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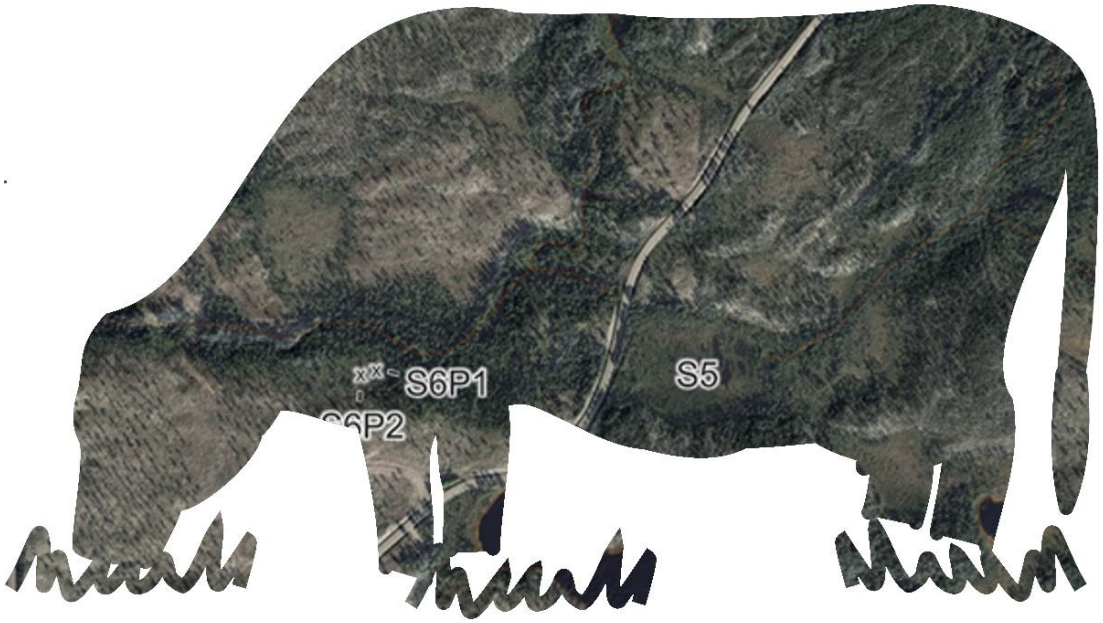

The Swedish Transport Administration's Toolbox and its Potential in Archaeological and Cultural Heritage Survey.

Including a brief review of remote sensing, prospection and geodata analysis methods for archaeology and cultural heritage.

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Extended abstract

This report provides an overview of the main remote sensing methods and geodata types used in archaeological prospection and cultural heritage survey. Based on a literature review, it provides an initial survey of the state of the art nationally and internationally, followed by details on the potential usage of different methods in a Swedish context. The details include pros and cons of methods as well as information on considerations that should be taken into account when applying the methods in different situations. Examples are provided where relevant to explain specific details or illustrate important points. Particular attention has been paid to laser scanning (LiDAR) data due to its increasing prevalence and prominence in landscape and archaeological surveys.

The report continues with a preliminary evaluation of the possibilities for using data provided by Swedish Transport Administration (Trafikverket), obtained for other stages of the planning process, in archaeological and cultural heritage work. Specifically, the report looks at a number of geodata types obtained from The Geological Survey of Sweden (Sveriges geologiska undersökning/SGU), a nature conservation survey in report form, a ground penetrating radar technical report, terrain laser scanning (LiDAR) and orthophotos (geometrically corrected aerial photographs). The SGU geodata consist of a number of Geographical Information System (GIS) layers describing bedrock and soil types, and the nature conservation survey included accompanying, but incomplete, GIS data. This section consists of concise descriptions of the potential of each group of GIS layers or data, and is complemented by brief, bullet point summaries along with additional technical information in Appendix 1. Comments have been made where additional, related, data sources would be useful. Swedish terms are included in parenthesis where the term differs significantly from the English equivalent.

A final summary provides a compact overview of the main points of the report before providing some conclusions and ideas for further work. This is in turn followed by a list of ideas for enhancing the efficiency with which the types of data discussed can be used in infrastructure projects which have a potential to impact on archaeology/cultural heritage.

References are provided to support important or potentially contentious points or where further reading or research would be advised for a more comprehensive understanding of relevant issues.

Abbreviations and terms used in the text

CAD - Computer Aided Design - software environments for manipulating 3D data

GIS - Geographical Information Systems - software environments for viewing, manipulating and analysing geographical data and producing maps, often including 3D data

LiDAR - Light Detection and Ranging - In this report 'LiDAR data' is used as an abbreviation for any form of map produced using this method

MAL - The Environmental Archaeology Lab, Umeå University (Miljöarkeologiska laboratoriet) http://www.idesam.umu.se/mal/

PPSM - Points per Square Metre - a unit used in connection with LiDAR data

SGU - The Geological Survey of Sweden (Sveriges geologiska undersökning) https://www.sgu.se/

Trafikverket - Swedish Transport Administration https://www.trafikverket.se/

For Swedish-English translations of legal terms please see the Glossary for the Courts of Sweden at http://www.domstol.se/Publikationer/Ordlista/svensk-engelsk_ordlista.pdf

Introduction

Project motivation

The Swedish Transport Administration (Trafikverket) undertakes a variety of data collection, collation and analysis tasks during the course of road and railway planning and construction projects. A number of these tasks overlap with processes, or analysis methods, common in archaeological and cultural heritage survey, particularly at the landscape scale. There is therefore reason to believe that there is potential for using material routinely obtained by Trafikverket in at least the cultural heritage evaluation stage of the same road and rail projects. Potential applications range from landscape survey with the aim of identifying archaeological sites, and other culturally and historically interesting features, to the identification of potential sampling sites for environmental archaeology analyses (which provide reconstructions of past human impacts, climate and landscape change). This project aims, therefore, to act as an initial investigation into the possibilities for a more efficient use of relevant Trafikverket analysis methods by extending their use beyond their original purpose.

In Sweden, the early use of the term 'cultural landscape' (*kulturlandskap*) led to the establishment of a landscape concept strongly orientated towards cultivation based economies (e.g. agriculture, livestock, forestry). Perpetuation of this concept resulted in a relatively conservative view of how and why past peoples may have established themselves in particular locations, and which archaeological traces of them could be expected to be found in the landscape at the present day. We now work with an understanding of more geographically diverse activities and a larger range of forms of evidence, and this has started to have an effect on the preconceptions which influence archaeological survey and excavation. Humans have had landscape impacts through a multitude of activities beyond those which can be directly associated with cultivation and permanent settlement. We now look for the, often scarce and ambiguous, evidence of phenomena such as the use of outfield areas (i.e. commons away from population centres), hunting, fishing and gathering, temporary settlements and transportation routes, as well as the indirect consequences of past human activity which may be evident in landscape changes.

As a consequence of this expanded view, it has become apparent during recent years that parts of the Swedish landscape that have previously been considered as more or less archaeologically uninteresting, contain a greater depth of time and archaeological significance than many cultivated landscapes. These areas have often been considered as unimportant outfield or remote areas, or as only containing more recent historical remains, such as smallholdings or torps (*torpbebyggelsen*) or recent charcoal production sites (*kolningsverksamhet/kolbottnar*). In some countries (e.g. UK and USA), historical remains (e.g. after 1850) are often seen as part of the continuity of a landscape from prehistory into the modern day, and thus just as important as older archaeological remains. Furthermore, recent changes to the Heritage Conservation Act (*kulturmiljölagen*) have raised the importance of clearance cairns and small enclosures (*torp*) as remains worth protecting. There is therefore a need for a broader handling of the cultural landscape, at an earlier stage in development plans, than was previously assumed. More efficient use of remote sensing and geodata will undoubtedly aid in this process.

Archaeologists are also now more aware of the importance of understanding past human activities in the context of natural landscape and climate change, something which is essential for building as complete a picture as possible of the past. Understanding the past, especially in terms of archaeological and geological empirical evidence, is crucial to our understanding of the sustainability of the modern landscape, as well as predicting the potential outcomes of future human activity in

similar contexts. The inclusion of environmental and geological evidence in the archaeological survey process is therefore indispensable.

Remote sensing and geographic data and information (geodata) are most often collected with a specific purpose in mind. LiDAR data, for example, may be collected for the route of a planned railway in order to build an accurate digital terrain model (DTM/DEM) for the calculation of construction material and extraction masses. The same model may have several applications (such as the production of 3D models for public visualisations) and the data may thus be reused. For this to occur in the archaeological context, however, the data must be collected in such a way that they are of sufficiently high quality for archaeological analyses. Archaeologists, for example, generally require higher resolution aerial photographs than conservation scientists, as well as a more careful use of processing algorithms when turning raw LiDAR data into a 3D surface. This report aims to highlight areas where an initial consideration of these requirements will help enable data reuse in the archaeological context, thus increasing quality, saving time and money in the overall planning process.

Aims of this report

The general aim of this report is to identify and evaluate a number of archaeological prospection methods within Trafikverket's planning tools. We describe how these tools could be more efficiently used in current, or future, investigations into the cultural heritage of areas potentially impacted by development plans, and where existing data could be used more efficiently across sectors. These methods and data are discussed in terms of their appropriateness in different circumstances, and with reference to the expertise required to successfully apply them.

The report also provides an overview of methods used in archaeological research and contract archaeology, with a focus on remote sensing (in broad terms), in Sweden and internationally. Extra attention is paid to methods, especially laser scanning (LiDAR), which are of special importance in archaeological field survey at the current time. This overview is aimed at providing Trafikverket with an improved foundation for the evaluation of possible future analysis methods within archaeology and cultural heritage studies.

Note that whilst the report makes a number of references to authorities, laws and acts concerned with cultural heritage and archaeology, it is not the aim of this report to provide an explicit connection between these and the use of the data and methods described herein. In this respect, the report is also fluid in its use of the terms ancient monuments, archaeological remains and cultural heritage or historical remains and objects. To many archaeologists, the legal and protection status of remains are of secondary importance to their scientific value. Further work is necessary for an evaluation of the relative importance of the methods described here with respect to the different protection status of remains.

Report layout

In order to put Trafikverkets methods in context, the report starts with an overview of the Swedish and international use of remote sensing methods in archaeology and cultural heritage survey. This is followed by an overview of the possibilities for using methods and data commonly used by Trafikverket in the context of road and rail projects. Data and reports were provided by Nina Karlsson, Trafikverket Umeå, for this purpose. These overviews are then summarised to provide a rapid overview and followed by a list of important points to consider with respect to the use of these

methods and data. An appendix provides more details and bulleted points relating to the specific files from Trafikverket examined in preparation of this report.

The report combines general overviews and lists with more detailed discussions in order to provide material for a broad spectrum of readers from management to field operative. The report has some similarities to a scientific report, but, with the exception of the overview section, references have been used sparingly to improve readability.

Material and methods

Methods

The first component of this report is based on a survey of recent literature on the use of remote sensing and geographical data in archaeology and cultural heritage survey. References are included in the brief bibliography at the end of the report, and citations are provided for important points in the text. This overview is used to frame the second component, which provides a systematic evaluation of the analysis potential of data and reports provided by Nina Karlsson, Trafikverket Umeå. A full list of these data are provided in section entitled 'The Swedish Transport Administration's Toolbox' and summary details in Appendix 1. This evaluation also draws on the ca 100 years collective experience of the authors in archaeological research and development, consultancy and administration in Sweden and internationally.

