size distribution and vegetation cover (Matsuoka, 2001). Larger stones or vegetation can stop soil movement and form the end of a solifluction lobe (Matsuoka, 2004).

**Initiation and self organization**

The development of non-sorted circles and stripes can be explained with frost and slope processes. The initiation of non-sorted circle and pattern formation is less well known. The regularity (equal distances and sizes) suggests a better organization than would follow from random initiation. Nicholson (1976) suggested that the random heaving of one non-sorted circle might trigger the formation of non-sorted circles in the surrounding areas, by changing the vegetation, soil moisture or by elevation differences. E.g. cryosuction depletes the soil surrounding a circle and thereby influences the surrounding soil and non-sorted circle formation (Fowler and Krantz, 1994; Peterson, 2011). This process could explain regular pattern formation. When a non-sorted circle field has developed, with bare centres and vegetated inter-circle areas, the pattern will maintain itself. The circle centre differs from the inter-circle areas in (soil) temperature, hydrology, thaw depth and nitrogen and carbon content (Boike et al., 2008). The circle centres are the higher locations in the landscape, where more heat escapes and are therefore more susceptible to freezing and ice lens formation.
Also vegetation contributes to the self-organization of non-sorted circles. Vegetation grows in the inter-circle areas where nutrient availability is higher and they insulate the surface, which decreases ice lens formation in the inter-circle area. Plants also promote nitrogen input in the soil which favours plant growth. Conversely, plants do not grow in the circle centres, because these areas are unstable and the plant roots experience frost damage (Jonasson, 1986).

Walker et al. (2004) made a conceptual model of non-sorted circle ecosystems, which consists of the circle and inter-circle area and ice lenses, vegetation and the soil. In cold arctic systems, the biological processes are weak and physical processes dominate in the formation and maintaining of non-sorted circles. In a subarctic climate, the vegetation processes dominate (Walker et al., 2004).

Activity of non-sorted circles

Non-sorted circles may be active or inactive and the activity is dependent on climate (Hopkins and Sigafoos, 1950). High amount of carbon buried by cryoturbation in non-sorted circles was for example found to occur during periods of climate warming when the permafrost was thawing (Becher et al., 2013; Bockheim, 2007). This may indicate that cryoturbation will increase as a consequence of climate warming (Bockheim, 2007; Henry, 2008). In Canada, frost heave was studied along an arctic to subarctic transect (Walker et al., 2008) and in Abisko, differential frost heave was studied along an elevation gradient (Klaus et al., 2013). Both studies concluded that differential frost heave is highest in the middle, where the difference in vegetation between the centres and inter-circle area is largest. A northward shift of vegetation as a result of climate warming may thus increase non-sorted circle activity in unvegetated arctic areas if the inter-circle areas gets vegetated. In the Abisko area, a net overgrowth of non-sorted circles by vegetation was found in the last fifty years, which indicates that the circles became less active (Becher et al., 2013). This conclusion was supported by the fact that no buried organic layers were found from the last decades. This overgrowth of vegetation may be the effect of less intense frost heave, or the inactivity is the result of an increase in vegetation, since roots can stabilize the soil (Raynolds et al., 2008).

1.2 Purpose and research questions

To be able to predict the effects of climate warming and a changing precipitation on non-sorted circle occurrence and activity it is important to study the drivers for non-sorted circle occurrence and activity. The purpose of this study is to determine landscape properties where non-sorted circles occur. Seven different terrain aspects will be tested: altitude, slope, curvature, Topographic Position Index, Topographic Wetness Index, northness and eastness.

The subquestions for this study are:

- What are characteristics of non-sorted landforms in the Abisko area?
- On what landscape position are non-sorted circles present and absent?
- How does the activity of non-sorted circles change with landscape properties?

Hypothesis

Prerequisites for the occurrence of frost heave are freezing temperatures, a high water availability and the presence of fine materials. Precipitation in the form of rain increases frost heave and a shallow bedrock or permafrost can impede drainage and therefore enhance non-sorted circle formation. The temperature is influenced by the presence of snow and vegetation, which insulates the soil and also sunshine and wind influence the soil temperature. A difference in frost heave between the circle and inter-circle area is required for differential frost heave to occur. This requires the presence of vegetation. Regarding the landscape properties that will fill be tested and there relation with presence and absence of non-sorted circles, it is hypothesized that:

- Since temperature decreases with altitude, non-sorted circle occurrence increases with altitude.
- The limited availability of soil moisture and fine materials at high altitude limits non-sorted circle formation.
- Non-sorted circles are found in areas with a low slope, because at steeper slope angles, solifluction will lead to the formation of stripes.
- More non-sorted circles are found in depressions, because these are the locations where fine materials and soil moisture collect.
- More non-sorted circles are found at the north facing slope. At south facing slopes, solar radiation is higher which raises the air and soil temperature and thereby limits non-sorted circle formation.

