Delineating bedrock outcrops and shallow superficial deposits in Southern Finland with LiDAR DEMs

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Abstract

This study utilizes visual identification of topographical textures of bedrock outcrops and shallow superficial deposit areas (BOSS) that can be interpreted from remotely sensed Light Detection and Ranging (LiDAR) based Digital Elevation Models (DEM) from four different study areas in S Finland. Accuracy of new delineations for BOSS areas were tested on the field and with elevation profiles in ArcGIS Pro. These four study sites represent different Quaternary deposits and varying amounts of BOSS areas. Main research goals for this thesis were the measurement of accuracy and the amount of new BOSS areas digitized in 1: 4000, describe the textural characteristics associated with shallow superficial deposits and bedrock outcrops visible on DEM, determine the geological processes affected to the distribution and origin of shallow superficial deposits in recently glaciated landscapes. Results suggest that there is great potential for the refinement and update of BOSS areas via LiDAR DEM usage and applications. Bedrock outcrop areas were increased by 30% while shallow superficial deposit areas decreased by 1.3% from the original BOSS data produced by MML&GTK in a scale of 1: 10 000. New delineations were on average 3.5 m more accurate than the existing ones, interpreted from 2 terrain profiles from Muurla. Overall ruggedness of BOSS textures is apparent on DEM maps, and Terrain Ruggedness Index (TRI) supports this. Outcrops were visually easier to delineate on shaded relief maps compared to shallow superficial deposits. This is because of the protrusions, slopes, edges and fracture surfaces they exhibit. In Southern Finland glacial and glaciofluvial processes have impacted greatly on the origin and distribution of BOSS areas. Bedrock structures, rock type and bedding plane orientations also play important role. This study emphasises also the importance of field work and field inspections during a re-survey of BOSS areas.

Key words: LiDAR, DEM, bedrock outcrops, shallow superficial deposits, Survey, Quaternary deposits

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1. Introduction

Remotely sensed Light Detection and Ranging (LiDAR) derived Digital Elevation Models (DEM) provide important insight into recognition and classification of various geological formations, processes, and deposits. These include for example remote identification and mapping of bedrock structure (e.g. Pavlis & Bruhn 2011, Scheiber et al. 2015, Ovaskainen et al. 2023), distribution and characteristics of glacial and glaciofluvial landforms and deposits (Bouvier et al. 2015, Ojala 2016, Putkinen et al. 2017) and superficial deposit thickness models (Patton et al. 2018). Information about the boundaries and distribution of shallow superficial deposits serves the land use sector and many more. This study focuses on the identification, distribution, delineation, and evolution of bedrock outcrops and shallow superficial deposits (BOSS) in four 25 km^2 study areas located at the municipalities of Muurla, Suomusjärvi, Veikkola and Tammela in Southern Finland. Fraser et al. 2020 defined BOSS as bedrock outcrops and shallow soils that consist of <50 cm soil cover. However, in this study BOSS is referred to as bedrock outcrops and shallow superficial deposits consisting of <1 m overburden according to GTK Quaternary map guidelines, where topsoil (shallow superficial deposits) is determined as <1 m and subsoil (moraine, sand etc.) >1 m thick. The data collected from mapping areas and geological deposits with LiDAR can be utilized in three-dimensional modelling for variety of geological and technical purposes from point data to 3D planes (Hodgetts 2009, Anders et al. 2016). Groundwater deposits and their flow regimes are influenced by topographical and structural variations of the bedrock, which can be interpreted from DEMs (Shrestha et al. 2021, Knott et al. 2019). Modelling groundwater aquifers and their flow using LiDAR derived data is crucial aspect of understanding how to best exploit and protect these valuable resources. The forest sector benefits from new information about soil thickness/sediment cover and areas that are prone to erosion can be identified. For example, the Norway spruce *(Picea abies)*, which is commonly grown in Finnish economic forests is quite sensitive to drought (Konôpka & Lukac 2013, Tresch et al. 2023). Shallow soil/superficial deposits and rocky areas are especially susceptible to drought simply because there is not enough soil matter to hold moisture for long drought periods.

The evolution of LiDAR technology began in 1960 when Theodore Maiman invented the ruby laser in the United States. LiDAR was first used in the mapping of atmospheric particles but soon after that, the new laser technology caught the eye of the military and passed their tests in 1961. The development was ongoing and in 1971 US military launched the world's first ruby laser ranging system. This first-generation laser ranging system had some disadvantages like high energy consumption, heavy weight, and large volume. It was soon replaced by the second-generation laser ranging system that consumed less power, was lighter and used near infrared neodymium laser. In 1977 US developed the first handheld laser rangefinder being the size of binoculars and weighing only couple of kilograms. Laser rangefinder technology was mainly used by the military and scientists in the first decades of its development. This was due to high prices of sensors. The prices of LiDAR technology devices have come down and thus industrial sectors etc. are applying them worldwide. Accuracy of the laser rangefinder systems have increased little by little since its invention and nowadays they can achieve even millimetre level in some cases (NOAA 2012, Wang et al. 2020).

LiDAR is a remote sensing tool that incorporates laser to measure distances and is closely linked to Global Navigation Satellite System (GNSS) and Inertia Navigation System (INS). Combined with these other systems LiDAR generates high definition, three-dimensional geospatial data about surfaces and objects that are being investigated. This data can be in the form of point cloud, DEM, and as digital surface models. Compared to radars that use radio wavelengths and aerial photography, airborne LiDAR is superior in many ways at high precision geological mapping: it has obviously high precision and resolution, and it can reveal geomorphological features under foliage (NOAA 2012, Wang et al. 2020).

The aims of the present study are to: i) Compare areal differences between re-surveyed and existing BOSS, ii) Measure the accuracy of re-surveyed BOSS delineations, iii) Determine geological processes that affect to the distribution and origin of BOSS areas in recently glaciated landscapes and iv) Describe the textural characteristics associated with shallow superficial deposits and bedrock outcrops visible on DEM. The accuracy of existing Quaternary maps and BOSS maps are basically very good in the scale they were designed to be used (1: 8000 – 1: 10 000). In this thesis the mapping/re-surveying scale was set to 1:4000.

2. Geological mapping

2.1 LiDAR in mapping of Quaternary deposits and landforms

Airborne LiDAR imaging has proven to be valuable tool in geological mapping and data collection: they provide high resolution data that compliments necessary field work. Field work can be time consuming and costly, but with the utilization of DEMs this process can be made more efficient and target the potential sites more precisely (Kielosto et al. 2012). It is well known that high resolution DEMs have vast utilization opportunities: identification from small scale features to large deposits and formations. The study areas selected for this thesis represent different glaciated geological environments in Southern Finland: some have more bedrock exposure than others and some exhibit more glacial landforms for example drumlins, De Geer moraines and other end moraines. Although there is wide agreement that visual identification of BOSS from LiDAR DEMs is accurate and credible, identification of local geological and morphological features of different environments might take some practice.

Since the widespread use of DEMs in Quaternary mapping, the resolution and accuracy of these maps have significantly improved. In addition to this, the overall time used for mapping has decreased and it has become cheaper. For example, The Geological Survey of Norway have estimated that basic Quaternary maps produced from ~ 700 km^2 area in the scale of 1: 50 000 correspond to 1: 35 000 resolutions after implementation of LiDAR DEMs. Mapping was also done 20–40% faster than before (Johnson et al. 2015).

LiDAR can be also utilized in updating existing Quaternary maps, enhancing their delineation. This is done especially around populated areas and is a valuable tool when targeted areas are covered by forest. Old maps before the use of LiDAR are often made with the combination of field observations and aerial photos. In heavily forested areas the boundaries between different soil/overburden types (incl. BOSS) were at the time rougher estimates and some landforms were not clearly visible in the field or in aerial photographs. Regardless of the advantages of LiDAR, field observations and aerial photographs are still important in Quaternary mapping, and they should not be neglected completely (Kielosto et al. 2012, Johnson et al. 2015).

Mapping of Quaternary deposits via LiDAR DEMs is usually conducted in a GIS environment, for example ArcGIS Pro (e.g., Kielosto et al. 2012, Ojala et al. 2013, Johnson et al. 2015, Ojala et al. 2015). In GIS software the DEM is easily modified and adjusted to serve the research purpose at hand. Most typically a hillshade is made from the DEM (e.g., Kielosto et al. 2012, Bouvier et al. 2015) so that the topographical features and relief of the landform or deposit is observable. For example, Ojala et al. 2015 applied DEM hillshades in GIS to interpret the length, width, height, orientation and interdistances of De Geer moraines in southern and western Finland, giving implications to glacial dynamics. Hillshaded DEMs were also used in the process of developing an ancient shoreline geodatabase in Finland (Ojala et al. 2013). Other applications include: i) mapping of ribbed/hummocky moraine and streamlined terrain by glacier movements (Möller & Dowling 2015, Greenwood et al. 2015), ii) mapping potential landslide areas and palaeolandslides (Tryggvason et al. 2015, Sutinen et al. 2014), iii) mapping of postglacial faults and associated Pulju moraines (Sutinen et al. 2014), iv) mapping of glaciofluvial alluvial fans (Regmi et al. 2014, Cavalli & Marchi 2008) and v) mapping of eskers and other geomorphological features to interpret glacial dynamics (Sarala et al. 2015).

2.2 Shallow superficial deposits and bedrock exposures

Such as in the case of mapping Quaternary deposits, applying high precision LiDAR DEMs in the manual mapping of BOSS in glaciated and forested terrains has also proven to be efficient and accurate tool (Kielosto et al. 2012, Fraser et al. 2020). Bedrock outcrops appear in areas where weathering processes have greater potential to directly alter the exposed bedrock rather than the overlying regolith (Humphreys & Wilkinson 2007). Spatial distribution of these areas in recently glaciated landscapes is most likely controlled by glacial and post-glacial erosion and deposition as well as weathering (Fraser et al. 2020). Sarala et al. 2015 concluded that in their study area in northern Finland, the bedrock outcrops occurred in highland areas and the structures of the bedrock were identified from airborne LiDAR data. Mainly schistosity and jointing in quartzite was observed from LiDAR. Rock types in these higher hill areas were mainly metasedimentary such as quartzite and mica schists (Sarala et al. 2015). Lithologies of local and regional bedrock exposures can vary considerably, but they usually consist of rather hard crystalline minerals that have endured weathering and erosion in recently glaciated environments. Other factors besides (post)glacial erosion and deposition that affect the nature and occurrence of bedrock outcrops in Finland may include post glacial rebound and isostacy of crust. Ovaskainen et al. 2023 analyzed and modelled structural bedrock fractures and lineaments in Åland, Finland from LiDAR DEMs. These outcrops consisted of wiborgite, rapakivi granite. Identification of underlying lithology based on LiDAR DEMs has been studied and the results are promising, though more research is needed on different locations and geological material. Camara et al. 2016 applied analysis of drainage networks from LiDAR DTMs to the identification of bedrock lithology. Their study sites were in Spain and most of the interpreted lithologies from terrain models consisted of metamorphic and igneous rocks.

Depending on the mapping or data collection project at hand, a sufficient scale is chosen. For example, in urban construction and land development, scale of mapping is picked in a way that every phase of land use planning can benefit from it the best. If the scale is large and the minimum polygon size for BOSS is set rather small and if the study area is large, this means a considerable amount of time consumed digitizing and making field observations. A compromise is made between the scale of mapping accuracy and time which is usually dependent on the size of a study area and occurrence of studied features (Kielosto et al. 2012). The objective of the mapping project or study is of course a very important factor when picking the right scale. Scheiber et al. 2015 demonstrated that when manually interpreting lineament features on bedrock outcrops from hillshaded map, there are three main variables which greatly affect the results. These are i) influence of illumination azimuth, ii) influence of scale and iii) influence of operator. Although these notions were made regarding lineament features, same principles can be applied to manual delineation of bedrock outcrops in general. It is revised to use at least two different illumination azimuths when delineating bedrock outcrops, so that the structural and geomorphological features are best represented. Bedrock surfaces exhibit lineaments and fractures that are oriented in different directions, hence it is favorable to illuminate these structures from more than one direction to achieve best shaded relief.