What is archaeological evidence?

Any human activity inevitably has some form of environmental impact. Today, the most visible impacts are those which concern the extraction of natural resources and the disposal of waste. Whilst humans have most likely only had a direct influence on the Earth's climate over the last century, we have dramatically influenced the landscape around us in large parts of the World. (We have also dramatically influenced the world's seas as well, but that not the topic of this report). Modern and historical landscape impacts are often evident even to an untrained eye in, for example, old field boundaries preserved long after farming has ceased and the visible scars of quarries and reservoirs. Any contemporary landscape is the result of a combination of its geological origins and the cumulative effects of its history of natural processes and human impacts. Humankind has survived as a species for 1000's of years through its ability to adapt to, and to adapt, the resources provided by the landscape, and archaeologists can often detect and interpret the evidence left behind these activities.

Broadly speaking, evidence for past human activities can be categorised in terms of four types:

1) The physical remains of structures for habitation, industry or other activities (e.g. embankments or walls from houses, graves, pits remaining from the production of charcoal). Some of these are visible at the surface and easy to spot (e.g. Greek temples, Bronze Age mining remains in England, Bronze Age burial cairns in Bohuslän, Sweden), but the majority of them require specialist training and knowledge to detect and interpret, as well as some form of field and/or remote sensing based survey. Many remains of this type will be buried beneath later sediments.

2) Tools, remains or waste materials (e.g. ceramics, flint axes, bronze pins, bones of humans or animals, quartz flakes left over from making arrowheads, slag from metal production). These are most often only detectable through field survey and excavation of sites identified through

archaeological prospection. Many remains of this type will also be buried beneath later sediments.

These first two types of evidence are commonly referred to as material culture or material evidence. They are most usefully complemented by environmental evidence, in the form of:

3) Changes in the chemical or physical composition of sediments (e.g. raised phosphate values around a site, increased organic content due to manuring). These are detected through physical sampling and the application of geoarchaeological prospection methods in the field, or more often field and laboratory, in combination with subsequent spatial analyses. Some indications of anomalies may be visible at the present day through patterns in vegetation.

4) Changes in the composition of biological organisms (e.g. fossil dung beetles indicating the presence of domestic animals, a reduction in the amount of tree pollen after deforestation). These are detected through the laboratory and microscope based analysis of samples from archaeological sites, peat bogs and lake sediments.

Remote sensing and geodata analysis methods are now routinely employed by archaeologists at different stages in the prospection for, and analysis of, all of the above types of evidence. In this respect, it may even be sensible to add a fifth line of evidence:

5) Persistent changes in the landscape as a result of previous human activity. For example, woodland pasture and selective felling have permanent effects on the structure of woodland; the boundaries of medieval homefields are still visible as grassy patches in Greenland some 500 years after the Norse farms were abandoned; the location of shielings on historical maps of Swedish forests can often be matched to modern vegetation patterns and the age of trees.

Establishing chronologies (the age and sequence of events in the past) is often difficult, especially without excavation and sampling of organic remains. What we see in the landscape is often a collage of fragmentary, direct and indirect evidence from different time periods. An area may have been subject to different landuse at different times, or the same form of landuse may have occurred multiple times. Adequate dating evidence is therefore essential to avoid incorrect or unsubstantiated theories. Remote sensing and survey rarely provides robust dating evidence, even if the approximate age of some remains can be assessed in the field. They must therefore always be used in combination with more detailed analyses later in the archaeological investigation.

Why remote sensing and survey?

A typical archaeological or cultural heritage survey will use a combination of methods to maximise the potential for finding archaeological remains. The choice of methods will be dependent on the type of terrain, vegetation and sediments expected to be encountered, usually after an initial overview of geological maps, vegetation surveys and historical maps. LiDAR data has been more recently added to this list. The survey results will usually be integrated using Geographical Information Systems (GIS) to allow tools to be used for the cross analysis of data and the production of maps for visualisation of result. Statistical packages may also be used to analyse more complex data, such as geoarchaeological survey results or hyperspectral imaging.

Archaeological features, or the evidence for past human activities in the landscape, may express themselves in various, and variably evident, ways. The most obvious and generally known remains are those of physical earthworks, structures or stone remains visible at the surface. Stonehenge in Wiltshire, England, or Ales Stenar in Scania, Sweden, represent one end of the spectrum, and although remote sensing methods are useful for mapping these and putting them in a landscape

context, they are hardly necessary for their discovery in an open landscape. At the other end of the physical remains spectrum are smaller burial mounds and hearths which, although visible at the surface, may be difficult to see from a distance and without expert archaeological knowledge. Should any of these types of feature be buried under sediments such as river deposits, landslides or other depositional environments they instantly become more difficult to find, and require prospection or remote sensing methods (such as Ground Penetrating Radar, GPR, see below) for locating them. The vast majority of archaeological remains are buried, and prospection/survey methods which combine surface and subsurface surveys are thus the most important initial set of tools in any archaeological investigation.

Human activities can also express themselves in other ways which are not immediately visible, and we must resort to laboratory based analyses of sediments in order to infer their location, age and impacts. These intangible remains often include changes in the chemical or physical composition of soils (e.g. phosphate enrichment through waste deposition) or changes in vegetation due to land-use activities (e.g. deforestation to make way for agriculture). These can never be measured directly and we must resort to so called *proxy analyses* in order to detect and measure them. This requires the location of appropriate sediments from which these signals (e.g. phosphates, pollen, fossil insects etc.) can be extracted from samples. Remote sensing and survey methods are extremely useful for locating potential sampling locations, and a number of the data sources used by Trafikverket would be useful for enabling environmental archaeologists and palaeoecologists to speed up the initial part of their work (see e.g. Buckland & Wallin, 2017, and Figure 1).

Figure 1. Orthophoto overlaid on LiDAR raster map with hillshade. Used to locate potential sampling locations (lettered) for the evaluation of peat sediments for environmental archaeology potential near Rörbäcksnäs, Dalarna. In this case, the subsequent pollen analysis proved the introduction of agriculture in the area before the historical record description (map from Buckland & Wallin, 2017, base images from Lantmäteriet).

Limits to detection

Remote sensing methods are an extremely import part of the archaeological survey toolkit, as described in this report, but all methods have limits. In fact, despite the range of tools available to the archaeologist, it is still never possible to fully and accurately assess the extent of buried features prior to excavation. This is of course dependent on context, but the depth and area of sediment in many situations may mean that sites are only detectable by test trenching at areas identified, through prospection or modelling, as being more probable locations for archaeological sites. In many cases, such as along the course of a past river channel which is now covered by metres of alluvial floodplain sediments, a bridge, or river-side settlement site could have been located anywhere along the river's former course. Such considerations are especially important where the machine based removal of large amounts of material is planned (e.g. a sand or gravel quarry) in an area of known or predicted past cultural activity. Many sites are thus detected by excavation machine drivers during the digging of a sand or gravel quarry. Many archaeological sites are still damaged through forestry, a number of the reasons for which are mentioned below, and better use of remote sensing data could help reduce these losses. Education on the identification of archaeological remains is thus important at many different levels in the construction and infrastructure industry if cultural heritage is not to be lost.

The Swedish context

In areas where isostatic rebound (land uplift as a result of the melting of an ice sheet, such as in northern Scandinavia) is in effect, the position of former coastlines may often be used as a guide to the maximum potential age of an archaeological site or landscape. With the passage of time, more land becomes available as it rises out of the sea. An archaeological site found at any altitude below the highest former coastline, may thus be safely assumed to be younger than the calculated age of the coastline directly below it. Similarly, the landscape around any site will have evolved over time as more land became available, and access to resources developed accordingly. (Note that this should not be confused with the mistaken assumption that all prehistoric sites were coastal, and therefore any site may be accurately dated by its proximity to a former coastline. People have been active throughout the landscape, from coast to ice or mountaintop throughout prehistory). Land uplift is still ongoing in many regions of Sweden, and is evident today in the historical changes seen in towns along the coast of Norrland - the site of Umeå's medieval harbour is, for example, about 21 km upstream of the current port at Holmsund.

Coastal communities have utilised marine resources for many thousands of years, and Sweden has been no exception. Past coastlines (*historiska strandlinjer*) may contain direct evidence of temporary or seasonal activities such as fishing and hunting. This may include fishing camps, fishing related finds such as hooks or traps or evidence of past coastal settlements. It is important to remember, however, that in an area of land uplift the same area may have subsequently been used for other purposes, now some distance from the coast. The same site might therefore also include evidence of cultivation or animal husbandry. A later phase of smallholder farming could also have cleared or ploughed up, and thus mixed, much of the earlier evidence as well as added their own. To complicate matters even more for the archaeologist, subsequent plantation forestry may also have contributed to the mixing of cultural deposits and the confounding of archaeological evidence. In general, the more intensively used an area, the more difficult the evidence will be to interpret, and thus the more scientific methods should be applied. It may even be difficult to resolve the timing of different forms of landuse, even with radiocarbon dating evidence.

The landscapes which have evolved in Sweden over the last 12 000 years vary considerably, as do the traces of human activity which can be found in them. The archaeological remains include a

multitude of features, including physical constructions in stone or wood, the traces of lost wooden or tent constructions, posthole marks or depressions in the ground where semi-subterranean structures would have been, as well as hearths, pitfall traps, cooking pits and rock art. There are direct indications of agriculture in the form of carbonised or waterlogged seeds of cultivated plants, and indirect indications of landscape change in the form of the pollen of plants which were cultivated or otherwise favoured by human activities. There are also both direct and indirect traces from people's use of the landscape in the form of elevated soil phosphate levels and sediments and stones which show evidence of artificial heating. Although each and every community in the past will have expressed itself differently in terms of the combination of its use of resources and technology, common patterns have emerged through archaeological research. For example, on the basis of the evidence to date, dryer areas of land have generally been preferred for settlement in much of Sweden's prehistory and history. There is, however, much regional variation, and there have been only a limited number of investigations in wetland environments and under floodplain sediments.

Whilst archaeology has traditionally focussed on the limited areas where physical remains have been found, as mentioned above, a more landscape oriented perspective has begun to permeate. This may be associated with a growing awareness of the spatial nature of our present day environmental impacts, but is also the result of decades of interdisciplinary research and development in environmental archaeology. Any archaeological survey or investigation should now be accompanied by an environmental investigation into any nearby peat and lake deposits which may contain direct or indirect indications of activities on and around the archaeological site. Whilst charcoal found in hearths indicates the burning of wood, only pollen and charcoal analyses from waterlogged sediments can show whether the wood was gathered locally and to such an extent that the landscape became more open (Figure 2).