In short, this study consisted of two parts. First field work was conducted in the Abisko area and second, analysis were done using a digital elevation model. In the field, several aspects of non-sorted landforms (circles and stripes) were measured and these data were statistically analysed. Using a digital elevation model, presence, absence and activity of non-sorted circles in relation to different landscape aspects were tested. The methods, results and discussion are presented in the following chapters.
2 | Methods

2.1 Study area

This study was carried out in Swedish Lapland. The study area is approximately 15 by 7 km, with the Abisko field station in the northwest corner of the study area (68°21′N, 18°48′E). The study area is bordered by the valleys of the rivers Bessjosjöka and Nissonjöka and at the north by Lake Torneträsk (fig. 2.1). Within the area, the elevation ranges from 340 to 1740 m.

The average yearly temperature measured at the Abisko Scientific Research Station (for the period 1980-2014) is −0.4°C and is increasing since 1980. The average January and July temperature is respectively −9.8°C and 9.8°C. The area is relatively dry, because it lies in the rain shadow of the mountains in the west. The average precipitation is 313 mm/year of which 19% falls in July, the wettest month. A snow layer is present from approximately October to May and the average snow depth is 34 cm, but average yearly snow depth is below average since 2000 (fig. 4.2). (Abisko Scientific Research Station, unpublished data) The snow layer is thickest in March, on average 54 cm. In the study area, the permafrost is discontinuous (Brown et al., 1998, revised in 2001) with active layers of approximately 60−90 cm deep which became thicker during the past decades (Åkerman and Johansson, 2008).

2.2 Materials and methods

2.2.1 Fieldwork

The fieldwork was conducted in July 2015. In the study area, six different non-sorted circle fields and two different non-sorted stripe fields were studied (fig. 2.2). In the field, for every landform it was noted down whether it was a circle or stripe and if it was active or not. With landforms, both circles and stripes are meant. Landforms were recognised as stripes because they had a length width ratio of approximately more than two. There is no universal definition for activity and of non-sorted circles and stripes and there is also no universal method to determine activity (Klaus, 2012). Klaus methods included the measuring of differential frost heave or vertical and radial soil movement. These methods require a longer period of measurements or repeated measurements which was not possible within this study. Therefore, the activity of patterned ground was based on whether recently brought up material was visible at the surface. Soil without a moss cover and stones without lichens were an indication of recently brought up material.

In the field, the x- and y-coordinate and elevation was determined for every landform using a gps and the slope was measured using an inclinometer. The length (in the downslope direction) and width (perpendicular to the length) of each landform was measured. The height of the top of the non-sorted landforms relative to the vegetation was estimated visually in the following classes: < −20 cm, −20 − 0 cm, 0 − 10 cm, 10 − 20 cm, > 20 cm. The surface stoniness (the percentage surface coverage of the non-sorted landforms with stones) was estimated visually for boulders (>25 cm), stones (7.5−25 cm) and pebbles (0.2−7.5 cm). The surface coverage by vegetation was estimated visually, where a distinction was made between all vegetation and green vegetation, where the latter included grasses, forbs and shrubs. Last, it was noted down if lichens, mosses, forbs, grasses, deciduous and evergreen shrubs were present in the circle and/or inter-circle area.

Soil moisture

Soil moisture of the circle centre and inter-circle area was measured for fourteen circles at sample locations 2 and 3 (fig. 2.2). Soil samples were taken at ∼ 10 cm depth or if present, below the purely organic layer. In the laboratory, the samples were sieved to remove branches, roots and stones. Approximately 10 grams of soil were weighed and dried in an oven at 105°C for 24 hours. The dried samples were weighed again and the soil moisture content was calculated as

\[
\% \text{ soil water} = \frac{m_{\text{wet soil}} - m_{\text{dry soil}}}{m_{\text{wet soil}}} \times 100
\]

For two circle centre samples, the samples were not weighed correctly and therefore the results of 14 inter-circle and 12 circle centre positions are presented.
During the sampling and sieving, water in the samples had condensed and therefore, the results underestimate the true soil moisture content.

2.2.2 DEM analysis

A Digital Elevation Model (DEM) was used to analyse on which landscape positions non-sorted circles are present and absent. A LiDAR DEM with a 2 m resolution was available from Landmäteriet, the Swedish National Land Survey. Since the DEM is used to study the landscape rather than the non-sorted circles themselves, a coarser resolution was preferred. To remove noise introduced by the patterned ground, the DEM was resampled to 20 m using the cubic convolution method. Also a geomorphological map of the area was available (Melander, 1977), where the presence of 'patterned ground at flat terrain' was marked, which were assumed to be non-sorted circles. This assumption is supported by the high agreement of non-sorted circles observed in the field and marks on the map. Furthermore no other types of 'patterned ground at flat terrain' were found during the field work. The scanned geomorphological map was georeferenced with help of 16 control points on a topographic map. A second order polynomial equation was used for the transformation, with a total root mean square error of 21 m. The DEM was checked for voids and outliers and sinks were filled using the function 'sink fill' in ArcMap. Lakes that could be identified from a topographic map were excluded from the sink fill process. The sink fill tool changed 0.26% of the DEM.