Manual delineation of geological features has always some human perception biases and this should be noted in every mapping project and study (Scheiber et al. 2015). Simply put, manual delineation is best for qualitative interpretation whereas predictive trained models work better at quantitative interpretation when study areas are large, and use of time is expensive (Scheiber et al. 2015, Fraser et al. 2020). Kielosto et al. 2012 pointed out that mapping the exact boundaries of bedrock outcrops only by field observations is extremely time consuming and practically impossible. They recommend that in Finland the boundaries should rather be interpreted by applying data from i) the National Land Survey delineations, ii) DEM derived delineations and iii) mapping observations. These guidelines have been implemented in this thesis.

In Finland and mainly near urban areas, the extent and distribution of shallow superficial deposits is important knowledge when assessing the thickness of overburden that is excavated from a given area. The exact locations of the boundaries of rock outcrops also serve drilling programs that are carried out for the needs of community construction (Kielosto et al. 2012). Areas that have < 1 m overburden often exhibit different texture, slope aspects and inclinations from surrounding terrain. This can be identified from high precision airborne LiDAR maps (Sarala et al. 2015, Fraser et al. 2020). Differences in texture, slope inclinations and visibility are contributed to bedrock structure and morphology beneath the thin overburden. Sometimes the morphological features of the underlying bedrock can be observed from LiDAR maps even if there is 2-3 m of overburden on top of it. When mapping shallow superficial deposits, this can give false interpretations, especially if additional field work is not conducted. According to Sarala et al. 2015, it is also possible to mistakenly interpret large boulders and antihills as bedrock derived morphology on dems. Delineating the extent of BOSS areas serves forest planning and gives implications about the spatial patterns of vegetation productivity and composition. Mapping of BOSS areas also helps to understand local hydrology, soil development and ecology (Fraser et al. 2020).

3. Study areas

Four 25 km^2 study areas were chosen in southern and SW Finland located at municipalities of i) Muurla, ii) Suomusjärvi, iii) Veikkola and iv) Tammela (Fig.1). Locations for all study areas exhibit varying amounts of BOSS. Also, all these areas represent recently glaciated (Weichselian and older glaciations) landscapes and contain distinct Quaternary deposits. Because all study areas are in southern Finland, they have been submerged after the Weichselian glaciation as part of the Littorina sea or older aquatic environment. Many rock types occur between sites but most abundant are plutonic and metamorphic rocks such as granites and paragneisses (GTK, maankamara).

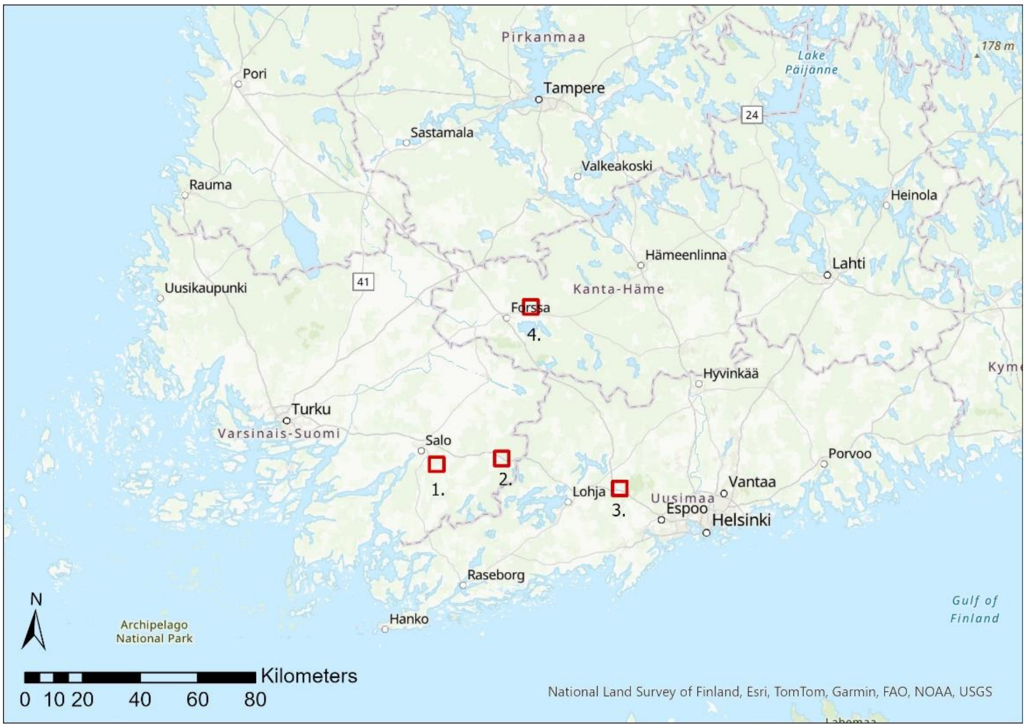

Figure 1. Map of the Finnish coast and study areas with their areal extent represented as rectangles in S and SW Finland. **1.** Muurla, **2.** Suomusjärvi, **3.** Veikkola and **4.** Tammela.

Located approximately 5 km South-East from the municipality center of Salo, study site of Muurla (291 923,13E 6 695 898,94N EUREF FIN TM35FIN) 25 km^2 has plenty of bedrock exposures. The general landscape of the area is characterized by large areas of continuous rocky hills separated by sand and moraine. At the southern and SE part of the area opens more uniform smooth land visible from hillshades, while rocky hills are concentrated in the northern parts. Bedrock of the area is predominantly composed of microcline- and porphyritic microcline granites (GTK, Salo bedrock map 1955, MML). There are also garnet bearing microcline granites and minor granodiorites, but metamorphic rocks are mainly absent. In the NW parts of the site, the general trend of bedrock structures is characterized by 30 degrees dipping foliation that has dip direction towards SE. In south, bedrock foliation is dipping 70 degrees and has general dip direction towards SW. Different overburden types occur throughout the area, but the landscape is dominated by shallow superficial deposits around outcrops, divided by clays as well as sandy moraine. There is a rather large sandur delta formation in the southern part of the site, which is composed of sand. Sandurs are ice marginal glaciofluvial deposits, formed at the margin of retreating terrestrial ice sheet. In addition, there are few smaller ice marginal glaciofluvial deposits which all align with each other. Other glacial and glaciofluvial deposits include a few small De Geer moraine ridges, small eskers, and drumlins. De Geer moraines mainly consist of sandy moraine; eskers are composed of sand and drumlins of sandy moraine with minor BOSS. Littoral deposits located south in Muurla study area are composed of sand and fine sand (GTK Quaternary maps).

Like Muurla, the study area of Suomusjärvi (314 503,18E 6 697 916,61N) has vast BOSS areas. It is located approximately 18 km west from Muurla study site. BOSS areas are separated by clays, sandy moraine, and water bodies. Rocky hills are relatively evenly distributed across the study area, but clay is the most plentiful in the western parts. Rock types are dominated by metamorphic rocks such as acid gneisses and mica gneisses as well as some igneous rocks like quartz- and granodiorites (GTK, Suomusjärvi bedrock map 1955, MML). Major bedrock lineaments (1: 500 000) are oriented NE/SW in the area (GTK, maankamara). Some structural characteristics of bedrock include vertical foliation at NE part appearing in gneiss with strike to NE and in SW parts in gneiss having approximately same dip direction, lineation around the center of study area dipping 10 degrees to NE observed in granodiorites and folding axis at SW part in gneiss having 80-degree dip towards NE. There is also foliation in acid gneiss dipping towards SE and NW in the contact with granodiorite. Some structural characteristics can be observed from LiDAR dem for example lineaments representing vertical or other jointing and or brittle structures. Compared to Muurla study area, Suomusjärvi has less clay deposits and a bit more moraine. Only one small ice marginal glaciofluvial deposit occurs in the study area located at SW but De Geer moraines are plentiful at SW and west of Suomusjärvi site. Drumlins and drumlinoids are spread widely in the research area. Some sandy littoral deposits and glaciofluvial river deposits are also present.

The study area of Veikkola (355 497,81E 6 687 502,59N) is located approximately 11 km south of the municipality of Vihti. being the southernmost study area. It is clay dominant with quite evenly scattered hills of BOSS all around. BOSS areas are not as uniform and continuous as in Muurla or Suomusjärvi but they appear numerous. Major bedrock lineaments mapped in the scale of 1: 500 000 (GTK, maankamara) are oriented NE/SW but there are also lineaments that are oriented NW/SE. The prevalent rock types of the area include granites which are partly pegmatitic. Also, mica gneiss and mica gneiss inclusions are present. Other minor rock types and noteworthy minerals include diabase dikes and garnets. Most of the measured foliations from Veikkola study site have dip direction towards SE or east (GTK, bedrock map 1994). Lakes of the area are predominantly oriented towards NE/SW. Besides vast clay and BOSS areas, there are numerous fine sand deposits in the site. Moraine is located around BOSS areas and not as plentiful as in Suomusjärvi and Muurla. Some peat and sand deposits are also located at Veikkola. Glaciofluvial deposits include ice marginal deposits, numerous littoral deposits and other indeterminate glaciofluvial deposits. De Geer moraines are absent at Veikkola study site, but some drumlins occur. Largest of the ice marginal glaciofluvial deposit, consisting of sand, is also determined as covering littoral deposit.

Tammela is the northernmost study site (324 599,24E 6 750 535,50N), located approximately 7 km NE from the municipality of Forssa. It has the least bedrock exposures and shallow superficial deposits while the general impression of the landscape is smoother. BOSS areas are focused to the north, NE as well as SW. BOSS areas are mostly surrounded by sandy moraine while smooth clay fields are most abundant in south and SE. Sandy moraine is the prevalent soil/overburden type but there are in addition vast clay and peat deposits. The study site of Tammela has basically only BOSS, sandy moraine, peat, and clay deposits, others are absent or haven't been mapped. Bedrock of the site consists of gabbro and diorite, basic and intermediate tuffite and amphibolite, phyllite and mica schist. Mica schist occurs also as garnet bearing and cordierite bearing varieties. The predominant dip direction of bedrock foliation is towards north and NE. A folding axis is in the south, in mica schist. One lineament line feature (1: 500 000) is observed having orientation towards SE/NW and located SW in the Tammela study area. Multiple glacial lineations e.g. drumlins and drumlinoids occur, concentrating in the NE section of the area where BOSS and sandy moraine are prevalent. Other glacial and glaciofluvial deposits haven't been mapped in the site, except for one very small littoral deposit in the SW edge of the study area. However, there are numerous small moraine ridges visible on LiDAR DEM that could be defined as glaciofluvial deposits. These are focused on the center of Tammela study site and include De Geer moraines and possibly small eskers and hummocky moraine.

4. Materials and methods

4.1 Materials

Geological maps for the study areas were provided by the Geological Survey of Finland via the Hakku downloadable map service. Another source for geological maps was the Maankamara online map service by GTK, which contains wide variety and amount of geological online maps for numerous purposes. Format of the downloaded maps from Hakku service were shape file polygons, dot data, line features or raster files, presented as feature layers on ArcGIS Pro. GIS products that were downloaded from Hakku include: i) a Quaternary map of study areas in scale of 1: 20 000 in which different topsoils are separated including shallow superficial deposits. Bedrock outcrops are not separated in this dataset from shallow superficial deposits, ii) glaciogenic formations, lineations, covering deposits as polygon shapefiles and line features, iii) Bedrock maps of the study areas as raster files in scale of 1: 100 000, iv) Aero electromagnetic anomaly raster data of Finland, v) Major lineaments interpreted from LiDAR, electromagnetic and magnetic data sources, mapped in scale of 1: 500 000 and represented as line features and vi) Point data that includes mapped bedrock outcrops, striations, observational data with drilling points and bedrock surface level.