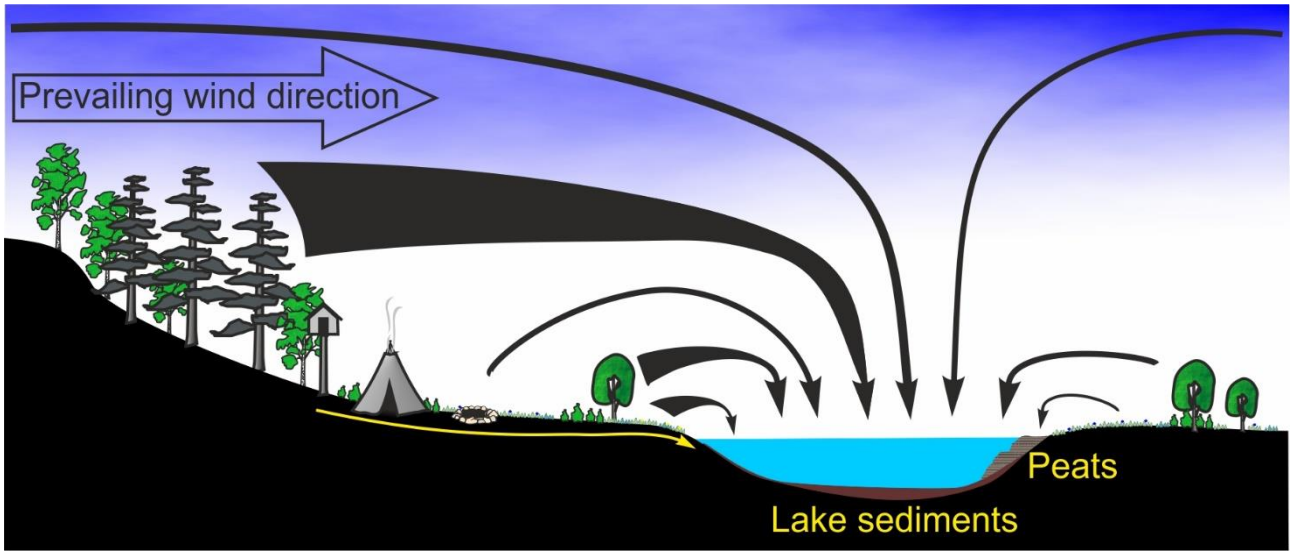

Figure 2. Pollen and plant macrofossils from the landscape around a site, along with microscopic charcoal from burning, find their way into nearby lakes and peat bogs over time. In addition to fossil insects and other organisms, these form the fossil record of environmental change for the area. Similar deposits away from areas of human activity have been essential for building up our understanding of natural climate and environmental change since the Ice Age, and provide the backdrop against which we measure human impact.

Cultural environments in planning

All of the archaeological remains described above are a part of our cultural heritage. They have been assigned different values in Sweden, and are managed through the application of laws and acts which govern the world of cultural heritage. At the time of writing, cultural environments are primarily managed through two laws: the protection of ancient monuments through the Swedish Heritage Conservation Act (*kulturmiljölagen*) and the Swedish Forestry Act (*Skogsvårdslagen*), which regulates remains in forests not considered ancient monuments (see below). The latter are referred to as 'other cultural/historical remains' (*Övriga Kulturhistoriska Lämningar, ÖKL*) and may be considered for protection under the Swedish Environmental Code (*miljöbalken*). For road and rail projects, further aspects of the management of cultural environments are regulated through reference to the Swedish Environmental Code (*miljöbalken*) and the Planning and Building Law (*plan- och bygglagen, PBL*).

In the latest revision of the Swedish Heritage Conservation Act (2014), ancient monuments were defined as remains originating from prior to 1850. County Administrative Boards (*länsstyrelsen*) also have the power to declare younger remains as ancient monuments, thus giving them equivalent protection to older remains. Cultural environmental work is also strongly connected to a number of joint environmental protection objectives (*nationella miljömål*). Several of the environmental objectives have cultural heritage values and are reported on annually (https://www.miljomal.se/Environmental-Objectives-Portal/). In June 2017, the Swedish Government gave ten government authorities, including the Swedish Forest Agency (*Skogsstyrelsen*), The Board of Agriculture (*Jordbruksverket*) and the Swedish Transport Administration (*Trafikverket*), the task of each producing a strategy for cultural environments. This is intended to ensure a more uniform management of relevant issues within and between agencies, as well as strengthen ongoing work with environmental protection objectives.

Sweden currently has two types of cultural history records (c.f. databases). The National Heritage Board's database for archaeological sites and monuments (Fornsök, https://www.raa.se/in-english/digital-services/about-fornsok/), which was created more or less in parallel with the creation of national economic maps (https://www.lantmateriet.se/en/Maps-and-geographic-information/Historical-Maps/More-about-the-archives/Geographical-Survey-Archive/Ekonomiska-kartan/). Managed by the Swedish Forest Agency, the The Forest and History Database (Skog och Historia-databasen, https://www.raa.se/kulturarv/arkeologi-fornlamningar-och-fynd/skogens-kulturarv/skog-och-historia/) has less national coverage. The latter is the result of employment creation schemes which ran from 1990 until 2006 to survey for archaeological remains in woodland areas. Approximately 80% of Sweden's woodlands are as yet not fully surveyed, and it is thus especially important that survey and prospection is undertaken carefully and efficiently in connection with infrastructure and construction projects which transgress Swedish forests.

Overview of remote sensing and geodata in archaeology and cultural heritage survey

Archaeologists have employed remote sensing techniques since the early 20th century, beginning with OGS Crawford in 1920s England, who focused on wartime aerial imagery (Wilson, 1982). In the following years, Crawford and others began photographing the landscape from the air, adapting methods employed by non-archaeological aerial photographers for archaeological purposes. This involved developments in primarily two directions. Firstly, the value of oblique photographs for

showing topography and features too faint to be detectable using vertical imagery, and secondly the recognition of the importance of producing a photographic series of the same landscape under different seasonal and lighting conditions (Cantoro *et al.* 2017).

These techniques developed into staples for archaeologists interpreting the landscape from the air, joined in the mid-20th century by the adoption of photogrammetry (see below) both as a way to survey landscapes and produce excavation records (Kilford, 1970). This development is detailed in Wilson's (1982) handbook, as well as Van Genderen's (1976) roughly contemporary review, and it is unnecessary to repeat their work here.

More recent applications of remote sensing in archaeology have expanded to include satellite remote imagery, airborne laser scanning, and the use of low-flying aerial vehicles, most prominently unmanned aerial vehicles (UAVs or drones). The following sections detail the current concerns in the field, followed by more detailed descriptions of methods included in the evaluation data from Trafikverket.

The use of digital elevation models (DEM) is prominent in both archaeological research and consultancy, and especially in connection with in modelling past human activities and landscapes. Advanced landscape analyses aside, this is perhaps mainly due to the advantages of a 3D landscape image in making a visual appealing and intuitive presentation. However, a focus on visualisation may sometimes be to the detriment of research potential. In particular there is some tendency to underestimate other factors in the landscape, such as empirical palaeoenvironmental reconstructions of past vegetation, and their importance for past peoples. This DEM dominance is most likely at least partly responsible for the prominence of LiDAR as a tool in archaeological prospection and landscape visualisation. This report therefore includes a more extensive description of LiDAR than other methods.

Aerial survey, image processing, and its relationship to ground survey

Recent years have seen a significant increase in the use of remote sensing data in archaeology; Agapiou and Lysandrou (2015) have shown a steady increase in the occurrence of terms related to remote sensing in archaeology from the early 2000s onward. This is due to improved access to aerial imagery and other remote sensing data produced outside the discipline as well as to the emergence of low-cost unmanned aerial vehicles allowing archaeologists to gather their own data at a much lower cost.

This has led to a widespread concern over the impact that remote sensing data has on more established methods of survey, such as theodolite and GPS ground survey, and recording by hand. As survey and excavation drawing is fundamentally interpretive, archaeologists have been at pains to meticulously detail the transcription of fieldwork into archival material (e.g. Roskams, 2001), so that later reinterpretation is possible. For that reason, archaeologists have urged caution about the use of ready-made software packages with automated, 'black box' workflows leading to results without a clear relationship to the underlying data (Rabinowitz, 2015).

In response, a number of recent articles have explored the suitability and caveats of adopting new developments in remote sensing for archaeology. These include Chase et al.'s (2017) survey of LiDAR for the study of archaeological research and historic landscapes; Chen *et al.*'s (2017) review of satellite remote sensing for the same purpose; Nikolakopolous *et al.*'s (2017) review of UAVs for archaeological photogrammetry, and Liang's (2012) review of hyper- and multispectral imaging in

archaeology, as well as comparative studies evaluating the accuracy of a number of methods (e.g. Sadr, 2016).

Some types of archaeological remains are proving more difficult to identify in LiDAR data than others. Krasinski *et al.* (2016) observed a high variability in the detectability of different types of archaeological feature in LiDAR based maps, and that the variability changed with different data quality (see method details later in this report). Larger structures have a higher tendency to be detected than smaller ones, and shape influences detectability. Sites that have been reused for other purposes are usually problematic. Observations from a number of studies internationally, seems to confirm that large, regular features are easier to detect than smaller, irregular ones. However, even some larger remains, such as the foundations of semi-subterranean structures, are also difficult to detect in poor resolution data.

A number of recent volumes aim to provide handbooks and best practice guidelines for the use of remote sensing techniques for the purposes of archaeological research. Sapirstein and Murray's (2017) article outlines a thorough best practice guideline for photogrammetry, for instance, and Sarris (2015) aims to do the same more broadly for geomatic (spatial science) techniques. The EU-funded Arcland project (http://www.arcland.eu/), that ran from 2007-2013, set out to address the imbalance between remote sensing and other archaeological surveying methods, in part by publishing a number of best practice guidelines aimed primarily at LiDAR and aerial photography (e.g. Kamermans, *et al.* 2014; Opitz & Cowley, 2013). Finally, a number of handbooks have been published in the past few years that all aim, to lesser or greater degree, at providing guidelines for adapting current remote sensing techniques to archaeological research, conservation and monitoring (Ch'ng *et al.* 2013; Corsi *et al.* 2016; Masini & Lasaponara, 2017; Masini & Soldovieri, 2017; Tapete & Cigna, 2017).

Multi- and hyperspectral analysis

Hyperspectral imagery has been used in archaeology since the 1990s (Liang, 2012). The technique has been widely used in aerial archaeology to provide a broader range of information about photographed surfaces (Verhoeven & Sevara, 2016). In particular, airborne hyperspectral scanning (AHS) has provided a much wider spectral resolution than has traditionally been available, and has led to a number of articles exploring its uses in archaeology (e.g. Aqdus *et al.* 2012; Cavalli, 2013; Cavalli *et al.* 2013; Kincey *et al.* 2014; Knoth *et al.* 2013). Internationally, researchers have primarily employed Principal Component Analysis (PCA) and vegetation indices to extract information from multispectral bands (Doneus *et al.* 2014). The object of study is predominately vegetation and soil properties, which has led to a much better understanding of crop circles/marks (see below) and other faint surface features with low detectability using optical sensors only capable of capturing the visible part of the light spectrum (Camaiti *et al.* 2017). Multispectral satellite images have been used in Sweden as a tool for identifying and monitoring changes in wetlands (Fröjd, 2006). These studies have highlighted the importance of variation in image quality between different years, and its influence on the delineation of objects on digital maps and thus the modelling of the occurrence of different landuse types. Such analyses are more common in landscape ecology and forestry science, although many of the statistical and image processing tools may be useful in archaeology. Hyperspectral analysis complements the visual analysis of aerial photographs, although their use has yet to become common in Swedish archaeology. Researchers point out, however, that there is still much work to be done in order to quantify and interpret the information contained in hyperspectral imagery, and to relate these to the archaeological features in the landscape (Doneus et al., 2014).