The topographical parameters used in the analysis were the altitude, slope, curvature, Topographic Position Index, Topographic Wetness Index, northness and eastness. The altitude was derived from the DEM and the slope was calculated in ArcGIS. The Topographic Position Index was calculated with the eponymous tool in SAGA GIS (Guisan et al., 1999). The TPI is calculated as the altitude minus the mean altitude of the surrounding area (fig. 2.4). The value for TPI depends on the scale factor, which is the diameter chosen to calculate the mean altitude (fig. 2.4). The TPI was calculated with a scale factor of 60 and 400 m (fig. 2.4). For the north border of the study area, the TPI at 400 m scale is overestimated, since the lake level was used to calculate the average altitude instead of the lake bottom. The Topographic Wetness Index was calculated in SAGA GIS.
2.2. Materials and methods

The TWI is calculated as:

\[ \ln \left( \frac{SCA}{\tan(\beta)} \right) \]

where the \( SCA \) is the specific catchment area, which is the inverse of the value calculated with the tool ‘catchment areas (parallel)’ and \( \tan(\beta) \) is the local slope. In ArcGIS the curvature is calculated using the function of Zevenbergen and Thorne (1987). The values for curvature are positive for a convex surface and negative for a concave surface. In ArcGIS the aspect was calculated and afterwards, the cells with an aspect of \(-1\), flat areas, were removed. The northness and eastness were calculated as resp. the sine and cosine of the aspect. The northness and eastness range from \(-1\) to 1, where \(-1\) indicates resp. south and west and 1 indicates north and east (fig. 2.4).

The areas with non-sorted patterned ground according to the geomorphological map were marked in ArcMap and a grid was created with the same cell size as the DEM with 0’s (non-sorted circle absent) and 1’s (non-sorted circles present). For logistic regression it is recommended to use equal portions of 0 (absence of non-sorted circles) and 1 (presence of non-sorted circles) (Ayalew and Yamagishi, 2005) and therefore, 2500 points with and 2500 points without non-sorted circles were randomly selected using the ArcGIS tool ‘Create Random Points’ (Appendix A). These 5000 points represented 2.4 and 0.58% of the total number of points resp. with and without non-sorted circles. The points were coupled to the in that grid cell present values for altitude, slope, curvature, aspect, TPI and TWI.

Also the coordinates for the in the field analysed non-sorted landforms were coupled to corresponding values for altitude, slope, curvature, aspect, TPI and TWI. A comparison between the in the field measured slope and altitude and the DEM calculated slope and altitude show that there is a high agreement between the two measures for altitude, but for slope the DEM derived slope is \(0.15^\circ \pm 3.0^\circ\) higher. The large difference for slope can be explained by a difference in scaling: in the field, the slope was measured very local, while the DEM had a resolution of 20 m. In the analysis, the field measured slope and DEM derived altitude were used.

2.2.3 Data analysis

For the measurements of the fieldwork, the relationships between the measured landscape properties altitude and slope and the non-sorted circle parameters were analysed using linear regression. A relationship was assumed to be significant for \(p\)-values \(\leq 0.05\).

Landscape properties of the active and inactive circles were compared visually and with t-tests. The landscape

![Figure 2.3](image-url) *Figure 2.3: The in the field measured altitude and slope compared with the altitude and slope derived from the 20 m resolution DEM. For slope and altitude, the correlation between the measured and DEM derived values is resp. 0.71 and 1.00.*

![Figure 2.4](image-url) *(a) The TPI is calculated as the altitude minus the average altitude of the surrounding cells. The scale factor determines the width of the area wherefore the average altitude is calculated. (b) shows the effect of different scale factors, 400 m compared to 60 m. (c) The northness and eastness are calculated as resp. the sine and cosine of the aspect.*
properties of active landforms were tested against those of all inactive landforms and against the in the same area found inactive landforms.

For the soil moisture samples, a comparison was made between the circle centre and inter-circle area. Also possible relationships between soil moisture content and non-sorted circle- and landscape properties were tested using linear regression.

For the DEM analysis, locations with and without non-sorted circles were compared using binary logistic regression. Binary logistic regression estimates the probability that non-sorted circles are present given the landscape properties. Logistic regression requires the explanatory variables to be uncorrelated. Curvature & TPI on sixty m scale were correlated ($r=77\%$) and are therefore not combined in the regression models. Different regression models were compared based on the ROC-curve and percentage false positive and false negative estimations.
3 | Results

3.1 Fieldwork

In total, 85 non-sorted landforms were sampled in the Abisko region, spread over eight locations (fig. 2.2). Of the 85 landforms, 72 were circles and 13 were stripes. All stripes were inactive. Of the 72 circles, seven were classified as active. The inactive circles were covered by vegetation and lichens were found at the surface stones. The active circles were to a less extent covered by mosses, forbs and shrubs. Furthermore, only a few small lichens were found on the surface stones. The absence of lichens and presence of soil without a moss crust may indicate that this material was brought to the surface recently. An other evidence for activity on these circles was a 40 cm high willow tree that was tumbled over by a stone. Apart from the difference in vegetation- and lichen cover between the active and inactive circles, more differences were observed. The active circles were lower than the surrounding inter-circle areas (±20 cm lower), while the inactive circles were elevated above the surroundings. Also the active circles had a little pool in the back. All stripes in the area were classified as inactive, since they were all overgrown with mosses and lichens were present at the surface stones.