In addition, downloadable open-source GIS material was acquired from the National Land Survey of Finland (MML). These include bedrock outcrops as point data and outcrops as vector data gathered from the terrain database of the National Land Survey of Finland and mapped in a scale of 1: 10 000. The MML outcrop maps are based on aerial photographs, laser scanning data, and information from other data producers such as municipalities and field observations. According to the National Land Survey, rock outcrop areas need a minimum of 1000 m^2 (0.1 ha) areal surface to be mapped in a scale of 1: 10 000 as vector polygons. The National Land Surveys isolated, and small outcrops are represented as point data, and they meet the required minimum 5 m in diameter. Figures 2 and 3 illustrate examples of outcrop and Quaternary landform vectors, plotted on a hillshade relief map. A LiDAR derived digital elevation 2m resolution raster data from each study site was acquired from the GTK. Karttaselain application for iOS was used to save point data coordinates from the field. Karttaselain contains for example hill shaded relief maps, terrain maps and aerial photo maps. Also, some field photographs were taken from interesting targets that appear also in hill shade maps. Aerial photographs were used in some cases to help determination and occurrence of bedrock outcrops if the forest and brush cover wasn’t too thick.

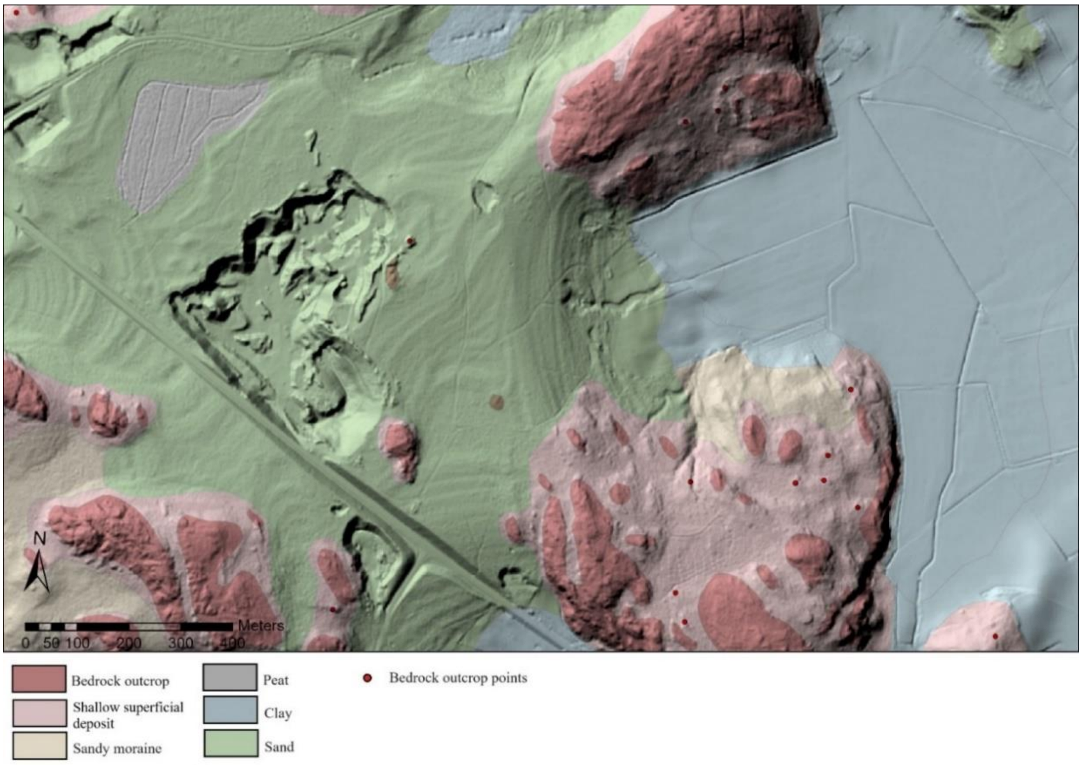

Figure 2. A hillshade Quaternary and bedrock outcrop map from Muurla study area (data from GTK and MML). Topographical textures and protrusions can be identified due to layer transparency. Scale is 1:7 000 and illumination azimuth is set from NW. The landscape of Muurla is plentiful of shallow superficial deposits and in this location, there is a large glaciofluvial ice-marginal deposit, which has some shallow superficial deposit areas within it. Boundaries of BOSS can be inspected and updated with the use of LiDAR DEMs and field work.

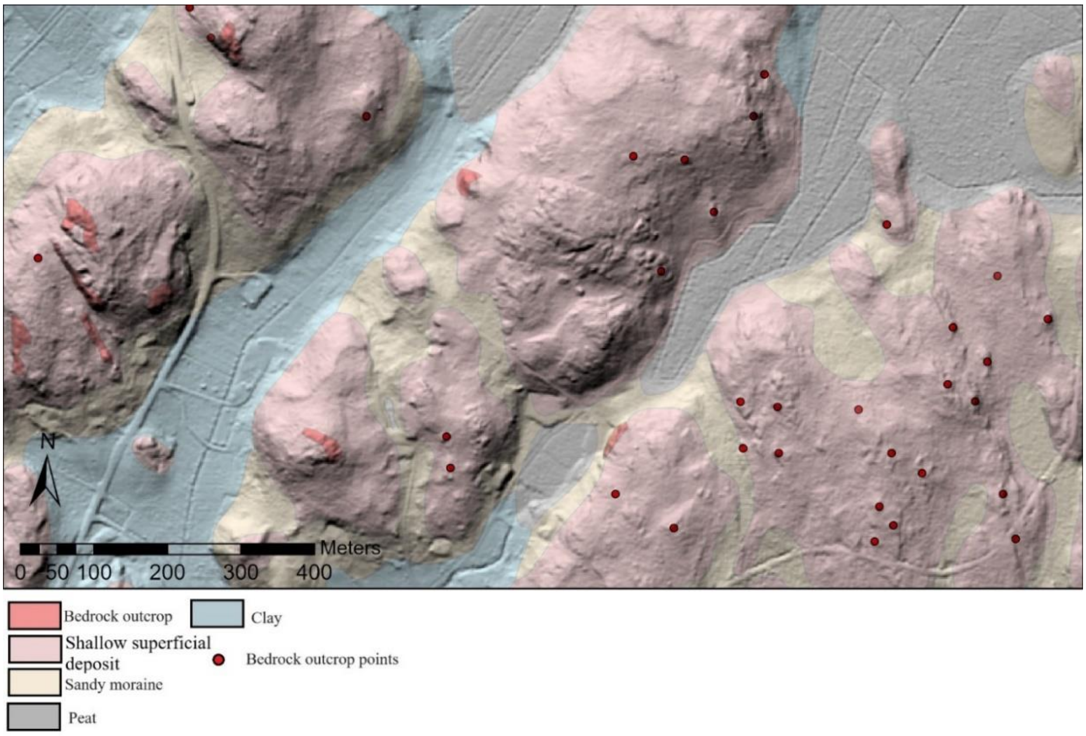

Figure 3. A hillshade Map of Veikkola area in a scale of 1:7 000. Illumination azimuth is set from NW. It can be observed that there is plenty of outcrop points located within shallow

superficial deposit areas and with related hillshade textures. Potential for the delineation and update of outcrop vectors is apparent. Data sources are MML and GTK.

4.2 Methods

The main research method in this study was visual delineation and update of BOSS in ArcGIS Pro applying scale of approximately 1: 4000. Digital elevation models were obtained from the Geological Survey of Finland (GTK) and interpreted with existing point data and geological maps provided by the MML and GTK. Two subgroups were made consisting of i) bedrock outcrops and ii) shallow superficial deposits digitized in polygons. Especially sharp edges, dipping slopes and controlling structures of bedrock surfaces are usually clearly identified from LiDAR maps. Overall roughness in texture of shallow superficial deposits in these maps is also visible but sometimes it can be hard to precisely identify, when the texture is smooth and resembles that of moraine. It is worth noting the interconnection in most cases between bedrock outcrops and surrounding shallow superficial deposits, which in this study mainly composes of sandy moraine. Field observations were made from multiple sites to analyse the accuracy of mapping with elevation models and other data.

Polygon shapefiles were created to correspond to i) bedrock outcrops and ii) shallow superficial deposits from four study areas. They represent collected data about the boundaries of said deposits, digitised on a scale of approximately 1: 4000. DEM derived hillshades were made from each study area and with the existing geological data they were utilized to manually delineate potential BOSS areas. Topographical terrain profiles were produced from chosen locations and field work conducted to assess the accuracy of manually digitized boundaries of bedrock outcrops and shallow superficial deposits. A topographical roughness index was applied for the DEM rasters to analyze textural heterogeneity of adjacent cells and aid in the digitization process. Delineation of the areal boundaries and surface area of interpreted BOSS was predominantly produced as vectors, but some point data of bedrock outcrops was also produced with field checks. It is beyond the scope of this study to record every potential point data from very small bedrock outcrops from study sites, given the amount of time in the field this would require. Rather, in this study, the polygonal areas representing bedrock outcrops are manually delineated to best serve future mapping endeavors in large scale for example 1: 3000 - 1: 5000. In this thesis, minimum areal surface for digitized bedrock outcrop areas was set to approximately 100 m^2 and shallow superficial deposit areas to approximately 600 m^2.

Visual interpretation of new delineations for BOSS areas was conducted mainly by applying Quaternary vector map (1: 20 000) at different transparency percentages on top of hill shaded DEMs. Because Quaternary maps in general have not differentiate outcrops from shallow superficial deposits, bedrock outcrop vector map (1: 10 000) by MML was also utilized as one of the main tools. This gave the opportunity to simultaneously assess the mapped boundary, and the areal terrain topography and texture revealed by hill shades. Field work and observations were carried out to support the digitization and use of spatial data.

Hill shaded DEMs were applied for each study site from at least 2 different illumination azimuths in a way that would best describe the prevailing structures and formations. Hill shade represents the raster data as 3D model in which the suns relative position is taken into consideration. In ArcGIS Pro, hill shades were created using the hill shade spatial analyst tool. Z factor was set as two for enhanced visual effect of elevation and relief, because study areas were not particularly rugged. Elevation values interpreted from the DEMs in study areas range in between sea level and 154 m above sea level, so rather modest elevation. Z factor one was also tried and applied for the study areas that had most outcrops and rocky hills, Muurla and Suomusjärvi. For the best visual representation of the hill shade layer, a layer blend option “multiply” was applied to it. Having all the map materials automatically transparent on top of hill shade makes the digitisation more efficient. The slope raster function was tried during digitisation, but its problem is lack of hill shading. This can lead to misinterpretations in digitization process, when confusing a concave landform and a convex one with each other. For this reason, mainly two directional hill shades were applied in digitization as well as minor multidirectional hill shade. Figures 4 and 5 visualize the differences between two directional hillshade map versus slope map in the digitization process of BOSS.