Site monitoring and conservation

Remote sensing has widely been used to detect archaeological sites (Masini & Lasaponara, 2017; Parcak, 2017; Rost *et al.* 2017; Wiseman & El-Baz, 2007). Aside from simply detecting sites, archaeologists have also used remote sensing data to monitor known sites to assess change due to erosion and other factors (e.g. Elfadaly *et al.* 2017; Tapete *et al.* 2013). On a similar note, researchers have used historic imagery of archaeological sites to generate three dimensional models and compared them to models derived from contemporary imagery to assess structural damage and change (e.g. Lazzari & Gioia, 2017). Remote sensing is likely to play an even larger role in future monitoring of sites, as more generations of high precision imagery allow heritage practitioners to monitor large numbers of sites at a relatively low cost (Bonsall & Gaffney, 2016; Rodríguez-Gonzálvez *et al.* 2017).

With damage to archaeological sites and other cultural heritage predicted to increase as a result of climate change (see e.g. Karlsson, 2018), these types of methods are anticipated to continue gain importance in the future.

Automated detection of archaeological features

Western society may be considered as having an over confidence in the capacity for new technologies to solve problems. Archaeology and cultural heritage studies are no exception, and the early days of remote sensing led to a number of calls for the fully automated extraction of information from digital terrain data using algorithms capable of recognizing archaeological features. Archaeologists have begun exploring the possibility of automated site detection and monitoring using a combination of remote sensing data and computational methods, such as GIS-based geoalgorithms (Traviglia & Torsello, 2017). Researchers have found success in predicting the locations of prominent features such as mounds by analysing LiDAR imagery using a combination of morphometric classification, image segmentation, morphological filters and computer vision (e.g. Cerrillo-Cuenca, 2017). Archaeological features are still proving too variable and complex in nature to lend themselves to full automation, but semi-automated or guided recognition has proved extremely useful and time effective (see e.g. Trier & Pilo, 2012 for an example relating to pit features in a forested landscape). Automated surveys should always be conducted in tandem with a field based assessment of the results to appraise their success rate in different circumstances. Different combinations of methods for data collection, post processing and interpretation must be evaluated in terms of the proportion of successfully identified features compared to false positives and missed features.

Automated site detection is still in its infancy, but a recent review is available (Kvamme, 2013), as is a comprehensive reading list as of 2016 (Lambers & Traviglia, 2016). Such systems may be compared to expert systems or decision support systems in any industry, and require a combination of technical skills, good data, reliable algorithms and domain science knowledge if they are to be useful and effective. Examples from the Scandinavian context, particularly in relation to LiDAR data, are discussed below.

The Scandinavian context: survey and analysis methods

Aerial photography, satellite images and orthophotos

Remote sensing has its origins in the use of balloons, followed by airplanes, for observation and mapping, primarily as part of military activities. The capacity to document and communicate

observations exploded with the introduction of the camera in the second half of the 1800s. These overview photographs were most often used to characterise broad structures in the landscape, or to identify specific features or structures. The use of aerial photographs to help produce maps began towards the end of the First World War and developed rapidly between the wars (James, 1972). During this period, orthogonal (vertical or geometrically corrected aerial) photographs (orthophotos) began to be taken with the purpose of extracting detailed and correctly scaled information on the landscape. These photographs allowed differences in vegetation and hydrology to be observed, as well as bedrock, soil type and other subsurface properties to be interpreted from other variation visible at the surface. Aside from military use, much focus was on the mapping of landuse properties in landscapes dominated by extensive agriculture (*fullåkersbygden*), and woodland areas were neglected. At the time, this was not seen as a problem in archaeology, as agricultural areas were considered as representing the vast majority of human activities, past and present. Aerial photography is also limited in its ability to see the ground surface through leaf cover, something which more recent developments in laser based technology have helped to overcome (see LiDAR below).

There is some overlap in the use of aerial and satellite based imaging, and both are now routinely used for visualising and communicating broad scale information on the landscape. Most often the choice between the two comes down to resolution required (aerial photographs are generally of higher resolution), availability (satellite data are already available for the entire world) and data requirements (images outside of the visible spectrum are currently more readily available as satellite images). Some of the highest resolution orthogonal photographs and digital elevation models for more remote Arctic regions are derived from military satellites. The increasing affordability of drone based aerial photography and light, high resolution multi-spectral cameras is, however, contributing to an increasing use of aerial photography at the landscape scale.

Orthophotos were most heavily used in cultural heritage (and other) surveys in Sweden between the 1930s and 1990s. Their use has declined since then as other methods have gained prominence (Törnqvist, 2015), despite a demonstrated relevance for retrieving information on landuse, transportation routes and scarification in areas of plantation forestry (Willén & Mohtashami, 2017). In many cases, the place of orthophotos has been relegated to that of providing background images for field surveys (see e.g. Olofsson, 2016) or when presenting the results of excavations (Ragnesten, 2013). Where the use of orthophotos is asserted, there is often a lack of information on exactly how the images have been used as a source of information (see e.g. Nilsson, 2015). A review of the international literature (see above) indicates that there is much more potential in aerial photography than the locating of easily visible of archaeological sites. In Swedish archaeology there appears, however, to be only limited reflection over the potential for extracting information on cultural environments from the images.

In consultancy and survey reports, the information extracted from orthophotos tends to be focused the observation of physical changes, such as those relating to planning errands and potentially unlicensed environmentally impacting activities. Orthophotos are thus clearly relevant for work on environmental objectives (Länsstyrelsen i Västra Götaland, 2005), and have been used to a greater extent in work evaluating or implementing landscape classification systems (see Noborn *et al.* 2017; and Trafikverket, 2011) relating to the European Landscape Convention (https://www.coe.int/en/web/landscape).

It is possible to derive reliable and detailed information on landuse histories from photographs and orthophotos taken from planes, UAVs and satellites provided images are of sub-metre resolution (i.e. each pixel represents no more than 1 square metre of the ground surface). In general, the higher

the resolution the better, as more features will be resolved. Many archaeological features, such as ditches and walls (or the circular well feature on Figure 3, see below), may be smaller than 1 m and thus potentially not visible on lower resolution images. The resolution problem is mainly an issue with digital photographs and older aerial images should be digitized at high resolution to avoid loss of fidelity. Such resolutions are common on modern digital aerial photographs and there are now a number of satellites which provide at least 1 m resolution (e.g. WorldView-2 and 3, GeoEye-1, Pleiades 1a-1B). A number of these also provide multispectral images at below 5 m resolution, enabling a broader range of image analysis techniques to be applied to landscape studies (Masani & Lasaponara, 2017). The capacity of different surfaces to reflect different wavelengths means that images restricted to different spectral bands (e.g. infrared, near-infrared, visible light) will emphasise different aspects of the landscape. By combining these images it is possible to predict and identify vegetation, landuse and buried features more reliably. Much of this data process can be automated, and the Swedish Land Survey's (*Lantmäteriet*) ground cover data (*marktäckedata, SMD*), now managed by the Swedish Environmental Protection Agency (*Naturvådsverket*), is largely based on this approach in combination with ground based surveys for quality control. It is often advantageous to drape both orthophotos and categorised maps over DEMs to provide for a more intuitive representation of landscape features (Figure 1; see also Frisk *et al.* (2006) for worked examples of how these types of data can be integrated into the planning and visualisation process through the use of GIS).

Figure 3. Aerial photograph of Wild Goose Cottage, Nottinghamshire, England, with crop marks showing indications of the subsurface wall and ditch remains of a Roman farm (as well as the modern field drainage system). The circular feature in the bottom corner of the clear rectangular enclosure (left of centre) is a well which was used in an insect based environmental reconstruction of the area (Buckland & Buckland 2016). (Photograph D Riley DNR 1013/19 - SK7087/13, © English Heritage).

Aerial photo interpretation in archaeology strongly relies on the image's ability to reveal subsurface structures through their effects on vegetation. A soil's ability to hold moisture and nutrients can be

significantly affected by buried archaeology, and these patterns are often most visible in arable fields or grasslands as ‘cropmarks’ (Figure 3). Cropmarks are most often expressed through variation in the size or quality of plants of a single crop (such as wheat); plants growing above a buried ditch may have access to more nutrients and water than those growing above a buried wall, and thus grow taller and more healthily. Subsurface variations may also lead to differences in germination times, or the type of weed assemblage growing within the crops, all of which may be visible from the air. Depending on the type of crop and environment, photographs will need to be taken at different times of the year to be able to capture these variations.

Photogrammetry

The principle of photogrammetry is simple, using overlapping photographs (or video) to provide an image base for establishing the three dimensional coordinates of objects located on at least two images. A large number of images is recommended for producing a high quality 3D model. These images are then loaded into a photogrammetry software package such as Agisoft Photoscan (http://www.agisoft.com/), and a sequence of tasks and calculations performed. These may including the evaluation of imported images, aligning of photos, creation of a point cloud which is then converted into a mesh model, followed by the generation of textures (Agisoft, 2017).