Size and shape

The measured non-sorted circles had an average length of 237 cm in the downslope direction and an width of 275 cm. For the stripes, the length and width were resp. 803 and 188 cm. Active circles were larger than inactive circles (length and width resp. 215 and 271 cm for inactive and 390 and 296 cm for active circles) (P < 0.05). Longer landforms (both circles and stripes) were found on steeper slopes and on higher altitudes (p < 0.05) (table 3.1). Analysing 13 stripes only, longer stripes are found on steeper slopes, but this relationship is not significant. The length in downslope direction is shorter than the width in the perpendicular direction for 58% of the non-sorted circles. The roundness, defined as width divided by length is not dependent on slope or altitude.

Landscape properties

In the field, non-sorted circles and stripes were found at the north, east and west facing slopes of the mountains at various altitudes. South facing slopes were also visited during the field work period, but no measurements were done on these slopes. Non-sorted circle fields were most present above the treeline and below the treeline non-sorted circles were present on non-forested locations only.

For the sample fields 2, 3, 5 and 8 (fig. 2.2), non-sorted circle fields were characterised as locally elevated, convex ridges in the landscape. The lower surroundings were covered with trees, high shrubs or a peaty vegetation. The stripes were found at higher slopes than circles (p < 0.05) (a mean slope of 11.9° for the stripes versus a mean slope of 4.2° for circles). Three stripes did not follow the steepest slope, e.g. one stripe flowed down a slope of 4° while the slope in the perpendicular direction was 10°.

Soil

The non-sorted circles were characterized by a grey silty soil, with reddish and bluish colors, while the soils of the inter-circle areas were dark and contained more humus. In the inter-circle areas, dark organic layers were found on top of the silt, with a depth of several cm up to 20 cm. In these organic layers, little to no silts and stones were present.

Soil moisture samples were taken in the circle centre and the inter-circle area. The soil moisture content in the vegetated inter-circle areas was higher (average = 26.7%) than in the circle centres (average = 12.4%) (p < 0.05). The soil moisture content in the circle centres was negatively correlated with the coverage by stones < 7.5 cm (p < 0.05). No other relationships were found between soil moisture content and non-sorted circle characteristics or landscape properties.

Stoniness

The total surface stoniness (percentage of the surface covered with stones) increased with altitude and slope (p < 0.05) (table 3.1). On average, 45% of the non-sorted circle and stripe surfaces was covered with stones, of which 31% of the stones was smaller than 7.5 cm. Below 400 m a.s.l., the inactive circles had a surface coverage of 14% and the active circles had a stoniness of 46%. Stones > 25 cm were sparsely present (0% on the inactive and 3% on the active circles). Above 400 m the surface coverage of stones > 25 cm was on average 5 % and independent of altitude. Analysing circles only, there was no relation between surface stoniness and slope, but for stripes, the total stoniness increased with altitude and decreased with slope (multiple linear regression, $R^2_{adj} = 74\%$).

Vegetation

Considering vegetation, three different areas can be described, the non-sorted circles/stripes, the inter-circle areas and the areas surrounding the non-sorted circle fields. All of the studied non-sorted circles and stripes were (partly) covered with a lichen- and moss vegetation
Chapter 3. Results

<table>
<thead>
<tr>
<th></th>
<th>Length [cm]</th>
<th>Width [cm]</th>
<th>Stones 0-7.5cm [%]</th>
<th>Stones 7.5-25cm [%]</th>
<th>Stones &gt;25cm [%]</th>
<th>Total stoniness [%]</th>
<th>Vegetation coverage [%]</th>
<th>Green vegetation [%]</th>
</tr>
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<tbody>
<tr>
<td><strong>All landforms</strong> (n=85)</td>
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<td>5</td>
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<td>62</td>
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<tr>
<td>Standard deviation</td>
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<td>151</td>
<td>20</td>
<td>8</td>
<td>5</td>
<td>24</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>Correlation with altitude</td>
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<td>+</td>
<td>+</td>
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<td>+</td>
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<tr>
<td>Correlation with slope</td>
<td>+</td>
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| **Circles** (n=72) |             |            |                   |                     |                  |                     |                        |                      |
| Mean                 | 236         | 275        | 30                | 8                   | 4                | 42                  | 66                     | 34                   |
| Standard deviation   | 116         | 160        | 22                | 7                   | 5                | 24                  | 24                     | 21                   |
| Correlation with altitude | +          | +          | +                 | +                   | +                | -                   | -                      | -                    |
| Correlation with slope | +          | +          | +                 | +                   | +                | -                   | -                      | -                    |

| **Stripes** (n=13) |             |            |                   |                     |                  |                     |                        |                      |
| Mean                 | 766         | 190        | 39                | 17                  | 8                | 64                  | 41                     | 14                   |
| Standard deviation   | 362         | 56         | 11                | 7                   | 6                | 10                  | 14                     | 10                   |
| Correlation with altitude | -          | +          | +                 | -                   | -                | -                   | -                      | -                    |