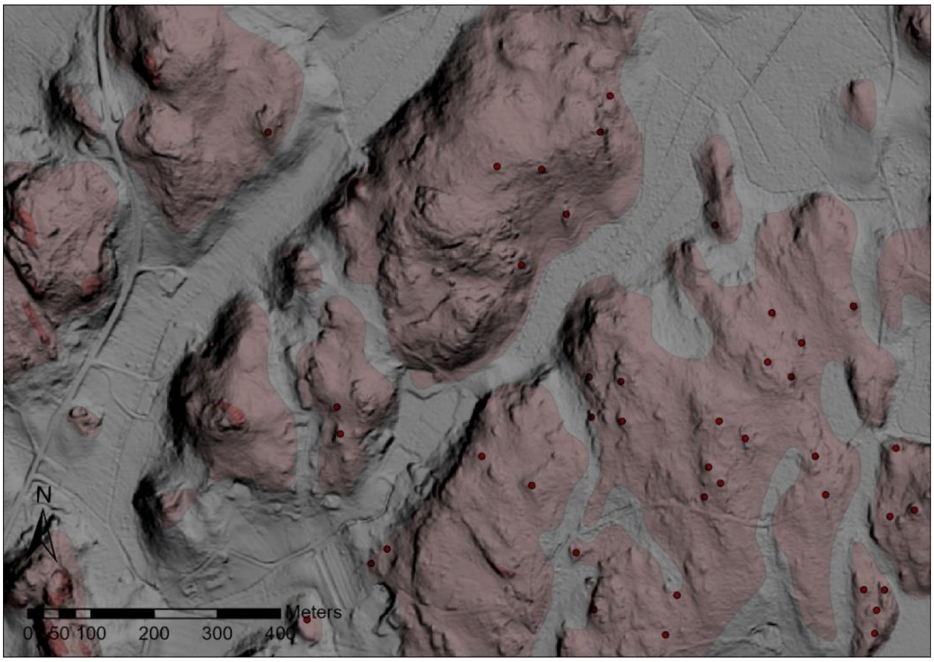

Figure 4. Shallow superficial deposit and bedrock outcrop map (1:7000) represented on top of two directional hillshade DEM. Light red represents shallow superficial deposits and darker red bedrock outcrop areas. Red dots are bedrock outcrop points verified from the field mapping. Textural differences between shallow superficial deposits and bedrock outcrops can be interpreted which aids the digitization process. Map is from Veikkola study site and all vector-, point- and LiDAR data are from MML and GTK.

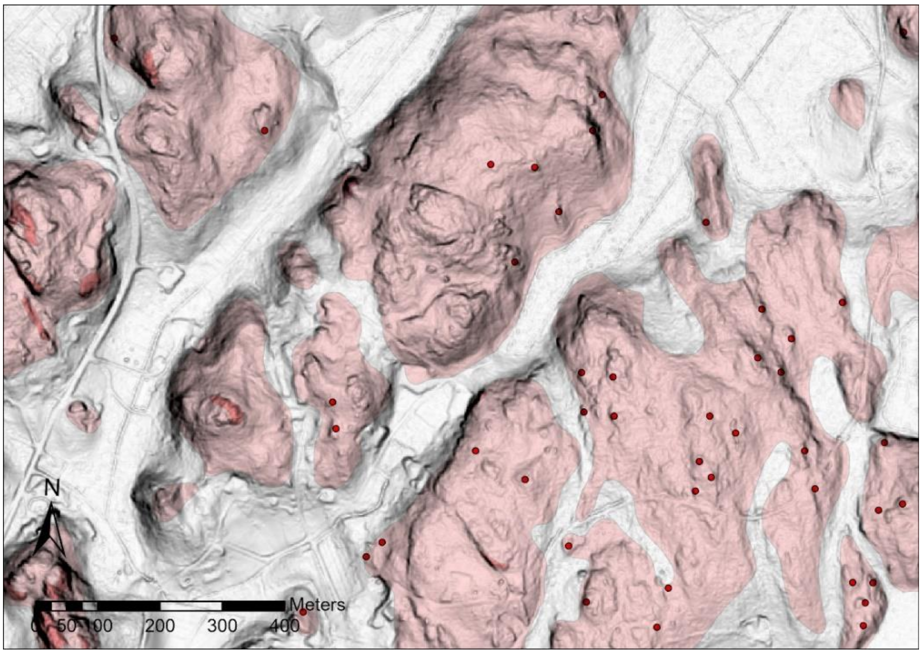

Figure 5. Shallow superficial deposit and bedrock outcrop map (1:7000) represented on top of slope DEM. Slope rasters are a good addition in the digitization process when delineating BOSS, though they should be accompanied with hillshaded DEMs for better topographical and textural interpretation. One and two directional hillshade maps visualize these features often better with little room for misinterpretation regarding the convex or concave nature of geological and morphological formations. Vector-, point- and LiDAR data are provided by MML and GTK.

Direction of illumination plays a crucial role in interpreting shaded relief maps and identifying various landforms. It is common practice to set illumination direction from NW (315°), when using hill shaded maps. For example, in ArcGIS Pro the illumination azimuth is set to 315° as default and altitude for illumination to 45 degrees when applying traditional hill shade. Biland & Çöltekin 2016 proposed that illumination azimuth of NNW (337.5°) should be applied in landform identification when using hill shaded relief maps, instead of the traditional NW azimuth. In their findings they conclude that this light direction yields the highest accuracy and confidence ratings in landform identification compared to other various light directions. In this study, when traditional hill shades were applied, one of the two directions of light was set to NW or NNW for each study area. The second direction of light was set according to structures and formations. Altitude for the light source was set to 45 degrees in all traditional hill shades.

Prevailing bedrock structures were measured from one granite outcrop in Muurla study site, consisting of four joint and fracture surfaces. Point data from field observations was recorded with Karttaselain application and structural measurements were conducted with FieldMove Clino application for iOS. Total of 91 field observation points were obtained in Muurla study site, some with the utilization of soil spike tool measuring 1m in length. These points included preliminary field data prior and during digitization of BOSS areas to aid in the digitization process and data gathered after digitization to determine accuracy of new delineations. Point data consists of i) Bedrock outcrop observations, ii) Shallow superficial deposit observations, iii) Sandy till observations, iv) Contact observations of previous deposits and v) Man made objects that can appear on DEM. Elevation profiles (N= 2) were created for Muurla study site, using the Exploratory 3D Analysis tool in ArcGIS Pro. Same profile lines were then walked in the field with a soil spike to determine boundaries and accuracy of digitization of BOSS areas in ArcGIS Pro. During field observations, photographs and coordinates were taken from objects that appeared in the field and on DEM and could possibly give false identification of outcrop areas. Preliminary field inspections were targeted to areas in Muurla study site which showed signs of potential unmapped bedrock outcrops: rugged textural patterns and sharp edges that could be interpreted as BOSS areas. These features were visible on DEM and needed to be inspected in the field to exclude them from being digitized as BOSS areas or confirmed as such. The field observations collected from Muurla also supported the digitization of other study areas in this thesis. Field observations were limited to only 1 study area, Muurla. Results from Muurla field observations were utilized in the identification of BOSS textures and topography on other study sites.

5. Results

In the process of LiDAR DEM survey and field inspections, many important notions were made regarding objects in the field that could resemble outcrops. Figure 6. showcases some of these features found at Muurla. A total of 40.91 km^2 of BOSS areas were digitized as polygon shapefiles in the re-digitization process compared to the original 38.44 km^2 (Table 1.). Increase of digitized BOSS areas is attributed to identification of BOSS in DEM, especially outcrops.

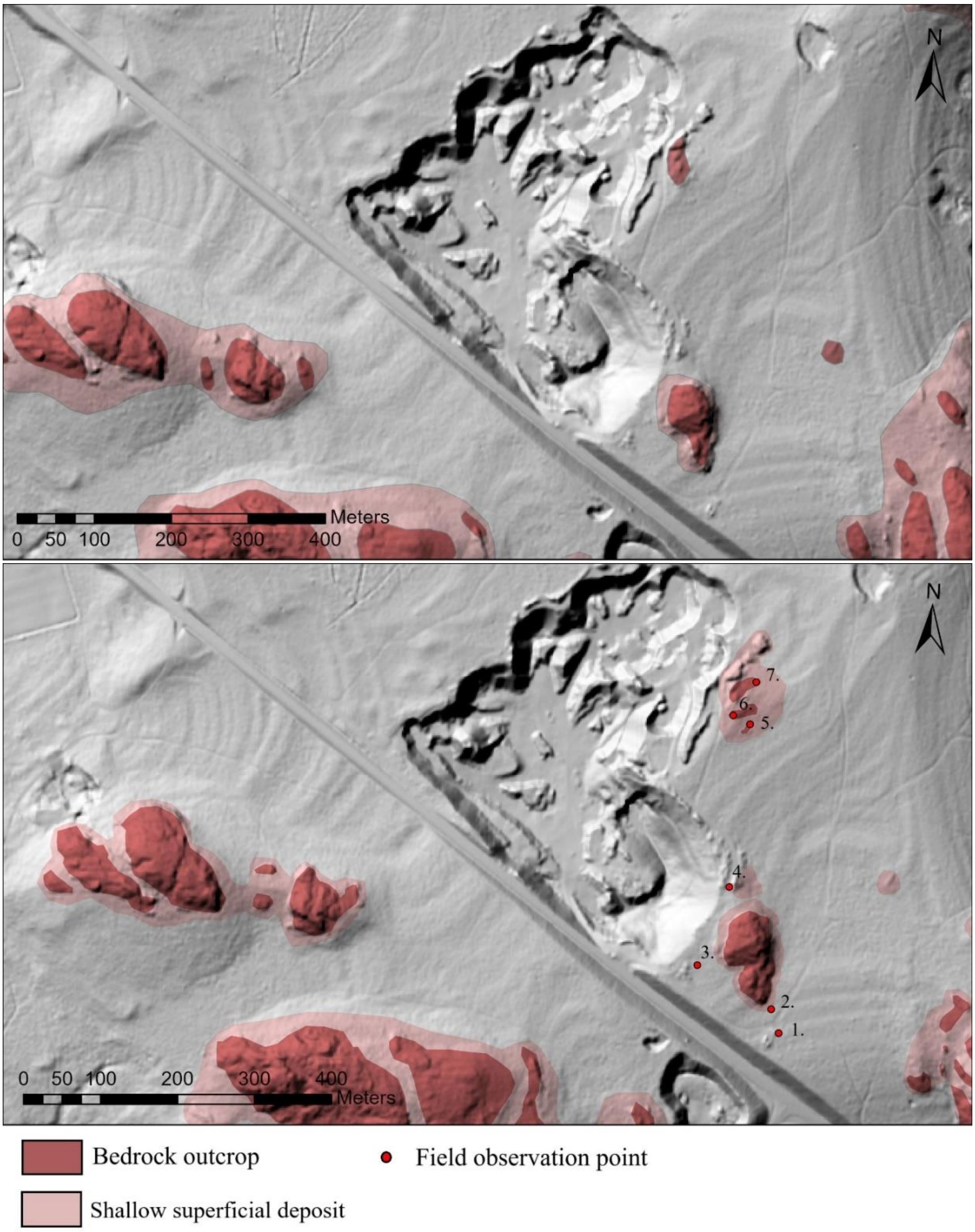

Figure 6. Above are the original delineations of BOSS areas at Muurla study site by the Finnish land surveying office and the geological research center of Finland. Below are the re-digitized BOSS areas from same area. Points 1 – 7 represent point data gathered in the field. These include observations like bedrock outcrop and shallow superficial deposit contacts and anthropogenic structures. Field checks were conducted to aid the digitization process and to get a better understanding about textural differences of BOSS areas during digitization. Points represent; **1)** large piles of pebbles/gravel visible on DEM, **2)** boundary of shallow superficial deposit, **3)** large piles of tree stumps and roots, **4)** concrete foundations near BOSS area, **5)**, **6)** and **7)** small bedrock outcrops. Photographs of features in points 1, 3 and 4 are presented in figure 7.

Table 1. Areal statistics comparison of BOSS in all four study sites prior and after the re-digitization and visual identification. In this table, shallow soils refer to shallow superficial deposits. Bedrock outcrop areas increased in the re-digitization process in all study sites while shallow superficial deposit areas decreased in all sites, excluding Tammela. Re-digitization of these four study areas yielded in total 2.47 km^2 of new BOSS areas.

Study area	Bedrock outcrops (km2) MML	Shallow soils (km2) GTK	Re-digitized bedrock outcrops (km2)	Re-digitized shallow soils (km2)
Muurla	3.14	9.14	3.69	8.83
Suomusjärvi	2.33	10.84	3.2	10.71
Veikkola	1.15	8.36	2.17	7.98
Tammela	0.17	3.31	0.61	3.72

Photographic examples of anthropogenic structures and features found at Muurla are presented in Figure 7. These features could be easily misidentified as bedrock outcrops on LiDAR DEM, but with field checks this was avoided in this thesis.