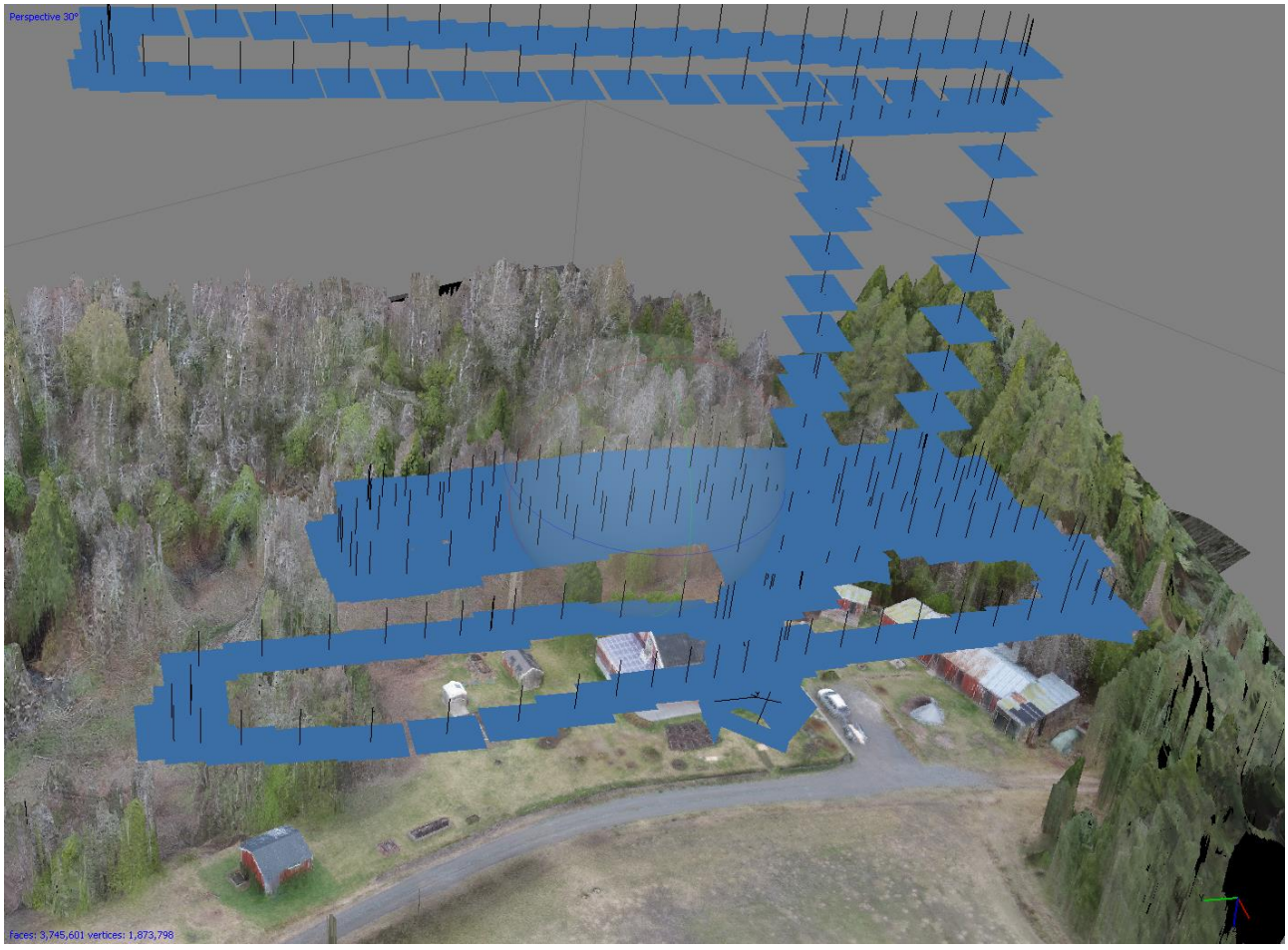

Figure 4. A screenshot of a 3D model of a small farm, with markers showing the position of the drone when it took each photograph that was used to make the model. In this example, the users have clearly made two passes in order to create a separate set of images for high and low resolution modelling (although this probably could have been achieved using software settings and the lower altitude pictures only). Screenshot from Agisoft Photoscan.

To help produce any particular model the results can often be viewed in a number of ways within the original software, often at several stages in the process, such as showing the location of the camera for each component image (Figure 4). Other viewing options for the final model (Figure 5) may include export to an Adobe PDF file (albeit with restricted resolution), uploading to a 3D image viewing service such as Sketchfab (https://sketchfab.com/), or exported as static images. An orthophoto equivalent can often be exported using the model as its source, but although potentially of very high resolution, these may suffer from distortions produced by the mesh and texture model.

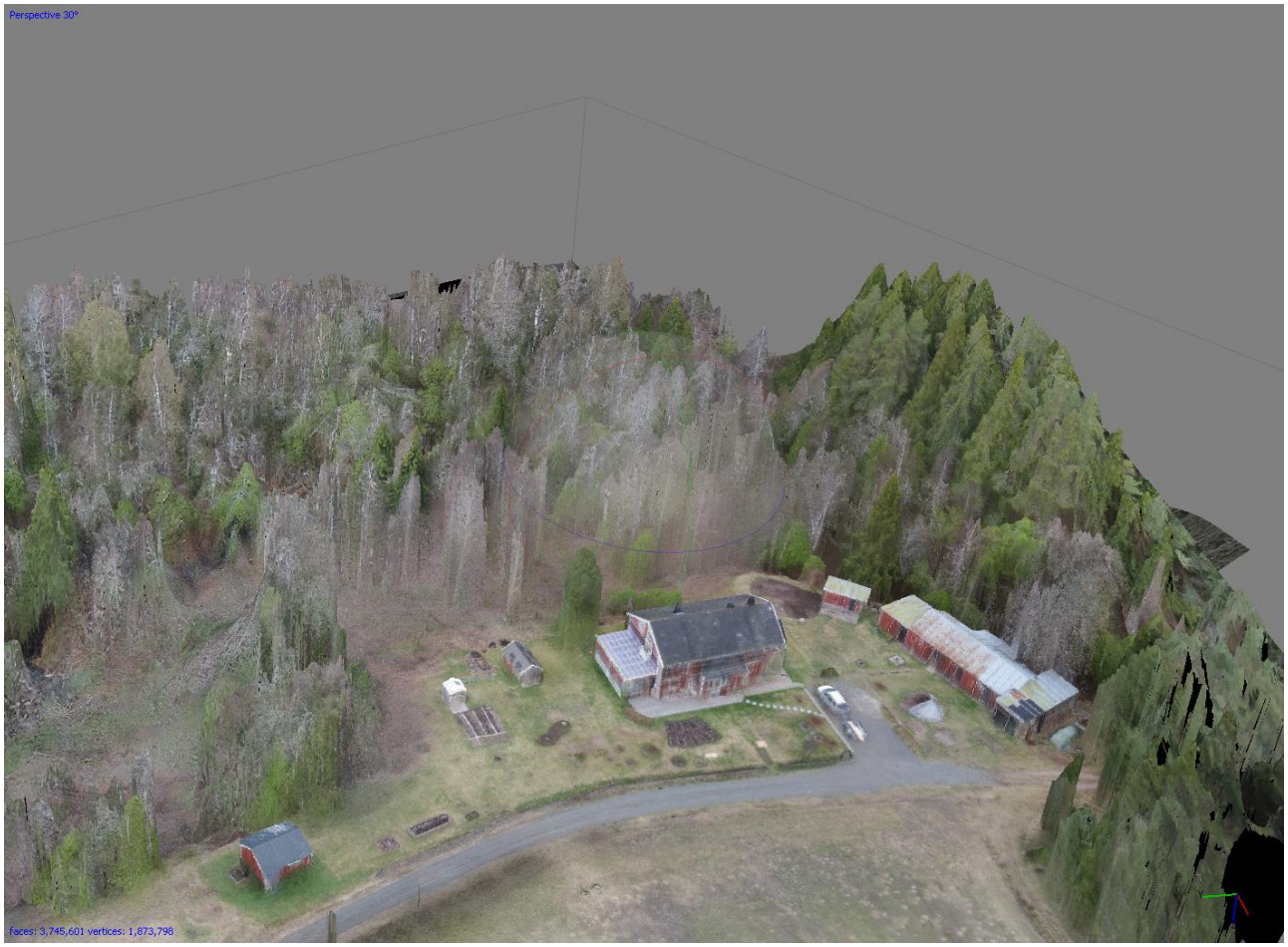

Figure 5. 3D model of a small farm created using photogrammetry. Note that highly complex structures such as trees, as well as vertical surfaces, are poorly reproduced through this technique. Screenshot from Agisoft Photoscan.

Horizontal accuracy can be improved by including at least three (geo)reference points in the area photographed, but vertical accuracy is difficult to refine due to the currently poor vertical accuracy of most drone based GPS receivers. For general landscape analysis and topographic modelling the vertical positional accuracy is most often not important as long as the model is internally consistent, as relative heights are sufficient to investigate an area without connecting it to a national or global model.

The process is simple, and the software reasonably intuitive. However, if there is no time for experimentation, an expert should be consulted prior to its use to ensure appropriate settings are used for the model required and the purpose of the project. It is easy to produce a model with too many points to be viewed in a PDF, for example (i.e. Photoscan will currently export a model in PDF format that is too large and thus cannot be opened in a PDF reader). Model generation may sometimes also enter an extremely slow calculation cycle, or even an infinite loop, and an expert

should be consulted for advice on when calculations should be restarted under particular model circumstances.

Photogrammetry was, until recently, mainly applied to the 3D modelling of artefacts and structures (mainly buildings and standing ancient monuments) in archaeological and cultural heritage applications. The increased affordability, positional accuracy (using GPS, gyroscopes and gimbals for image stability and georeferencing) and flexibility of drones has produced a growth in the use of photogrammetry for small scale landscape modelling in archaeology. At a lower resolution and accuracy, photogrammetry has been used from aeroplanes based aerial photographs to create large scale landscape models, although LiDAR (see below) has, where available and cost-effective, perhaps made this application somewhat obsolete. However, orthophotos are still draped over DEMs based on LiDAR data to give them a more realistic appearance and allow viewers to more easily relate to features in the landscape.

Ground-penetrating radar (GPR) (Georadar)

Ground-penetrating radar relies on the reflection of an electromagnetic pulse from buried objects and surfaces between a ground orientated transmitter and receiver. The return time of the signal is used to model the depth of objects, which can be more accurately measured than other when using other techniques. The resulting radargram (Figure 6 and Figure 7) indicates the strength (amplitude) of signal returns from reflection surfaces, objects as well as patterns from diffractions around objects. It provides an indication of the depth and size of objects which may be worth investigating, some of which may be of archaeological or stratigraphic significance. Note that such surveys can benefit from coordination with laser scanning in order to produce a model which shows radar data in relation to the true ground surface rather than an abstracted horizontal datum. Although a GPR survey can be undertaken from an airplane, ground based surveys, by way of their better accuracy and resolution, are more useful for identifying archaeological features. GPR is also useful when assessing the depth of peats and other organic sediments for palaeoenvironmental sampling, especially where the aim is to locate the deepest or longest possible profile (which often provides the oldest material and longest sequences for analysis).

Although GPR has often been used in archaeological and geological prospection in parts of Europe for over 20 years, it has, as with numerous other prospection methods (see e.g. Clark, 2003), until recently, been little used in Sweden. Its use is becoming more common, helped by a number of factors, including collaboration between the Swedish National Heritage Board (RAÄ) and the Austrian Ludwig Boltzmann Institute (LBI) on the development and marketing of a suite of archaeology specific technology and expertise. Perhaps a limiting factor in the adoption of GPR has been the need for combined geophysical and archaeological training, which has not been available in Sweden. Interpreting radargrams requires specialised software and specialist knowledge, and it is equally unlikely that either an archaeologist untrained in geophysics or a geophysicist untrained in archaeology will be able to reliably predict the location of archaeologically significant structures (e.g. Figure 7). Although standard GPR equipment used for utilities or material surveys may provide some useful results, these techniques are usually of too poor a resolution to be reliable archaeological use.