Table 3.1: The linear regression results for the non-sorted landforms and for a subset of circles and stripes. The mean and standard deviation are presented and the results of the linear regression. For coefficients significantly different from zero (p ≤ 0.05) a + indicates a positive relationship, a - indicates a negative relationship.

and also grasses and various types of dwarf shrubs (dwarf birch, blackberry, salix, and heather were most common) were found on most of the landforms. The coverage by grasses and dwarf shrubs was resp. 67% and 86%. The vegetation cover of inactive circles and stripes decreased with altitude (p < 0.05) (table 3.1). Above 800 m a.s.l., the total and green vegetation cover was resp. 35% and 12%. The vegetation cover was highest in the areas below 400 m altitude, on average 92% of the inactive circles was covered with vegetation, of which 45% with green vegetation. For the active circles on the same altitude, the vegetation cover was 57% of which 46% was green vegetation.

The inter-circle areas were characterized by a higher and denser vegetation of mosses, grasses, forbs and dwarf shrubs.

Non-sorted landform fields were bordered by forest or by a higher and more dense vegetation of shrubs or peat than the non-sorted landform fields itself. In some areas, the transition between a non-sorted circle field and the surrounding vegetation was sharp, but in other other areas, the transition was more gradual with overgrown non-sorted circles at the side of a non-sorted circle field.

3.2 DEM analysis

Comparing locations with and without non-sorted circles

From fig. 3.2 it is clear that more than half of the study area is a north facing slopes. At south facing slopes, non-sorted circles are relatively more abundant than areas without non-sorted circles compared to the north facing slopes. The presence and absence of non-sorted circles does not change with eastness.

The 5000 analysed random points are found between altitudes of 342 and 1682 m. Ninety percent of the locations with non-sorted circles is found between 555 and 988 m, with a peak in abundance between 850 and 900 m. No non-sorted circles are present above 1080 m. The altitude of the area is different for the north- and the south facing slopes and also the occurrence of non-sorted cir-
3.2. DEM analysis

Non-sorted circle occurrence does not increases linear with altitude and therefore ‘the absolute deviation from mean altitude’ was included in the analysis as an extra explanatory variable, which was derived from the altitude. The variable was calculated as:

\[
\text{Absolute deviation from mean altitude} = |\text{Altitude} - 786.3|
\]

**Binary logistic regression**

The absence and presence of non-sorted circles at different landscape positions. Note that for both groups, 2500 points were random selected and that this selection is not representative for the ratio between locations with and without non-sorted circles and that the sum of 2500 with 2500 points without non-sorted circles is also not representative for the whole area.
Chapter 3. Results

Where 786.3 m is the mean altitude for the 5000 random selected points. This variable was chosen as explanatory variable for the prediction of non-sorted circle occurrence, since this gave a better prediction for non-sorted circle occurrence than altitude (table 3.2). Altitude, slope, northness, TWI and TPI (at 400 m scale) are significant predictors for non-sorted circle occurrence. Non-sorted circle occurrence decreases with increasing distance to the mean altitude. Furthermore, the probability of non-sorted circle occurrence decreases with increasing slope and increases with increasing TWI. The coefficient of northness is negative; there are more non-sorted circles at south facing slopes. TPI at the 400 m scale decreases with non-sorted circle occurrence, which indicates that non-sorted circles are more often found at areas which are lower than the surrounding 400 m.

Using slope and absolute deviation from mean altitude, the probability of non-sorted circle occurrence is best estimated. The probability for non-sorted circle occurrence is then calculated as:

\[ P = \frac{1}{1 + e^y}, \]

where

\[ y = -0.012 \times |(\text{Altitude} - 786.3)| - 0.074 \times \text{Slope} + 2.729 \]

For the 5000 points, the percentage correctly estimated is 78.6%. The probability map for non-sorted circle occurrence created from this formula is presented in fig. 3.4. For median altitudes non-sorted circle occurrence is correctly estimated. In the low altitude, north facing area, a few non-sorted circle fields are present, while the probability of occurrence is below 20%.

3.3 Activity analysis

Comparing seven 7 and 78 inactive landforms (circles and stripes), the active landforms are found at lower altitude, close to lake Torneträsk (fig. 3.3). Furthermore, the active circles are found at lower slopes and at locations with a higher TWI and lower TPI (\( p < 0.05 \)). The latter is most pronounced for the 400 m scale. The curvature does not differ between position with active and inactive circles.

When zooming in on the shore of lake Torneträsk, active and inactive circles were found within a distance of 100 m. The active circles were found at a lower altitude, lower slope, higher TWI and lower TPI at both the 40 and 60 m scale (fig. 3.3). Furthermore, the active circles are found on average 45 m closer to the lake than the inactive circles. In the field, no differences in surrounding vegetation, solar radiation and soil texture was visible between active and inactive circles.