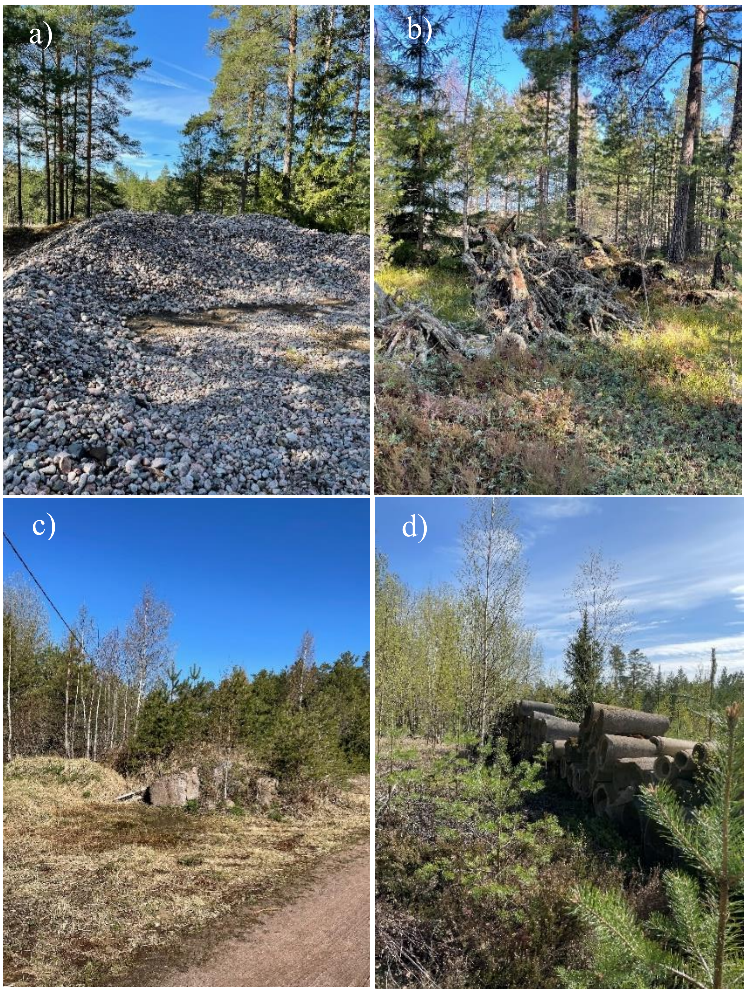

Figure 7. Photographs of **a)** pile of gravel/pebbles, **b)** pile of tree stumps and roots, **c)** concrete structures and **d)** concrete drums on a pile. Identifying these features without field checks purely on DEM might be challenging. Some of these features are visible on DEM, see **Figure 6.** Similarity of the textures of these features on DEM to BOSS areas can be identified, especially when they occur adjacent to actual BOSS.

Figures 8, 9, 10 and 11 represent BOSS areas prior and after the re-digitization from each study site.

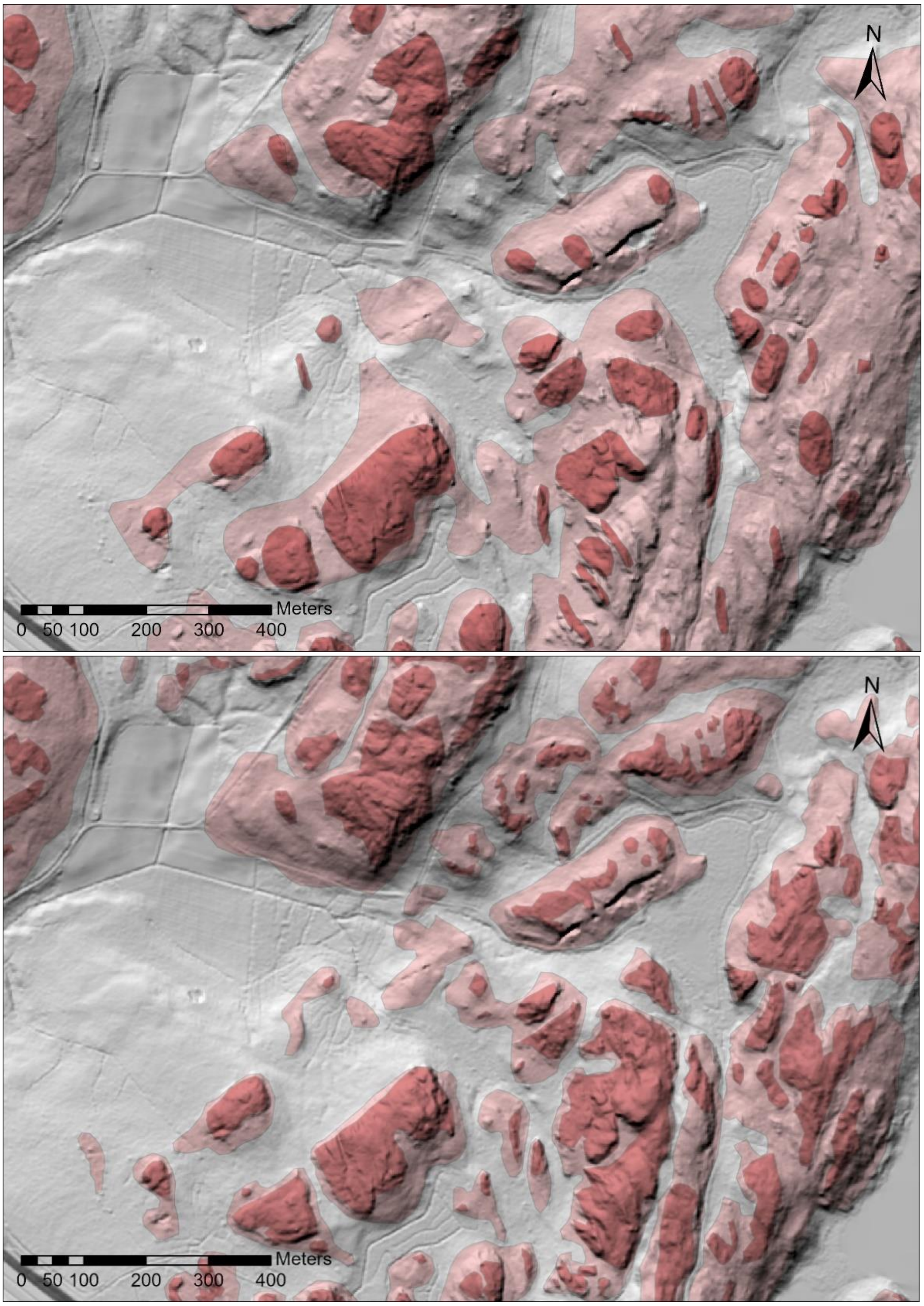

Figure 8. Above is a map of the original BOSS areas in Suomusjärvi study site, prior the re-digitization. Below are the new delineations of BOSS areas.

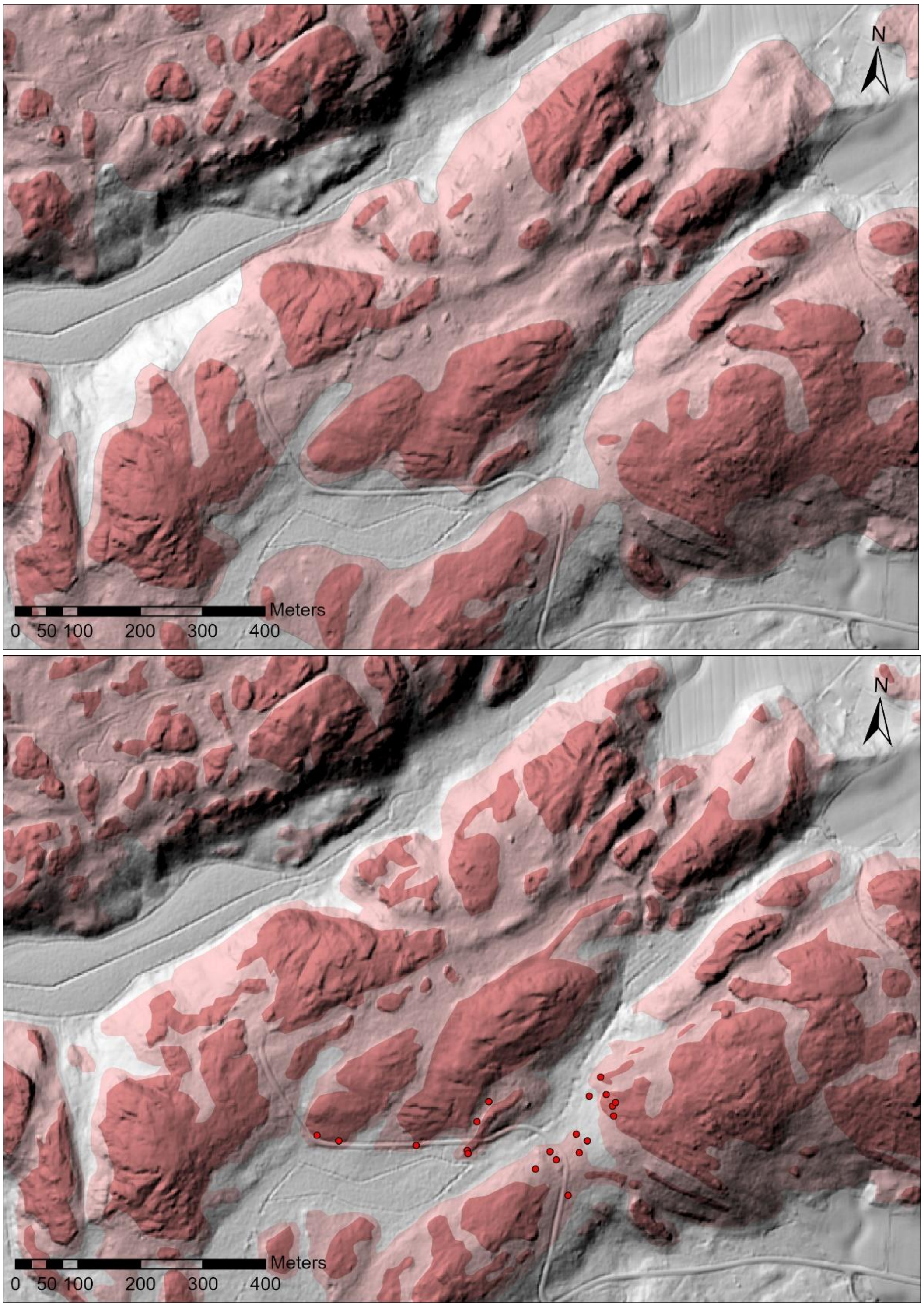

Figure 9. Above is a map of the original delineations of BOSS areas. Below the new re-digitized delineations at Muurla study site. Pale red indicates shallow superficial deposits, darker red bedrock outcrops. Red dots are field checkup points that were utilized in digitization. These points were observations of either shallow superficial deposit/their boundaries or outcrops/boundaries. Also included observations of moraine and shallow superficial deposit boundaries with ground spike tool and visual inspection.