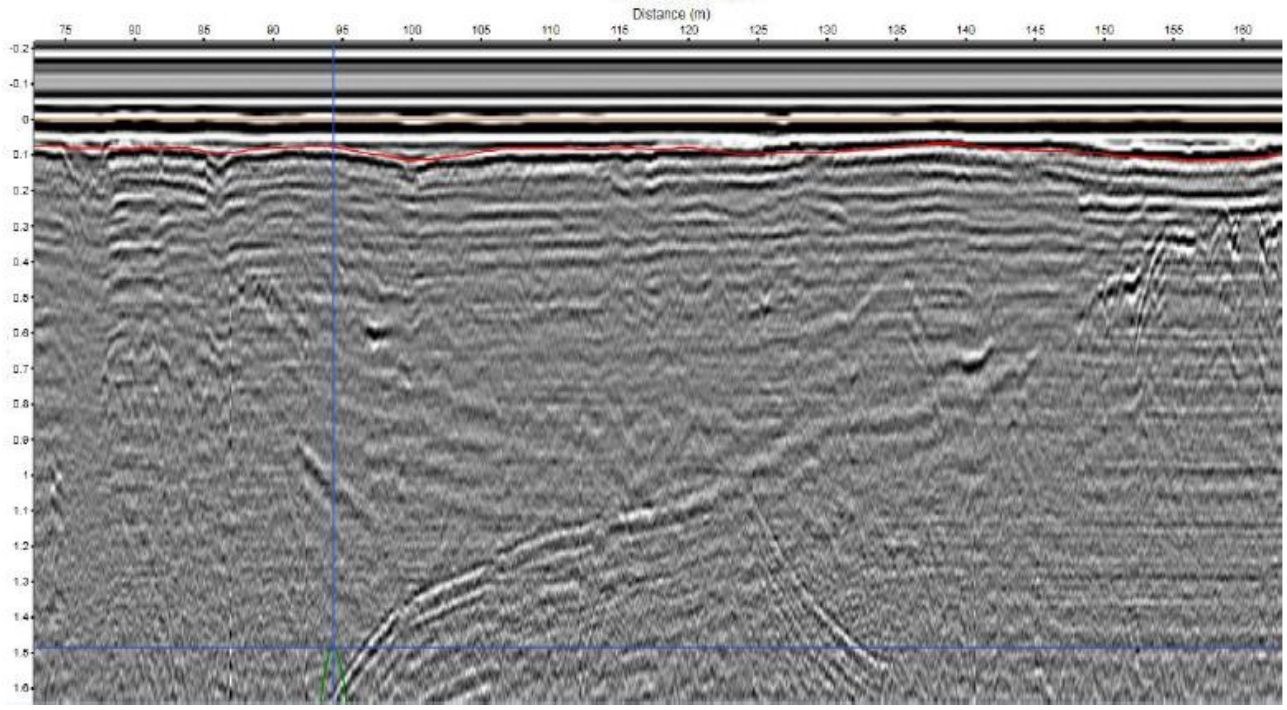

Figure 6. Radargram profile (depth section) from a GPR investigation showing a series of probable older road surfaces underneath the current surface level, as well as possible stratigraphic boundaries deeper down. For archaeological applications it is preferable to combine such transects with a series of horizontal slices (plans) to help understand the changes that have occurred over time at different depths. Archaeological GPR exploration is most usefully undertaken in 3D, using software such as GPR-SLICE (http://www.gpr-survey.com/), ApSoft 2.0 (http://archpro.lbg.ac.at/apsoft-20) (see Figure 7). Image created by Ramböll RST and provided by Trafikverket.

Survey methodology varies considerably between applications, and archaeological use is most often more labour intensive than others. Using either portable wheeled equipment, towed equipment or specially designed vehicles, large areas can be scanned in a single day under favourable conditions. Recent improvements in software design and the increased data management capacity of desktop PS's now allow for GPR data to be explored in 3D in realtime (using software such as GPR-SLICE (http://www.gpr-survey.com/), ApSoft 2.0 (http://archpro.lbg.ac.at/apsoft-20)). This also requires that multiple GPR transects are used, rather than the widely spaced or individual transects more common in projects using GPR for utility scanning or construction projects (Karlsson *et al.* 2016). GPR works best in uniform, sandy sediments (although it also works well in ice), and the utility of the method is heavily influenced by natural variation in sediments. For certain types of soils, and for the investigation of particular types of remains (hard structural remains in particular, or distinctive unconformities in sediments), the method can be extremely effective. Karlsson *et al.* (2016) report the ability to efficiently map up to five hectares per day in sandy and dry soils, where the ground surface is level, free of obstacles and high vegetation.

GPR is most effective then, in agricultural or pasture lands, bare ground or other level surfaces (such as tarmac/asphalt) and more problematic in woodland and areas with less than minimal vegetation or uneven surfaces. Ground stoniness strongly affects the efficiency of identifying cultural influence, and moraine sediments are particularly difficult to work with (Stamnes & Baur, 2018), as are areas where groundwater content is spatially variable. Sediment/material types also affect the effective depth of a GPR survey, and although the method is able to scan deep within the Greenland ice sheet (see e.g. Nobes, 2011), it may only penetrate a few centimetres in wet, clay rich soils due to their high electrical conductivity.

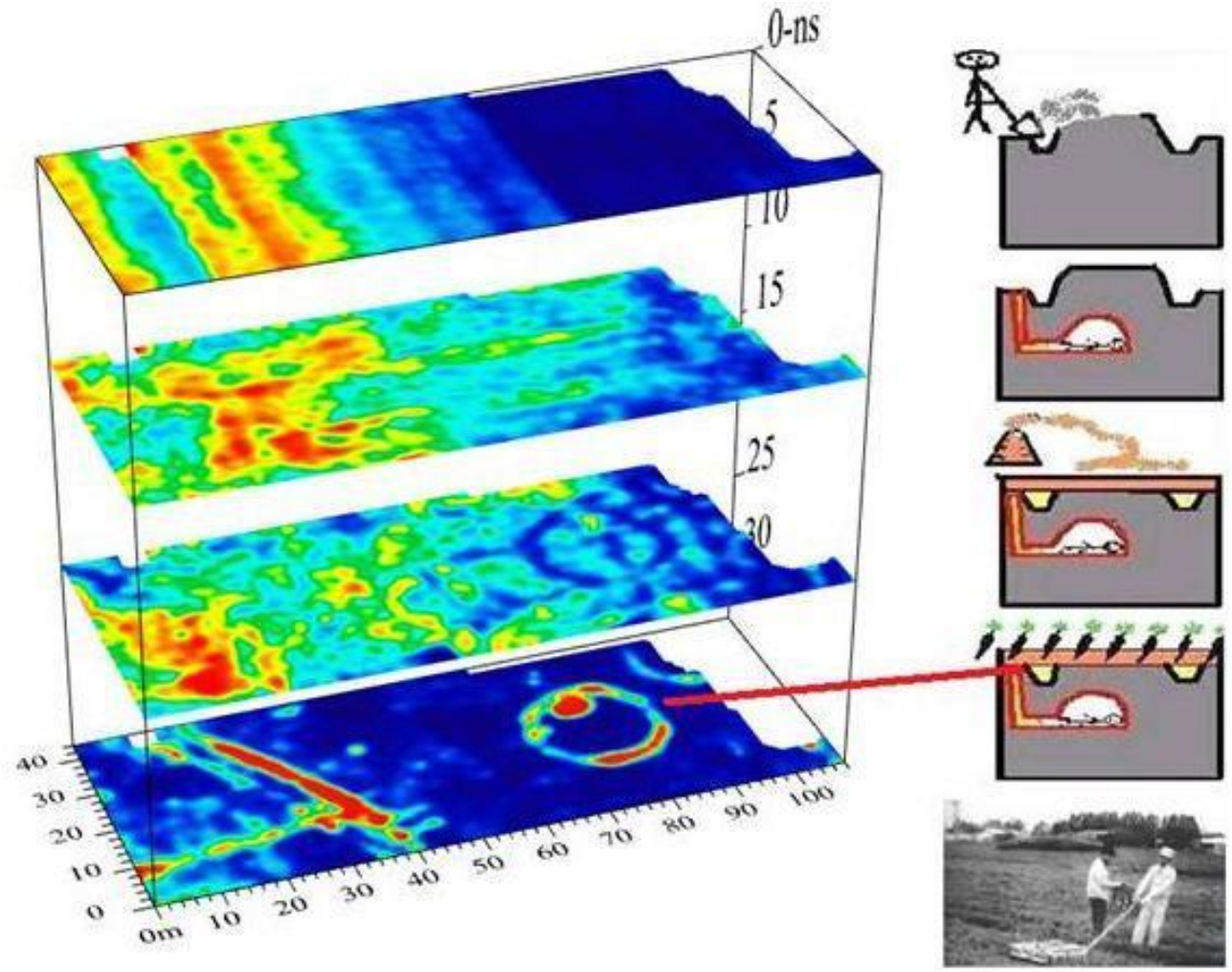

Figure 7. A set of horizontal section (plan) images from the GPR survey of a buried grave with surrounding ditch. A series of pictures illustrate the development of the soil after the grave's construction (on the right, top to bottom). (Image from the website of GPR-SLICE software at http://www.gpr-survey.com/gprslice2.html where further images and videos explaining the use of 3D data can be found).

The resolution of GPR equipment sets a physical limit to the size of object which can be detected - it may be useful to think of GPR results as a 3D grid (in which the spatial units are referred to as 'voxels', rather than pixels), where the grid size sets the limit to detection. Although softer anomalies in sediments may be visible, GPR is most effective when there is a physical contrast (technically an electrical conductivity contrast) between materials. Thus pits and postholes may be easier to detect in hard sediments, but may need to have been filled with stones in order to be detected at all in softer sediments (Stamnes & Baur, 2018).

The above considerations, and especially the different needs between archaeological prospection and utility or construction orientated GPS surveys, are essential when commissioning a GPR survey. It is also essential to consult GPR trained archaeological experts on the appropriate survey type for any particular soil type, and be aware that other prospection methods may be more efficient or cost-effective (such as magnetometer or magnetic susceptibility based prospection, see below) in any given situation. The importance of potential difficulties at the interpretation stage should also not be underestimated (see e.g. Ragnesten 2013), and expert knowledge will always be required to integrate GPR results with other forms of prospection and sampling.

Laser based terrain data (LiDAR/laserdata)

LiDAR, is a laser based technology for measuring distances, allowing differences in elevation to be read from a surface, and thus the creation of 3-dimensional models of a landscape, as well as information on the vegetation which covers it. Laser scanning can be undertaken from airplanes, helicopters, vehicles or drones. Underwater LiDAR is an emerging technology used to map sea, lake and river beds, which could have future applications in archaeological site discovery. Hand or tripod based laser scanners are also available for working with smaller objects or surfaces (such as artefacts or rock carvings). Laser scanning is alternatively named as LiDAR (Light Detection and Ranging), ALS (Airborne Laser Scanning) or TLS (Terrestrial Laser Scanning). The production of a final product, often in the form of a digital elevation model (DEM), is a multistage process: Raw data is collected, most often from the air, by firing laser pulses at the ground and collecting the reflected signals into a so called 'point cloud'. The points, which represent points of reflection, are then classified and filtered to separate those representing the ground surface and other types of object. The filtered data are then interpolated for the production of a DEM, which is most often presented as a raster file (e.g. TIF) or TIN (Triangulated Irregular Network). This final product is then interpreted through a combination of manual and automated processes, details of which are explained below.

The choice of method at each stage in the above process will have consequences for the final result, both in terms of its appearance and possibilities for interpretation. It is essential, therefore, that method choices are always made in the context of local terrain conditions in combination with the research questions under consideration (Fernandez-Diaz *et al.* 2014; Doneus *et al.* 2007; Chase *et al.* 2017). Each point in the cloud is a 3-dimensional coordinate with an intensity value (see below) for a point of reflection, which may or may not represent the ground surface. The greater number of laser pulses used, the greater the probability of at least one pulse hitting the ground surface. A return signal may include reflections from the ground and vegetation which are filtered and classified into groups such as vegetation, structures, water and ground. Often, where only elevation data is required, the data may be classified as either 'ground' or 'other' points.

By simply applying and adjusting hillshading (i.e. creating shadows by simulating oblique lighting over the surface) to a LiDAR based DEM, any number of known or unknown archaeological features can be accentuated. The method can thus make archaeological field survey more efficient by helping to identify potentially interesting objects before fieldwork is undertaken. Laser scanning is a tool used at several different levels in archaeology and cultural environmental studies. It is used as a basis for regulatory inspection (*tillsyn*), investigations, surveys and research. It is used in forestry as a tool for measuring productivity, but also when planning activities to help reduce their impact on cultural heritage. In Dalarna, LiDAR has been used as part of the basis for mapping shielings (*fäbodar*) and to assess the state of knowledge before large scale changes in, or consolidation of, forestry estates. Further examples are provided below.