Figure 3.3: Comparison of active and inactive circles in the study area. In total, there were seven active circles measured, but because they were found in the same DEM raster cell, they appear as four.
3.3. Activity analysis

Figure 3.4: Probability map of non-sorted circle occurrence. The presence of non-sorted circles is based on a geomorphic map of the area. The probability is calculated as a function of altitude and slope.
4 | Discussion

4.1 What are characteristics of non-sorted landforms in the Abisko area?

Non-sorted stripes were found on steeper slopes than circles. This was expected because solifluction rates increase with inclination (Matsuoka, 2001). Non-sorted stripes are reported to be oriented down the steepest slope (Åkerman, 1980), but in the Abisko region three stripes were oriented down a less steep slope. An explanation for this can be that flow down the steepest slope was hindered by the occurrence of larger stones, since they can stop soil movement (Matsuoka, 2004). The coverage of landforms by stones was highest on the stripes. The amount of surface stones is found to increase with elevation and is correlated to a decrease in vegetation. A decrease in vegetation can be expected because of higher wind, less soil and lower temperatures. Since vegetation covers the soil (and stones) the observed correlation between vegetation and surface stoniness was not unexpected.

During the field trip, one location was found to have active circles and no other active circles were observed in the area. Klaus (2012) studied activity of non-sorted circles in approximately the same area and he did measure differential frost heave and lateral soil movement in areas that were classified ‘inactive’ in this study. Ridefelt and Boelhouwers (2006) concluded that their landforms were active because ‘outflows of silt and clay slurry’ were visible. This was also observed in the field, but these circles were classified as inactive if they were covered with mosses and the stones were covered with lichens. There are different proxies for activity and no definition of activity is given in literature. This leads to inconsistent conclusions regarding activity. In this study, by activity was meant that radial movements in the soil were occurring, meaning that fresh stones are brought up and organic matter is transported down. Differential frost heave itself will not result in a downward transport of organic material and is therefore of less interest when for example the effects of activity on soil carbon storage are studied. But when vegetation and hydrology pattern are of interest, differential frost heave is a useful measure for activity since ice lenses cause damage to plant roots and affect soil water movement.

4.2 On what landscape position are non-sorted circles present and absent?

Altitude, slope, northness, TWI and TPI are significant predictors for non-sorted circle occurrence in the Abisko region. Below the different hypothesis are discussed regarding the occurrence of non-sorted circles and landscape properties.

Hypothesis 1: "Since temperature decreases with altitude, non-sorted circle occurrence increases with altitude."

Hypothesis 2: "The limited availability of soil moisture and fine materials at high altitude limits non-sorted circle formation."

From the binary logistic regression analysis, non-sorted circle occurrence was found to increase with altitude. Distance to the mean altitude was however a better predictor for non-sorted circle occurrence. Ninety percent of the points with non-sorted circles was found between 555 and 988 m. The tree line, at 550 m a.s.l. (Milbau et al., 2013) and a relation with non-sorted circle occurrence above the the tree line was also shown by (Hjort, 2006). Below the tree line, higher and denser vegetation limits the formation of non-sorted circles, through the insulating effect and stabilization by the roots. As hypothesized, non-sorted circle occurrence was limited at higher altitude. A lower Topographic Wetness Index was found at higher altitude. But there are more possible explanations than only the absence of finer materials and soil moisture. An explanation for the lack of circles at higher altitudes can be found in the presence of higher slopes at higher altitude. Also a lack of vegetation and a prolonged period of snow cover can explain non-sorted circle absence at high altitudes.

Hypothesis 3: "Non-sorted circles are found in areas with a low slope, because at steeper slope angles, solifluction will lead to the formation of stripes."

Both the results of the field work and the DEM analysis support this hypothesis. In the field, non-sorted stripes were found at on average higher slopes than non-sorted circles and also the geomorphic map shows stripes on higher slopes.
Hypothesis 4: "More non-sorted circles are found in depressions, because these are the locations where fine materials and soil moisture collect."

According to the DEM analysis, non-sorted circles were found to have a higher Topographic Wetness Index (TWI) than locations without non-sorted circles. This was expected because ice lens formation requires a high water availability. The Topographic Position Index (TPI) indicated that flat and slightly concave or convex areas are most favourable for non-sorted circle formation, which can be explained by the corresponding low slopes. The higher occurrence of non-sorted circles at areas with a negative TPI at 400 m means that areas below the surroundings (associated with concave areas) are more favourable for non-sorted circle formation. This result was also found by Hjort (2006) who studied non-sorted circle occurrence in Finnish Lapland, 300 km northeast of Abisko. In my study, for a 60 m scale factor, the mean TPI for non-sorted circle presence was positive. This is in agreement with the field observations that, on a local scale non-sorted circles were found on low convex ridges in the landscape, instead of in valleys. The concave positions are the areas where fine material and soil moisture accumulates, which favours ice lens growth. The concave areas are however also the areas where wind driven snow accumulates which limits ice lens formation. Within larger concave valleys, my results suggest that the formation of non-sorted circles in the small scale concave areas is limited by snow, while availability of fine materials and moisture is not limited on the small scale convex locations. Summarizing, on a 400 m scale, hypothesis 4 can be confirmed, but on a 60 m scale, non-sorted circles are found on convex positions.

Hypothesis 5: "More non-sorted circles are found at the north facing slope. At south facing slopes, solar radiation is higher which raises the air and soil temperature and thereby limits non-sorted circle formation."