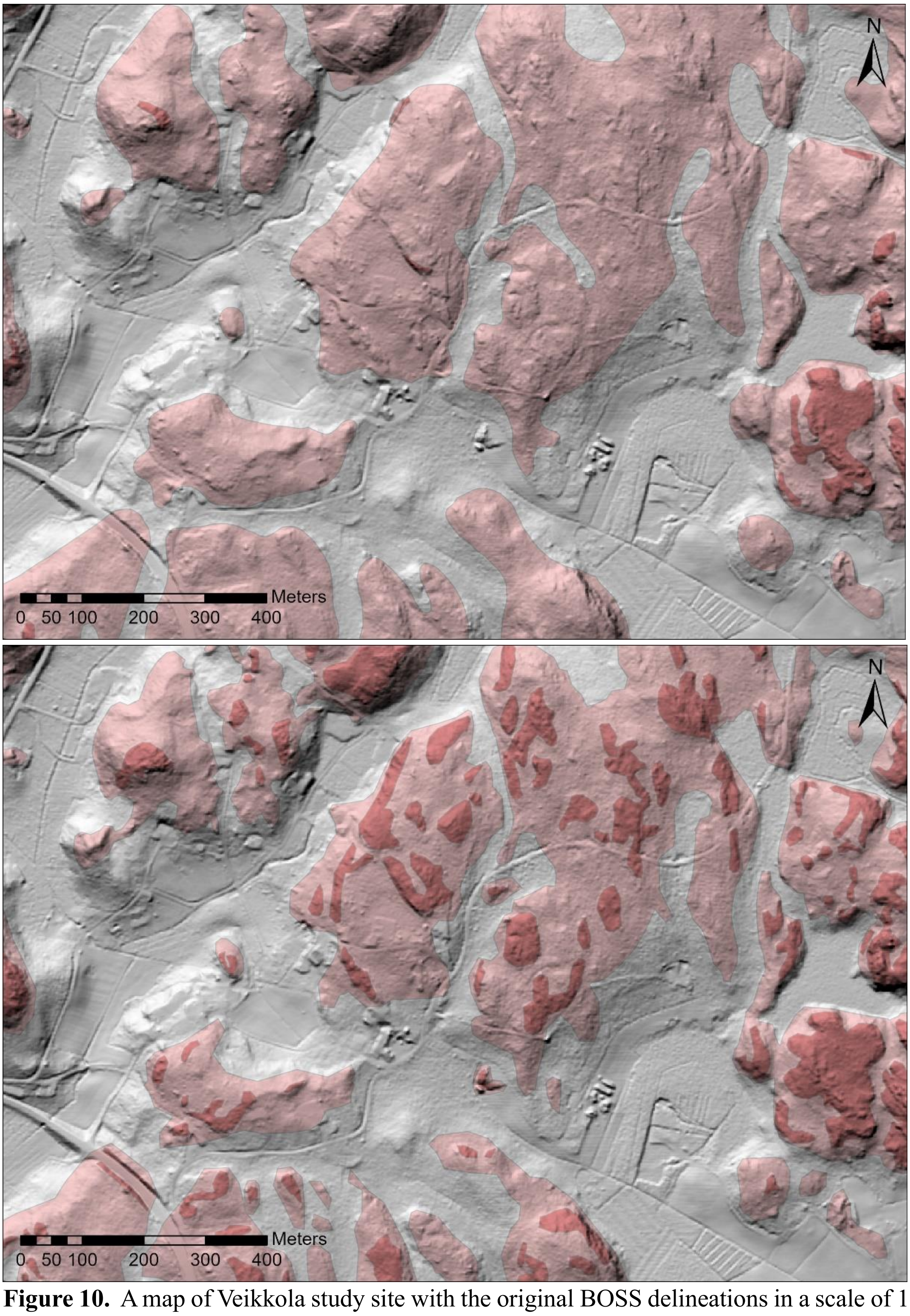

Figure 10. A map of Veikkola study site with the original BOSS delineations in a scale of 1:7000 above. Below are the re-digitized delineations for BOSS from the same area. A large amount of bedrock outcrops was digitized in the process.

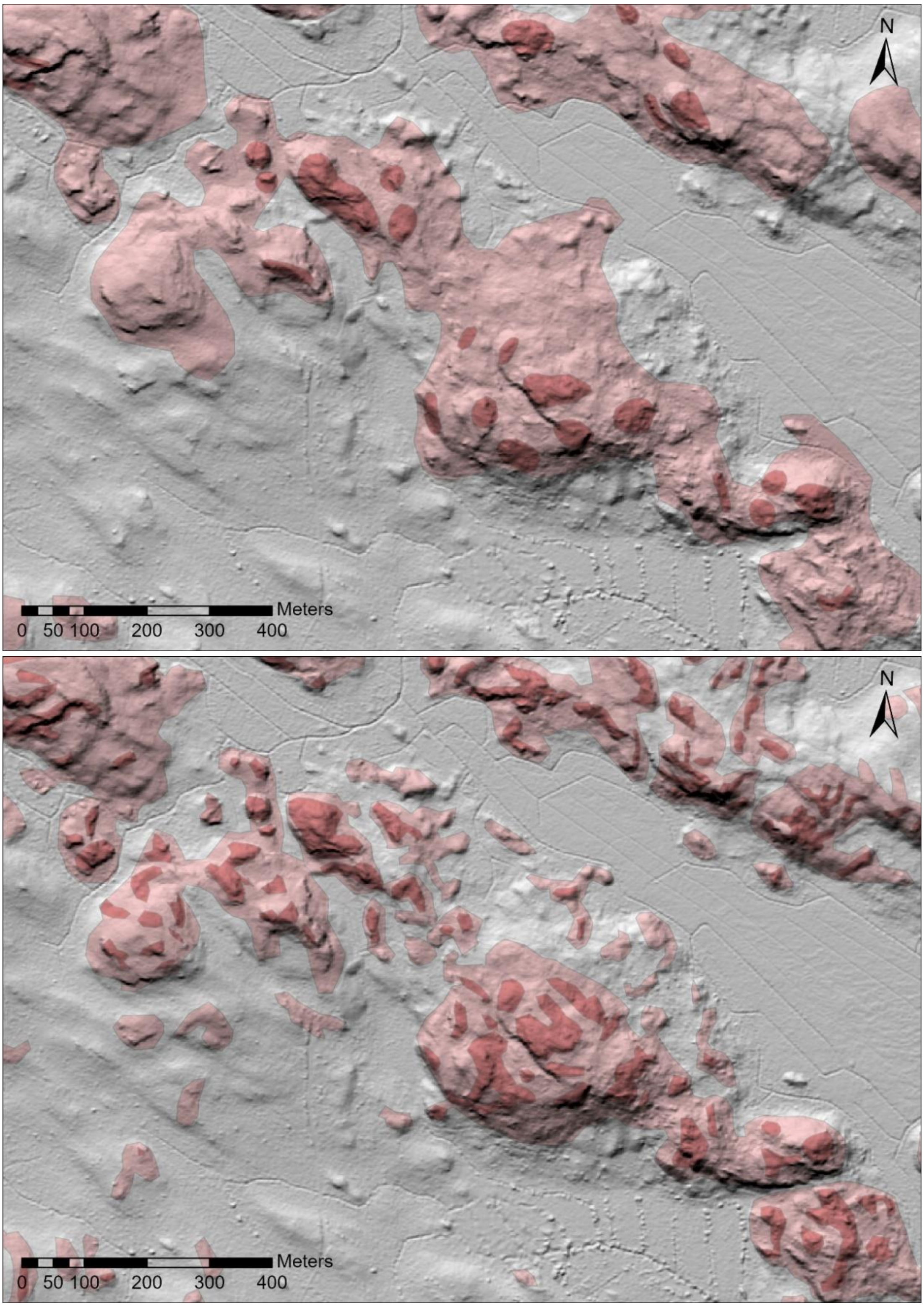

Figure 11. A map of Tammela study site with original BOSS areas. Below the re-digitized boundaries. A lot of small new bedrock outcrop delineations occurred during the digitization process

Statistical terrain topographical analysis was produced with ArcGIS Pro spatial analyst tool focal statistics. In focal statistics, neighborhood for cell size was determined the default 3. For each DEM a mean, maximum and minimum focal statistics raster file was produced. A terrain ruggedness index (TRI) was produced via raster calculator tool, with the formula of: (focal mean – focal minimum) / (focal maximum – focal minimum) for each study site. Methods for TRI were developed by Riley et. al 1999 and it expresses elevation differences between adjacent cells in a DEM. Figure 12 presents 3 different maps of same area from Muurla. A visible correlation is noticeable with TRI map trends, digitized BOSS areas and DEM texture. In Figure 12, highest ruggedness values (eg. highest elevation differences) are presented as red and lowest as green raster cells. Yellow values indicate moderate elevation difference. Figure 13 gives a different visual perception on TRI, because a cell size of 5 was used in neighborhood setting. Increasing the neighborhood cell size for focal mean, -minimum and -maximum will generate a TRI for smaller scale mapping purposes of larger areas. Respectively a decrease in neighborhood cell size would create a TRI for larger scale mapping purposes of smaller areas. Two terrain profiles were created (Fig. 15 & 17) in ArcGIS from two BOSS areas in Muurla. Profiles include field checkup points which were i) outcrop boundary points, ii) outcrop points, iii) shallow superficial deposit boundary points, iv) shallow superficial deposit points and v) other Quaternary deposit points (Fig. 14 & 16). The re-digitization of these areas took place before the field checkups and creation of elevation profile to assess the accuracy of new delineations.

Data gathered from two different elevation profiles from Muurla study site, suggests that there is good potential for the refinement and update of BOSS areas using LiDAR DEM in large scale mapping. The first elevation profile (Fig. 15) yielded 3.8 m more accurate delineations for bedrock outcrop (BO) boundary in re-digitized compared to original delineations. In the same graph, re-digitized shallow superficial deposit (SS) boundary was off approximately 1.7 m from the real field checked boundary. Sandy moraine was absent in the original Quaternary map (Fig. 14. left side map) but was identified in the re-digitization process and in the field. Areas of moraine were digitized originally as shallow superficial deposits. Second elevation profile (Fig. 17) yielded total of 3.6 m more accurate bedrock outcrop boundaries for the re-digitized compared to original delineations. In the same graph re-digitized SS boundaries were 3.5 m more accurate compared to originals.