Although laser scanning is becoming increasingly common in archaeology, it has a number of limitations which should be considered when planning projects and using the data. It is important to remember that different types of remains are more visible than others in the LiDAR data, and that a number of factors can affect the capacity of the data to reveal different types of object. Different types of ground surface, such as blocky moraine, make it more difficult to spot archaeological features. The method works best for remains with a regular structure and distinctive height or depth which deviates from the rest of the surface. Larger features are generally easier to detect than smaller ones, which may be lost in the noise of the surrounding data. It is also not always possible to distinguish naturally occurring anomalies (such as the scars from uprooted trees) from features made by people. Filtering algorithms may also remove these smaller features from the surface model if they interpret them as noise or consisting as non-surface points. The time of year at which an area

is scanned is also important, as thick, leafy, vegetation reduces the amount of pulses which reach the ground.

In other words, LiDAR is a very useful tool for aiding archaeological survey, but it does not replace the skills of the archaeologist. Ground truthing, i.e. field survey to investigate features highlighted by the LiDAR data, will always be necessary. It is therefore important that archaeologists experienced in the use of LiDAR are involved in the planning of any new data scanning exercise where cultural heritage survey is one of the aims, and that archaeological field personnel are aware of the uses and limits of the data when using them as the basis for survey.

Quality control of existing cultural heritage information

A significant problem with the National Heritage Board's database for archaeological sites and monuments (Fornsök) is that of geographically incorrectly located sites. (Note that similar problems exist with the national monuments records of many other countries). In many cases, sites marked as points or areas are in reality somewhere else from where, or considerably larger than, they are shown in the database. This is especially a problem with older site registrations, where the accuracy of GPS equipment was poor or other positioning methods were used.

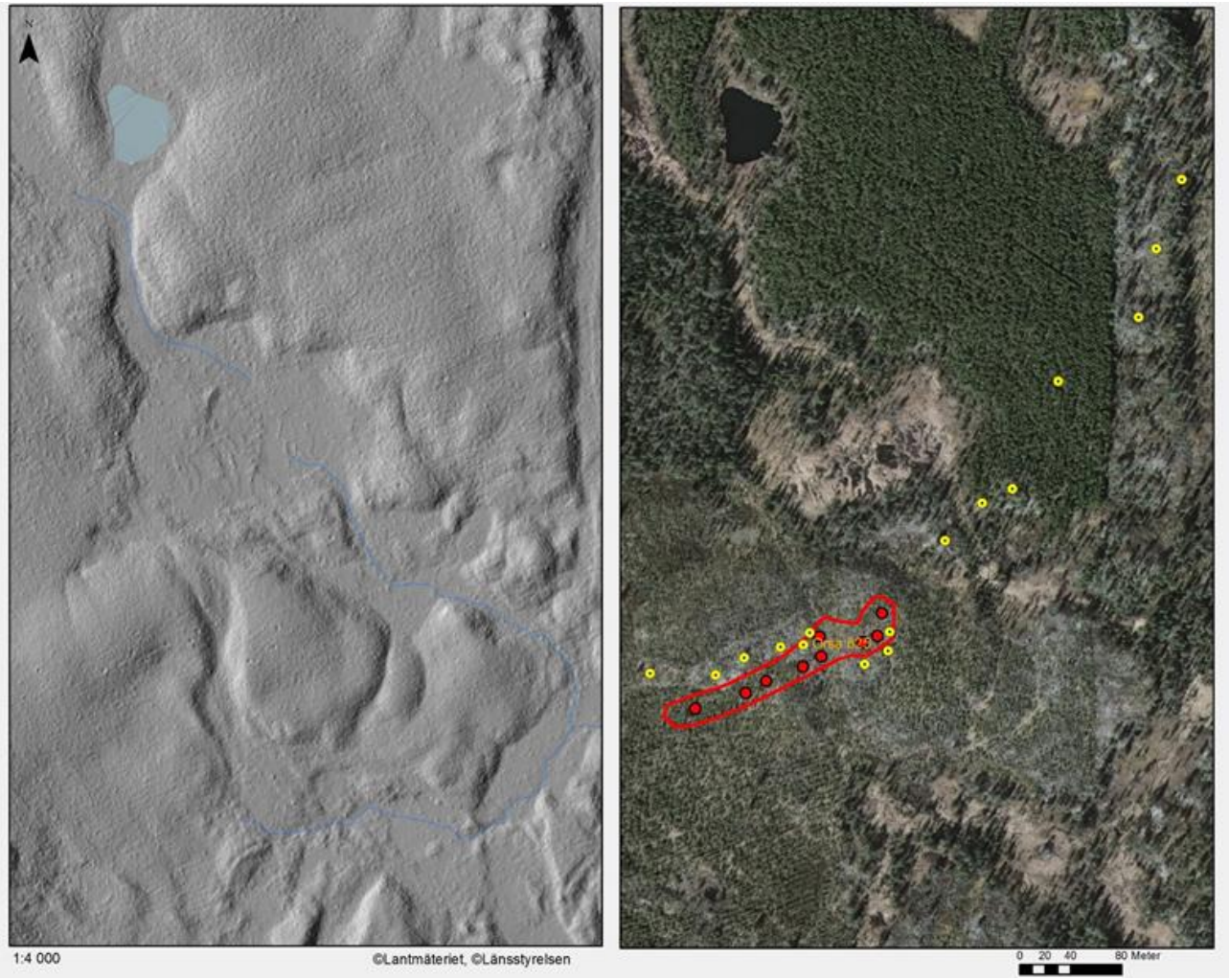

Figure 8. On the right, red dots and areas indicate the registered location of the pitfall trap complex Orsa 625. Yellow dots show the actual positions, based on LiDAR data (left panel), as well as a number of previously unidentified potential traps (Alexander, B. 2014a).

This can lead to problems for archaeologists in the field, wasting time looking in the wrong place, and creating frustration which may lead to further errors. It can also lead to potentially costly discoveries in construction projects that were planned to miss an area of archaeological interest that was incorrectly located. Forestry machinery may also damage archaeological sites if their GPS information includes incorrect locational data. Laser based data can be used to help check a large proportion of these sites. It can be used to investigate discrepancies between what is registered and what exists (Figure 8), help clarify the descriptions of earlier surveys, and even help discover new sites that have not been located through earlier field surveys (Figure 9). Although never a failsafe method, as it is not always possible to relate older field survey notes to specific objects seen in the laser data, the use of LiDAR can improve the efficiency of cultural heritage investigations.

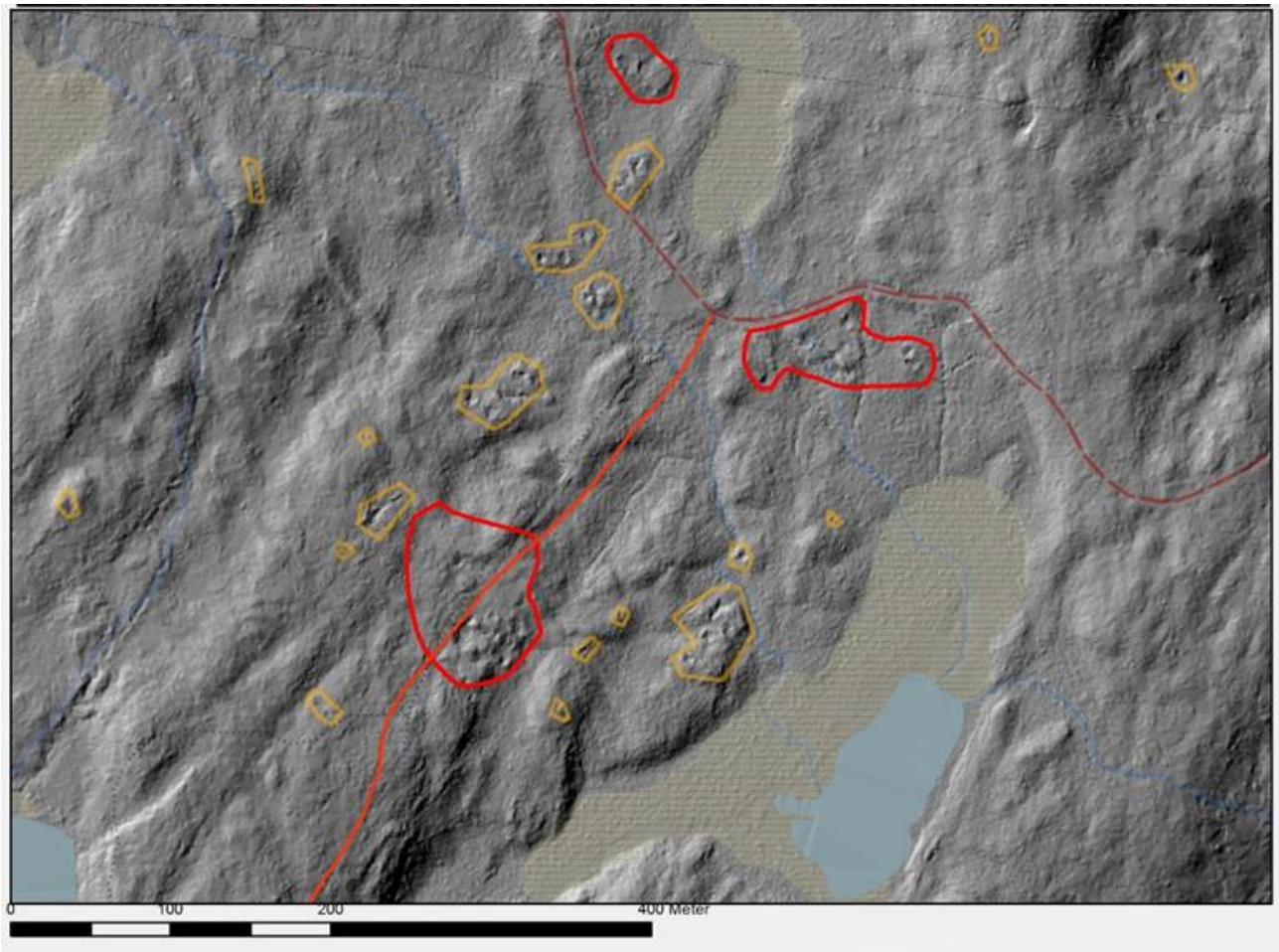

Figure 9. A historic mining area near Tuna-Hästberg in Borlänge, Dalarna. Registered sites are marked in red, including Dammsjögruvan (Stora Tuna 723:1). Several other unregistered mining sites can be identified in the LiDAR image, marked in yellow, and the ancient trackway Stora Tuna 835:1 can be seen to be incorrectly marked towards the north (orange line).

Using laser data in archaeology and cultural heritage

A brief overview of the methodology for locating archaeological remains using raster maps derived from LiDAR data is provided below. Further summarised discussions of laser data based survey methodology and its use in archaeology can found in the Norwegian *Håndbok, bruk av luftbåren laserskanning (lidar) i arkeologien* (Risbøl & Gustavsen, 2016) and the Swedish *Fjärranalys för kulturmiljövården Steg 2: Rekommenderade derivatprodukter och produktionsmetoder* (Törnqvist, 2015).