Non-sorted circles are found to be more abundant at the south facing side than on the north facing side of the mountains. In the study area precipitation and solar radiation are higher at the south facing side than at the north facing side. Higher precipitation and consequent soil moisture content favours ice lens growth. At first sight, a higher solar radiation and snowfall seem to inhibit non-sorted circle formation. But on the other hand, snow cover will thaw more at the south facing side or will melt completely away in the beginning of winter and at the end of spring which increases the number of freeze-thaw cycles. Furthermore, a higher daily temperature differences on south facing slopes can also increase freeze-thaw cycles (DeGraff, 1976).

In this study in south facing areas, non-sorted circles were found at higher altitudes than on north facing areas. A similar relation was found by DeGraff (1976) for relict patterned ground. In this study, no explanation for this can be found in a comparison between the other studied landscape properties and aspect and altitude. The found relationship can be an artefact of the study area, because > 60% of the 5000 points lie on north facing slopes and the average altitude of north facing slopes (741 m) is lower than the average altitude of south facing slopes (873 m) \((p < 0.05)\). It is also possible that other factors than studied here which are influenced by altitude and aspect affect occurrence of patterned ground. For example the higher solar radiation, more freeze-thaw cycles and a higher soil moisture content may make soils up to a higher altitude suitable for non-sorted circle formation on the south facing side.

Predicting non-sorted circle occurrence

Of the studied parameters; altitude and slope are the most important predictors for non-sorted circle occurrence. The binary logistic regression model including altitude and slope predicted 78.6% of the 5000 random chosen points correctly. A part of the variation is not explained by this regression model. Variables that were not included in this model, but that might improve the prediction of non-sorted circle occurrence are the canopy cover, presence of fine materials/bedrock and relative radiation. Also Hjort (2006) found that slope and altitude are important predictors for non-sorted circle occurrence. Hjort also successfully included canopy cover and relative radiation as explanatory variables. On a larger scale, precipitation is important to include in a model, since yearly precipitation varies strong in the Abisko area and soil moisture is found to be important. Variance in soil temperature is partly explained by differences in aspect and altitude, but small-scale variation as a result of cold-air drainage, snow
depth and vegetation are not captured by these parameters. Also vegetation coverage is expected to improve the model, since below the tree line, non-sorted circles were found on non-forested sites.

In this study, it was not tested if the regression model can be extrapolated to other areas. Both this study and the study of Hjort (2006) indicated that altitude and slope are the most important predictors for non-sorted circle occurrence; also both studies showed that non-sorted circles are most abundant above the tree line and that their number decreases at higher altitudes. This makes it likely that a similar relation exists for other subarctic areas.

4.3 How does the activity of non-sorted circles change with landscape properties?

Comparing the active circles with the 78 inactive landforms, they differ in altitude, slope and TPI. Air temperature is expected to be lower at higher altitude and low temperatures favour ice lens formation and thereby activity of circles. Low in the valley, close to the lake temperatures in winter can however be lower because of cold air drainage (Geiger et al., 2003).

In the same location as the active circles, also inactive circles were found. The active and inactive circles were found close together. When comparing these active and inactive circles at the shore of lake Torneträsk it was found or can be expected that air temperature, aspect, soil texture, slope and vegetation do not explain the difference in activity. However, two other differences might explain the difference in activity. First, the seven active circles were found six meters lower in the landscape and second, the active circles were found 45 m closer to the lake compared to the eight inactive circles. Probably, the active circles are in contact with the groundwater which makes that ice lens formation is not limited to the little precipitation in the area. This possibility is supported by the presence of little pools bordering the north or east of the active circles (fig. 4.1). If these active circles are indeed groundwater fed instead of rainwater fed, this explains why they are not correctly predicted by the regression model. Unlike the regression model suggests, the active circles are found below the tree line. And the TWI, which is a measure for surface water rather than groundwater accumulation might also not be applicable to model groundwater fed non-sorted circles.

Together with the at a large scale observed differences in TPI and slope between active and inactive circles, it is likely that in this area soil moisture content is the most important parameter to determining activity under current climate. This result is in line with the conclusions of several other studies Becher et al. (2013); Klaus (2012); Daanen et al. (2008), who found higher activity in areas with more precipitation or a higher activity during periods of permafrost melting. This does however not directly explain why the majority of circles became less active in the area during the last decades, because precipitation did not decrease since 1980. Long-term soil moisture measurements for the active and inactive circles at the lake shore would be interesting to test the soil moisture-activity hypothesis, but soil moisture measurements are unfortunately not possible in this position, because disturbing the protected area is not allowed.

4.4 What are the effects of a changing climate?

During the last fifty years, a net overgrowth of non-sorted circles by vegetation was found in the Abisko (Becher et al., 2013). Also the circles that were classified as inactive during this study were active in the past. Activity is dependent on climate (Hopkins and Sigafous, 1950) and therefore the for the 21st century predicted changes in the climate are expected to influence activity of non-sorted circles. Since 1980, average temperature increased and snow depth decreased in the Abisko region (p < 0.05) (fig. 4.2). An increase in air temperature leads to warmer soil temperatures (Helama et al., 2011) and this may have reduced ice lens growth during the last decades. Soil temperature however also depends on snow depth (e.g. Helama et al., 2011; Zhang, 2005) and the observed decrease in snow depth could have decreased soil temperature during winter (Overduin and Kane, 2006; Roennefarth, 2015) and thereby increased freeze-thaw cycles and needle ice growth (Smith, 1987). Overduin and Kane (2006) researched differential frost heave in Alaska and did not found a different differential frost heave for years with a thin and thick snow pack and suggested that soil moisture content is more important. This is in line with the results of this study.