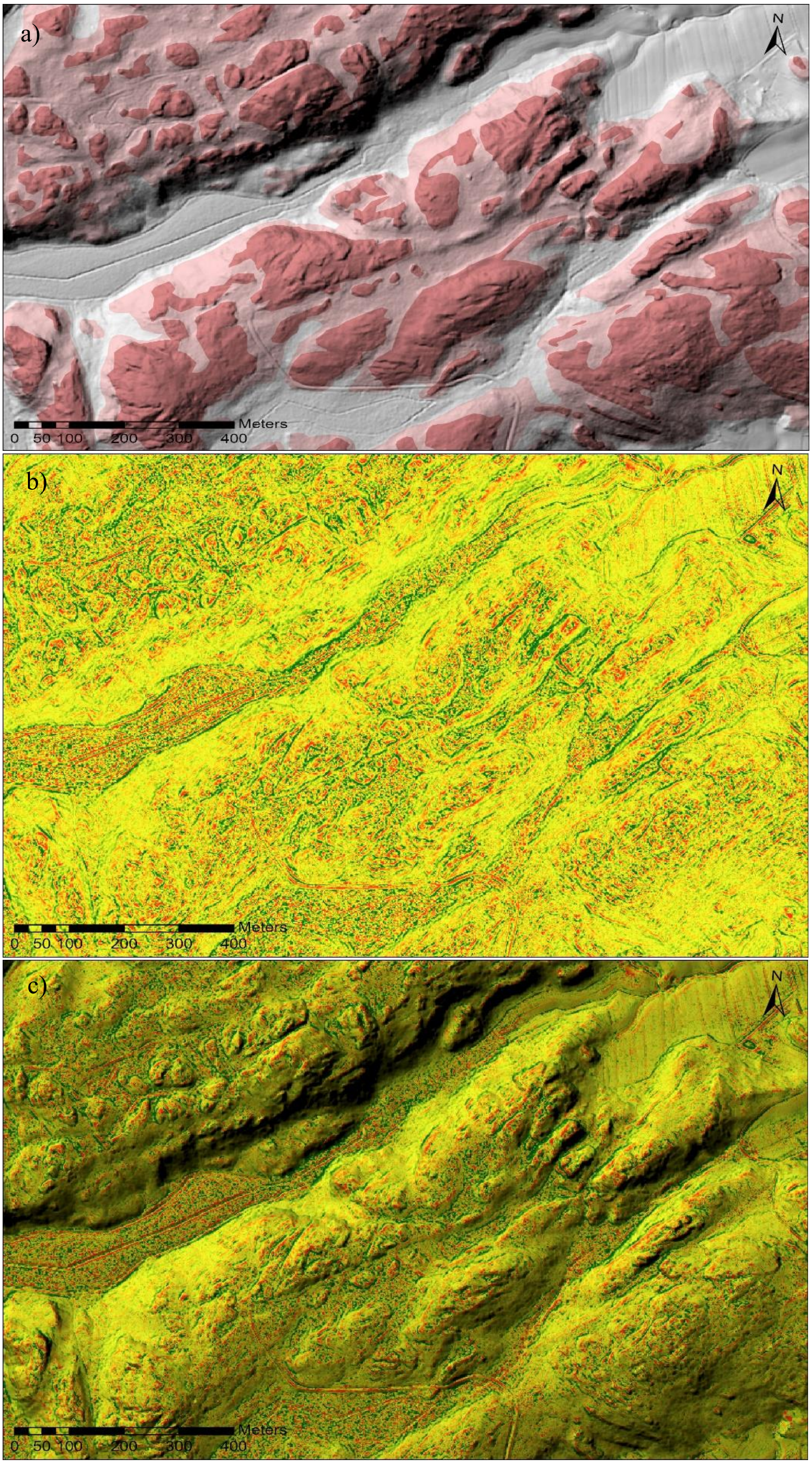

Figure 12. A compilation of three different maps from the same area at Muurla: **a)** re-digitized BOSS areas plotted on DEM hillshade, **b)** TRI map and **c)** TRI plotted on DEM hillshade. Symbology for the TRI is set to stretch values and stretch type as standard deviation. BOSS areas seem to be surrounded by more yellow/orange colour, which is indicative of average and high elevation value differences in TRI.

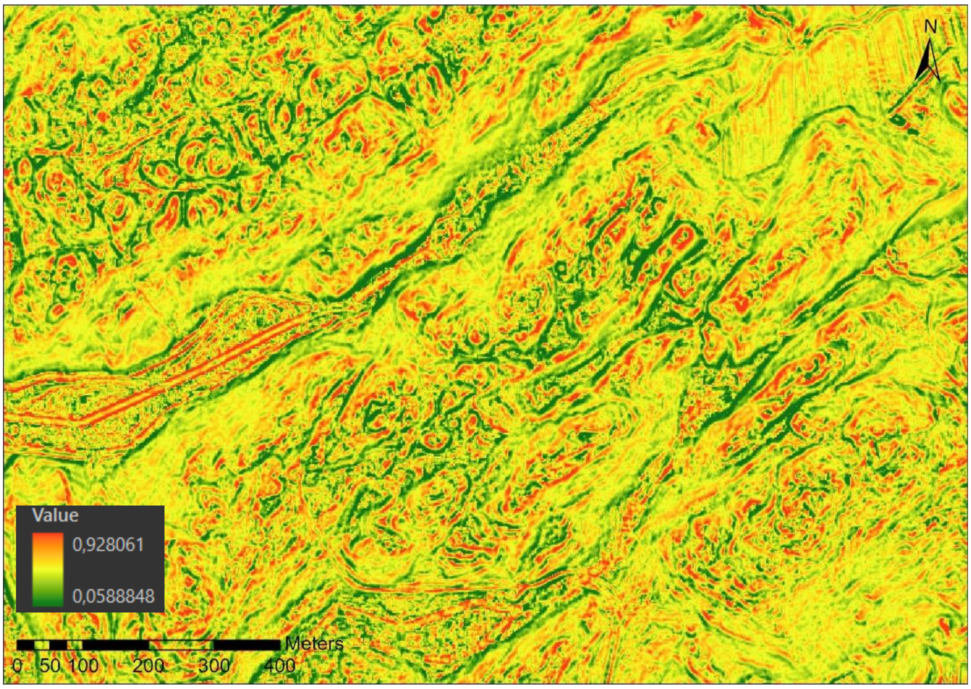

Figure 13. TRI map of the same area in Muurla. A neighbourhood cell size of 5 was applied. Topographical elevation differences between adjacent cells can be identified from different color values just like in figure 12. The scale for TRI has decreased because of increase in neighbourhood cell size.

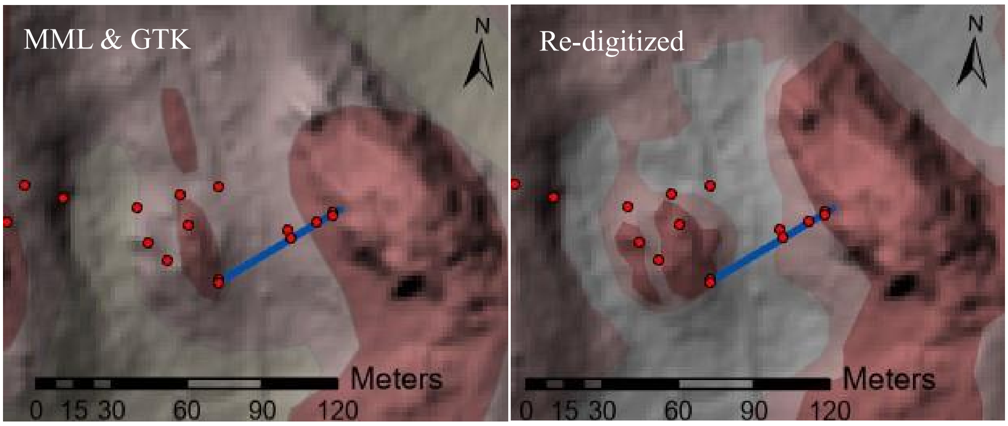

Figure 14. Two maps from the same area in Muurla showing location of first elevation profile. Left are the original delineations of BOSS areas and right are the new. Yellowish color on the left side map is sandy moraine. Red dots are field checkup points. Blue line is the terrain profile line which was walked in the field and plotted in figure 15. Terrain profile starts at SW side of the line, and distance increases towards NE.

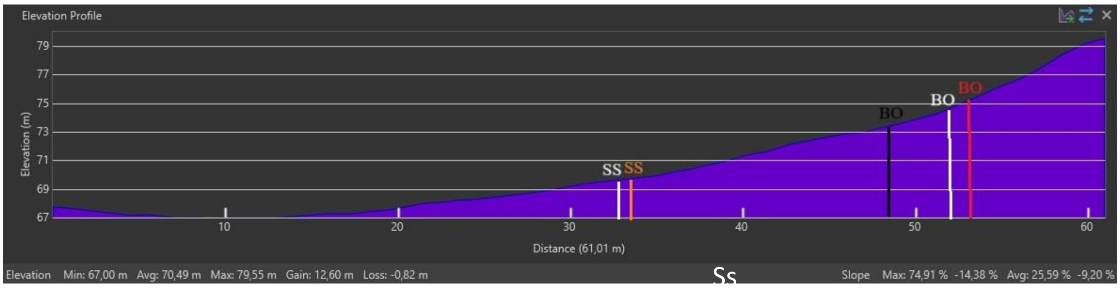

Figure 15. Elevation profile from BOSS boundaries at Muurla, see Fig. 14. **BO** marked in red = bedrock outcrop boundary determined in the field, **BO** marked in white = re-digitized outcrop boundary, **BO** marked in black = MML & GTK boundaries. **SS** marked in orange = shallow superficial deposit and moraine boundary determined in the field, **SS** marked in white = re-digitized shallow superficial deposit and moraine boundary. No boundary for **SS** in MML & GTK data, because the area was originally mapped as shallow superficial deposit without moraine. There was approximately 2.2 m offset from the field checked **BO** boundary and re-digitized boundary. Offset of approximately 6 m in GTK & MML versus field checked **BO** boundary was recorded. **SS** field checked- and re-digitized boundary is within 1.7 m from one another.

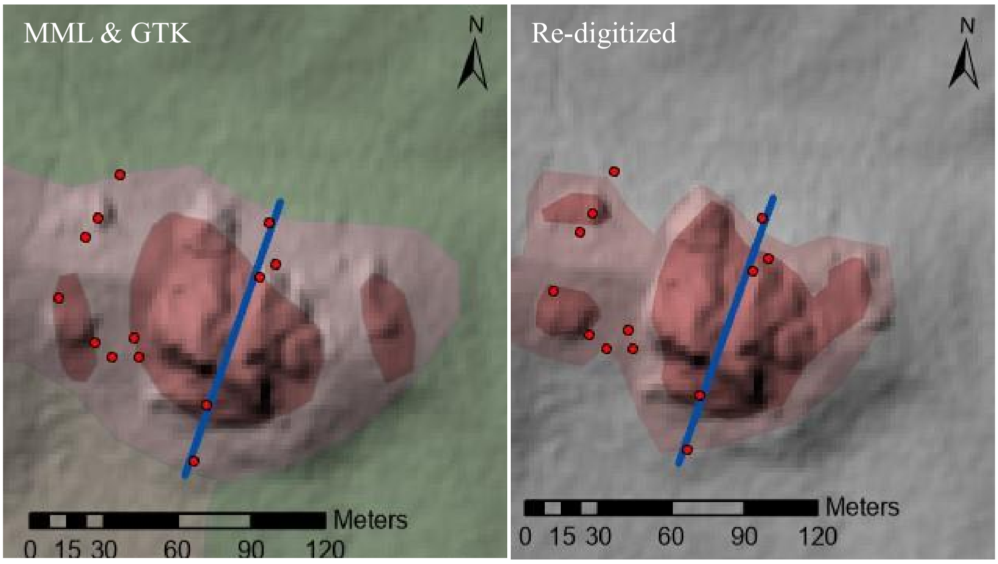

Figure 16. Two maps from Muurla showcasing location for the second elevation profile (Fig. 17) that was field checked, and boundaries of BOSS were determined. On the left side are the original delineations from MML & GTK and on the right new delineations. Red dots are field checkup points similar of that in Fig. 14. Green polygon color on the left side map is sand and the yellow is moraine. Profile starts at S side of the blue line and distance increases towards N.

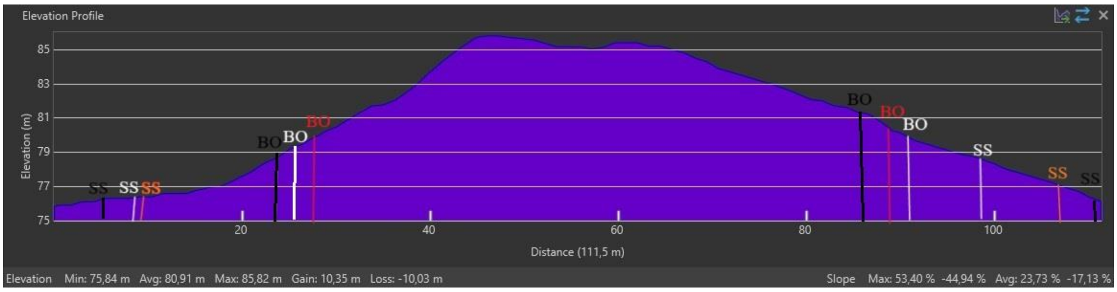

Figure 17. Elevation profile of BOSS boundaries from Muurla, see Fig. 16. Boundaries of BOSS areas are named and coloured according to Fig. 15. Distance between field checked **BO** boundaries vs. re-digitized **BO** boundaries from left side of the elevation profile to right: 2.8 m and 3 m. Distance between the field checked **BO** boundaries and the MML & GTK bedrock outcrop boundaries from left to right: 5.7 m and 3.7 m. Distance offset of field checked **SS** boundaries vs. re-digitized **SS** boundaries from left to right: 1.7 m and 5.6 m. Distance between field checked **SS** boundaries and MML & GTK **SS** boundaries from left to right: 5.9 m and 4.9 m.

In Muurla study site, four structural measurements were taken from a granite outcrop. Measurements are shown in Figure 18. Granites, granodiorites, gneisses and gabbros are hard and durable igneous and metamorphic rocks which occur at all study sites. Muurla, Suomusjärvi and Veikkola exhibited the most BOSS areas and the main rock type being one or more of the previously mentioned. The lithology of the rock is one of the key factors that determine how weathering processes can affect it. For example, on average, sedimentary rocks produce higher erosion rates than massive crystalline rocks, thus creating thicker sediment covers (Pinet & Souriau 1988, Schaller et al. 2001, Tucker 2015). Fracture density and alignment of fractures and bedding planes plays also an important role in the erosion variability and -rates in different rock types. Hard crystalline rocks are often covered by shallow superficial deposits and moraine in recently glaciated landscapes, or they occur as outcrops. When considering the rock's resistance to chemical weathering, the rock's mineral composition and stability are the most important factors. Although vast fracture networks could enhance for example acidic pore water flow in the rock mass. Fractures, relief of bedding planes and brittle structures are on the other hand important factors when considering resistance to hydraulic plucking (Whipple et al. 2000, Tucker 2015). Major bedrock fracture lineaments (mapped in 1: 500k scale), are visible at all study sites. Especially lakes and clay deposits develop in these brittle weak zones in the bedrock. In addition to lithology and relief properties of the rock, a third factor, tectonic processes, can have direct correlation to erosion and sediment yield (Hovius 1998, Dadson et al. 2003, Von Blanckenburg 2005). The main lithologies in all the study areas were either granite or metamorphic rocks, that have been eroded by chemical dissolution and physical weathering. Bedrock of Finland has been physically eroded during the Quaternary period by glaciers and related meltwaters, which can be observed from the sediment records, geomorphology and features in the bedrock carved by the continental ice sheet.

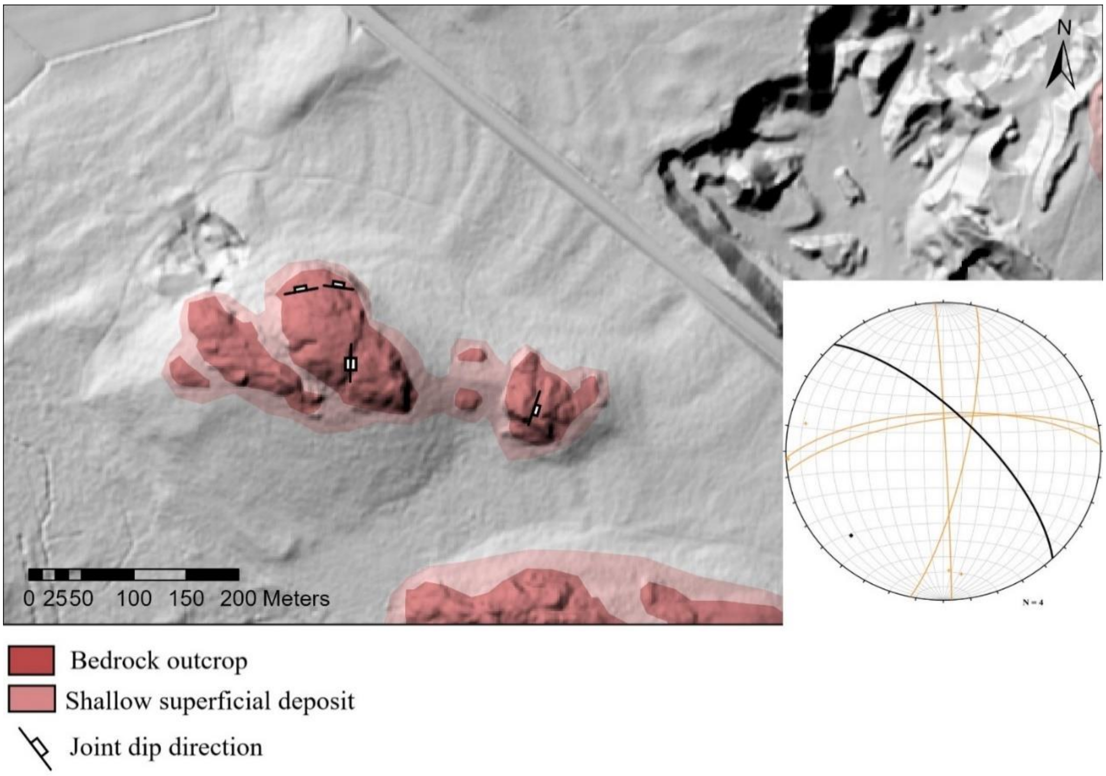

Figure 18. Map of shallow superficial deposits and outcrop area that is surrounded by sandy moraine (not visible in the map). Bedrock outcrops consist mainly of granite. Four joint dip directions were measured and plotted on a stereonet. In close inspection and with large enough scale, it is possible to identify bedrock structures on LiDAR DEM.

Because all the study areas have been affected geomorphologically by the Scandinavian ice sheet (SIS) and its ice lobe provinces and interlobate regions, they exhibit Quaternary glacial and glaciofluvial deposits of varying grain sizes and geomorphologies. In Finland GTK applies mainly morpho-lithogenetic methods in the classification and division of Quaternary landform map units. This provides valuable information on sedimentation environment: identification of ancient shorelines, modelling movement of glaciers and meltwaters for example (Palmu et al. 2021). During the Quaternary period from 2.58 mya to present day, Southern and SW Finland and its pre-Cambrian bedrock have been glaciated multiple times. It is not known how many glaciation stages there have been exactly, because of glacial erosion of interglacial and glacial sediments by younger glacial advances and retreats. The center of SIS was situated near Finland, therefore ice sheet- and related erosion was particularly effective. Visible geomorphological deposits in the present day consist of Weichselian sediments, that were deposited during the most recent cold period (Johansson et al. 2011). Both Muurla and Suomusjärvi study sites contain numerous ice marginal glaciofluvial deposits. These are part of a bigger ice marginal formation known as Salpausselät. In Muurla and Suomusjärvi there is also the most BOSS areas from all four study areas, indicating different sedimentation environment than in Veikkola or Tammela. Indeed, none of the other study areas have sandur deltas formed by the meltwater streams near the ice margin or numerous De Geer moraines formed by especially the retreating ice sheet. It is common for De Geer moraines to occur on shallow superficial deposits and (sandy)moraine. In Veikkola, situated east from Muurla and Suomusjärvi, there is the most littoral sediments, which were deposited during the littorina sea stage of the baltic sea around 7500 – 4000 BP. These littoral deposits are indicative of ancient shoreline deposition during this period. Absence of De Geer moraines and presence of littoral covering deposits indicates deeper waters when sediments were deposited. Tammela has the least covering glaciofluvial deposits, almost none. At the same time, it has the least amount of BOSS areas among study sites. The presence of vast areas of peat, clay and sandy moraine correlate with the main direction of major lineaments in the area. It is possible that these overburdens/sediment covers have been deposited in the major brittle zone of the bedrock, where sediment cover is thicker. Also, the possibility of Tammela study site being an ancient meltwater feeder channel to ice lake is worth considering but is beyond the scope of this study. Littoral deposits are absent in Tammela, most likely because it is the northernmost study area and Littorina sea didn't submerge it completely.

Topographical and textural characteristics of BOSS areas were identified during the mapping and digitization process. BOSS areas exhibit commonly elevated topography with rugged texture. Especially bedrock outcrops and their visible large-scale structures can be identified by their fractures and rugged slopes. Even smoother outcrop surfaces can be identified from LiDAR DEM with large enough scale because their appearance on DEM is different than for example sandy moraine. Sandy moraine exhibits smooth texture with wavy bumps, without any structural relief. Boundaries of bedrock outcrops that have sharp and elevated slopes are often the easiest to delineate. Texture can change quickly when moving away from the outcrop, meaning in this case an increase in overburden thickness. Shallow superficial deposits are also identified and delineated on DEMs quite accurately, but in some cases, it might be challenging to determine the boundary between moraine and shallow superficial deposit when they are phasing into one another. This in turn affects the textural properties of the elevation surface. Delineations made purely on textural analysis and visual inspection on DEM without field checks especially with shallow superficial deposit and moraine boundary, would yield less accurate results than with sufficient field checks. Field work can be focused on key areas with the application of DEM textural and topographical analysis, making the process very accurate and efficient in general.

6. Discussion

In the field of geological and geomorphological mapping, LiDAR DEMs have revolutionized the process completely. They are now invaluable and produce accurate data which can be implemented in various applications. In this thesis the main goals were to assess the accuracy of new BOSS delineations made with larger scale (1: 4000) than the originals (1: 10 000 or more) by GTK & MML and to identify textural differences between outcrops, shallow superficial deposits and moraine. Four 25 km^2 study areas were included with different geomorphological features. Field checks were made from only Muurla study site, although numerous field points and observations were collected, it would be more ideal situation to get field data from all the studied areas. In this thesis the field data collected from Muurla was utilized in sort of visual guidelines and textural type examples, which aided in the digitization process of other study areas. Elevation profiles including boundaries from 2 different BOSS sites in Muurla yielded accurate results. Regardless, it would be beneficial to field check with elevation profile sites from example Tammela which has much more moraine and the least BOSS areas, if the delineations are as accurate as in Muurla. The combination of visual identification and field work is proven to be ideal approach when aiming to the most accurate results in BOSS mapping with LiDAR DEMs. The decrease in re-digitized shallow superficial deposit area versus original delineations in this study, could be because of the larger mapping scale in this thesis, and over estimation of shallow superficial deposit areas in the original data. Development in Laser scanning technology and methods could increase the resolution of DEM data even further in the future, thus allowing more accurate identifications and delineations based on textural characteristics of surficial deposits and outcrops.

7. Conclusions

LiDAR DEM based new delineations of BOSS areas in a scale of 1: 4000 in four different 25 km^2 study areas in S Finland yielded total of 6% increase compared to original delineations. Bedrock outcrop areas were increased by 30% while shallow superficial deposit areas decreased by 1.3% from the original BOSS data produced by MML&GTK in a scale of 1: 10 000. New delineations of BOSS areas measured from two different elevation profile lines at Muurla were approximately 3.5 m more accurate than the existing ones. Bedrock outcrop delineations being slightly more accurate in general than shallow superficial deposit ones, because of their distinct relief and texture. On the other hand, completely new boundaries for shallow superficial deposits and moraine were confirmed during field checks in one of the elevation profile locations at Muurla. Topographical textural characterizations of BOSS areas on LiDAR DEM include rugged texture and structural shaded relief for outcrops, surrounded by in most cases smoother appearing shallow superficial deposits which often reflect the topography and structures of bedrock below. During field checks, a few interesting anthropogenic structures were identified that can resemble the texture of outcrops on DEM. Application of DEMs in visual delineation of BOSS areas have been shown to be accurate and cost-efficient method in recently glaciated landscapes, especially when it comes to larger scale mapping. More research should be implemented to the visual delineations of BOSS areas from DEM accompanied with sufficient field work in different landscapes to get more comprehensive understanding on local variations in BOSS texture and identification.

8. Acknowledgements

I would like to warmly thank the supervisors of my master's thesis, Prof. Antti Ojala from University of Turku/GTK and Dr. Jukka-Pekka Palmu from GTK for the introduction to the subject of LiDAR DEM application in Quaternary and BOSS mapping. They both provided comprehensive expertise and guidance in both the mapping process and field work regarding BOSS delineations and identification of various Quaternary landforms.

Their expertise of ArcGIS Pro was also very valuable in this thesis. I would also like to thank university lecturer Eila Hietaharju for the helpful advice regarding the layout finalization.

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