Sælthun and Barkved (2003) studied different climate models and concluded that in the Abisko region, air temperatures will rise (highest increase in winter) and precipitation will increase (highest increase in winter and autumn). How will these changes influence non-sorted circles?

As described above, a direct influence of warmer air temperatures is a higher soil temperature. Furthermore warmer air temperatures are also related to shallower snow depth (Helama et al., 2011). Over a longer period, warming will reduce the extent of permafrost occurrence (Åkerman and Johansson, 2008) and deepen the active layers which will lead to deeper drainage and consequent lower soil moisture content (Leffer et al., 2016). Rising temperatures are expected to increase the quan-
4.4. What are the effects of a changing climate?

The above described effects of changes in temperature and precipitation and their combined effect on patterned ground occurrence are uncertain. Other uncertainties lie in the effect of a changing temperature on the decomposition of organic matter and the positive feedback between organic matter content and vegetation growth. Also the effect of an earlier snow melt on ice lens formation is unknown. Overall, the effects of a warmer climate and higher precipitation are expected to differ throughout the area. Directly above the current tree line, non-sorted circles are expected to get overgrown with vegetation, although reindeer grazing will slow down the overgrowth. If temperatures stay sufficiently low to allow for freezing, activity might increase at higher altitudes as a consequence of more vegetation growth and higher soil water availability. More insights in the magnitude of the different effects is important if we want to study future arctic ecosystem functioning in terms of water and nutrient fluxes, vegetation pattern and carbon storage. Interesting questions to gain more insight in the drivers of activity are:

• What requirements for non-sorted circle formation are not met at altitudes above 1000 m?
• Why did the majority of the non-sorted circles become inactive during the past decades?
Figure 4.2: The average yearly temperature, precipitation and snow depth measured at the Abisko Research Station (Abisko Scientific Research Station, unpublished data)
When studying the effects of climate change on subarctic ecosystems, it is important to study the responses of non-sorted circles and other forms of patterned ground. For non-sorted circle forming processes, a cold temperature, high soil moisture content and the presence of fine materials are the main prerequisites and therefore it was hypothesized that non-sorted circles would occur at higher altitudes, concave positions and positions with a high Topographic Wetness Index.

In total 72 non-sorted circles and 13 non-sorted stripes were measured in the field. Of the circles, seven were classified as active, while no active stripes were found. The active circles were found at the shore of Lake Törnetrask. From the DEM it was concluded that non-sorted circle occurrence is highest at median altitudes: above the tree line, but not above 1000 m a.s.l. At higher altitudes, the slopes were steeper and non-sorted circle formation may be limited by a low soil moisture content and limited presence of fine materials and vegetation. Both the results of the field and the DEM analysis suggest that circles are found at lower slopes because at steeper slopes, solifluction leads to the formation of stripes. Non-sorted circles were found at concave positions at larger scale where fine materials and soil moisture are present. On smaller scale however, non-sorted circle fields were found at small ridges in the landscape. Suggested is that a higher snow depth and longer period of snow cover in the lowest positions limits differential frost heave. As hypothesized positions with non-sorted circles have a higher Topographic Wetness Index than positions without non-sorted circles. Altitude was the most important predictors for non-sorted circle occurrence, followed by slope. Differences in predicted and observed occurrence were found mainly below the tree line. Including vegetation cover is expected to improve the model.

Active circles were found at the shore of the lake. A comparison with the inactive circles in the close surroundings indicated that, under current climate, water availability is most important driver for activity.

Considering the main prerequisites for non-sorted circle formation: cold temperatures, high soil moisture content and fine materials, what will be the influence of a warmer and wetter climate? Presence of fine materials will not change on a short time scale. An increase in temperature will increase vegetation and decrease freeze-thaw cycles. Both will decrease non-sorted circle activity and occurrence. Soil moisture content will increase with increasing precipitation and favour non-sorted circle occurrence and activity. Deeper active layers will however decrease soil moisture content. The magnitude of the different processes should be studied to gain a better insight in future non-sorted circle occurrence and the effect on vegetation, soil moisture, nutrient and carbon storage dynamics of subarctic ecosystems.


Melander, O., 1977. Geomorfoligiska kartbladet. 30 h riksgrensen(öst), 30 i abisko, 31 h reurivare och 31 i vadvetjåkka. Statens Naturvårdsverk.


Appendix A

Figure 5.1: The locations used in the logistic regression. In total 2500 points with and 2500 points without non-sorted circles were selected randomly.

Figure 5.1: The locations used in the logistic regression. In total 2500 points with and 2500 points without non-sorted circles were selected randomly.