Surface visible archaeological features are identified by looking for deviations from the natural form of the ground surface. The most common method for locating potential archaeological sites is visual examination after the application hillshading (also called terrain shadows, *terrängskuggning*). This requires the raster data to be converted into a 3D model using the raster's grayscale elevation values. This model is then illuminated to simulate incident light, the angle of which is adjusted through the altitude and azimuth (direction) properties of the light source as well as its intensity. Anomalies in most terrains, including many archaeological features, pits, trenches and raised areas will then be highlighted with light and shadows. In general, a lower altitude of the light source will produce longer shadows, and a more intense light will create sharper shadows, but the implementation of these properties may vary between software packages.

Asymmetric features may benefit from experimenting with illumination from different directions, although the capacity to do this in real time will depend on the software and computing power available. The incident angle is extremely important for revealing landscape features, as some, such as pathways and other linear features, will not be visible at angles which do not cause them to create shadows (Figure 10). Long and dark shadows may also lead to other features becoming lost in the shadows of other objects or geographical features. Multiple hillshade (or multi-directional hillshade) attempts to solve some of these problems by creating several hillshade models and overlaying them (Figure 11). Alternatively, the user can create multiple models and switch between them during analysis. Different levels of transparency between models and the overlaying of orthophotos and other data may also help interpretation. Vertical exaggeration (z-value) of elevation models is also often useful for making features more visible, as well as providing more visually attractive models for presentations.

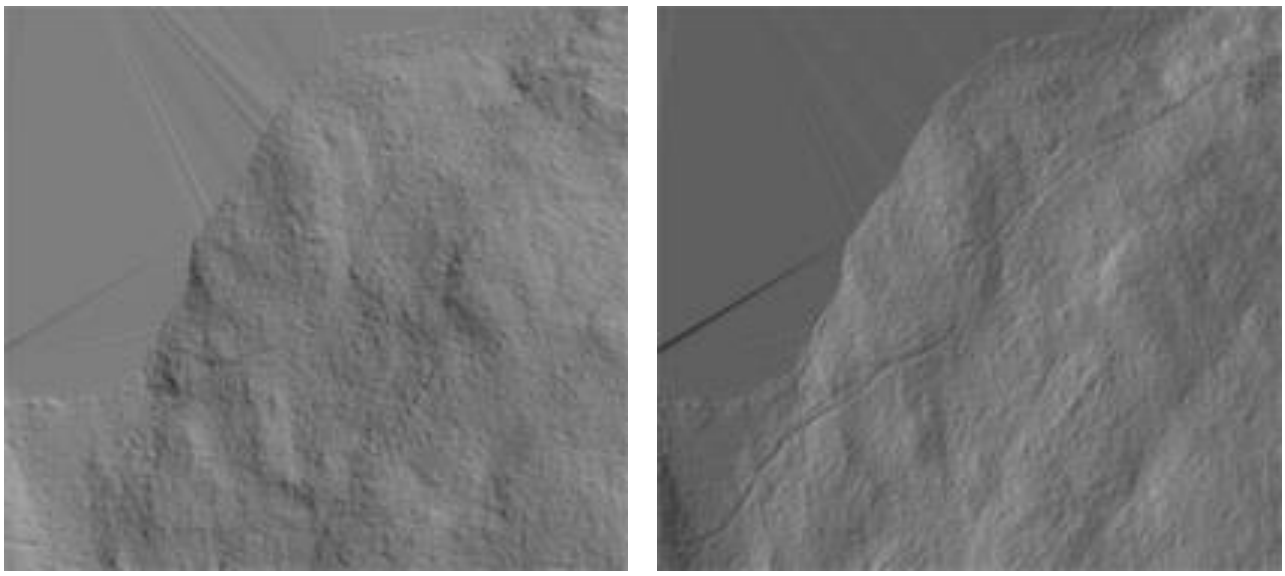

Figure 10. Two different hillshade settings and a shieling pathway in Leksand County, Dalarna. The visibility of the pathway, which runs diagonally from bottom left to top right, is much clearer in the right hand panel (Jansson, et.al 2009).

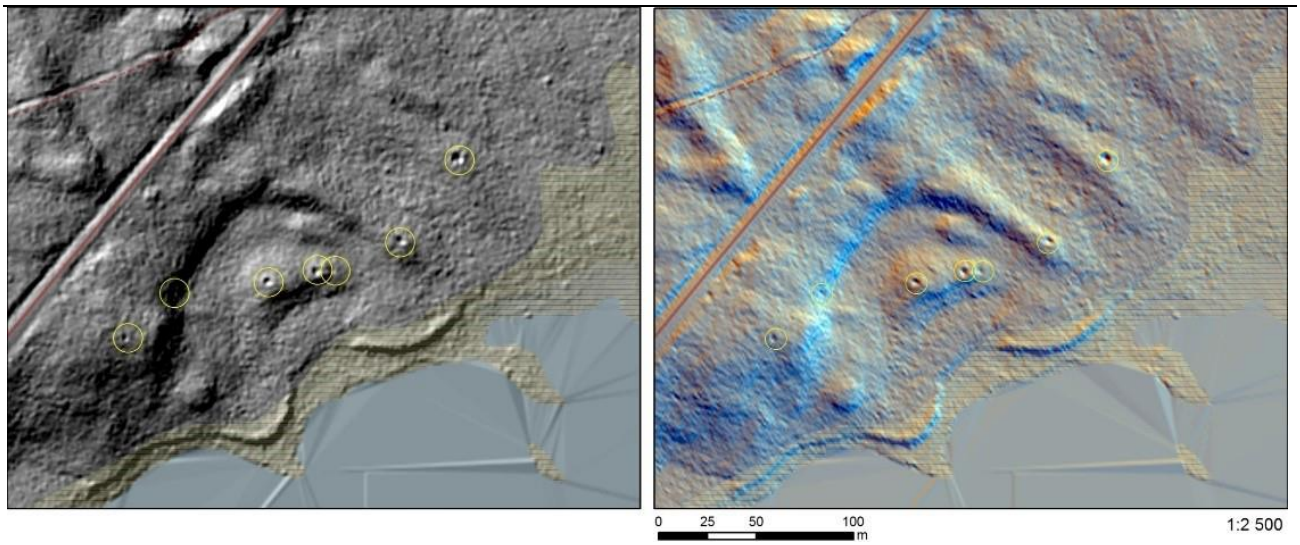

Figure 11. Hunting trap/pitfall trap system Älvros 252 near Sveg, Härjedalen, with pits marked by circles. The left panel shows the application of Hillshade (HS) and the right hand panel Multiple Hillshade (MHS). The deep shadows of the HS image have been eliminated in the MHS image, making the identification of features easier (Willén & Mohtashami, 2017)

A number of other functions or parameters are also available for manipulating raster images and 3D models, including Sky View Factor, Positive Openness and Negative Openness. Although it is not difficult to experiment with different processing techniques and settings, comparing and combining the results to help interpretation, much experience is required to use these efficiently. Certain settings work best for particular types of landscape and for particular types of remains. Multiple Hillshade, for example, can make it more difficult to distinguish between positive and negative vertical differences (e.g. mounds versus pits, ridges versus ditches). This in turn may make it more difficult to visualize an object in its landscape context.

As mentioned above, it may be advantageous to combine LiDAR data with other geodata. Historical maps are routinely used in archaeological investigations, and are particularly useful for helping to locate, identify and understand features in archaeological and other cultural heritage or landscape analyses. These maps, being hand drawn, are almost always difficult to fit to modern maps, needing to be rectified to fit to real-world coordinates and projections. Whilst this requires a number of identifiable reference points (at least three, but often many more) to relate the map to modern geography, overlaying LiDAR data may help locate features common to the historical and modern maps. This is often useful when locating features such as clearance cairns, abandoned pathways or ancient field systems and boundaries.

Archaeologists now routinely work with GIS and should thus be able to at least use raster maps produced from LiDAR data. Raster image data (e.g. TIFF format) is probably the most useful format for the majority of archaeological users. Raster data is most often produced from raw LAS data or processed DEM data formats. The most common software systems used are ESRI's ArcGIS, the open source Quantum GIS (QGIS), Quick Terrain Modeler, Relief Visualization Toolbox (RVT) and LASTools. A small number of archaeologists work in CAD software, but this is becoming increasingly uncommon due to the greater usability and generally lower cost and learning curve of GIS software. Few archaeologists have the skills to manipulate raw point cloud data, and it is thus extremely important that conversion into more common formats is undertaken in such a way as to maximise the potential for locating archaeological remains. Consultation with archaeological LiDAR experts is therefore required at all stages.

Vegetation and filtering of surface points

The time of year at which a laser scan in undertaken will strongly influences its results. To maximise the potential for using LiDAR data in archaeology, the scan should be undertaken when there is as little vegetation cover as possible, i.e. when trees and bushes are leaf free and when understory vegetation is minimal. The flying height of the scanning aircraft can also significantly affect vegetation penetration. Of course, the area also needs to be snow free to ensure that surface features are clearly visible (although note that aerial photographs taken with a light snow cover can often help highlight archaeological features). With this in mind, it is important to realise that as the majority of LiDAR data is scanned for purposes other than archaeological investigations, it some of it may have been obtained under conditions which are sub-optimal for archaeological purposes.

It is thus extremely important that the vegetation, time of year, forest structure and age etc. are well documented at the time of the scan and transmitted to the archaeologists to inform their interpretation. Good background information is essential for the archaeologist to predict the potential differential visibility of different types of remains in different types of landscape. The optimal landscape for laser scanning, as for many other prospection methods, is open ground with low vegetation. Sparsely wooded pine heath (*tallhed*) has also shown to give good results. A landscape with distinctive elevation differences, slopes and blocky moraine results in fewer LiDAR surface points and is thus more difficult to interpret. Spruce woodland (*granskog*) can, depending on its composition and structure, have a negative effect on the number of laser pulses which reach the ground surface. Deciduous woodland may also be problematic, especially when leaf cover is extensive. Vegetation affects the classification and filtering of the point cloud. Archaeologist are mostly interested in points classed as ground surface reflections, and should be aware that errors occur and that their frequency is strongly influenced by vegetation. For example, a dense undergrowth that has been incorrectly classified as ground surface may be misinterpreted as clearance cairns or graves.

Conversely, filtering may remove archaeological features if the algorithms involved regard them as anomalies or incorrectly classify them as vegetation. This type of processing artefact is prevalent in Lantmäteriet's LiDAR based elevation data (the national elevation model). Reservoir dams, dry stone walls (Figure 12) and burial mounds are filtered out if they are too prominent or if they are interpreted as vegetation. Objects which clearly deviate from the ground surface are often classified as non-surface, and objects with a smooth transition to the ground surface are usually classified as ground. A clear example of this problem is provided by the data for the burial cairn Grundsunda 40:1 in Ångermanland (Figure 13). The cairn is 12 m in diameter and 2 m high, and although it has a smooth transition to the surrounding ground surface, it would be expected to be easily visible in the LiDAR data. However, parts of the cairn are incorrectly classified as non-surface, making it more difficult to detect in the elevation data (Alexander, 2016).

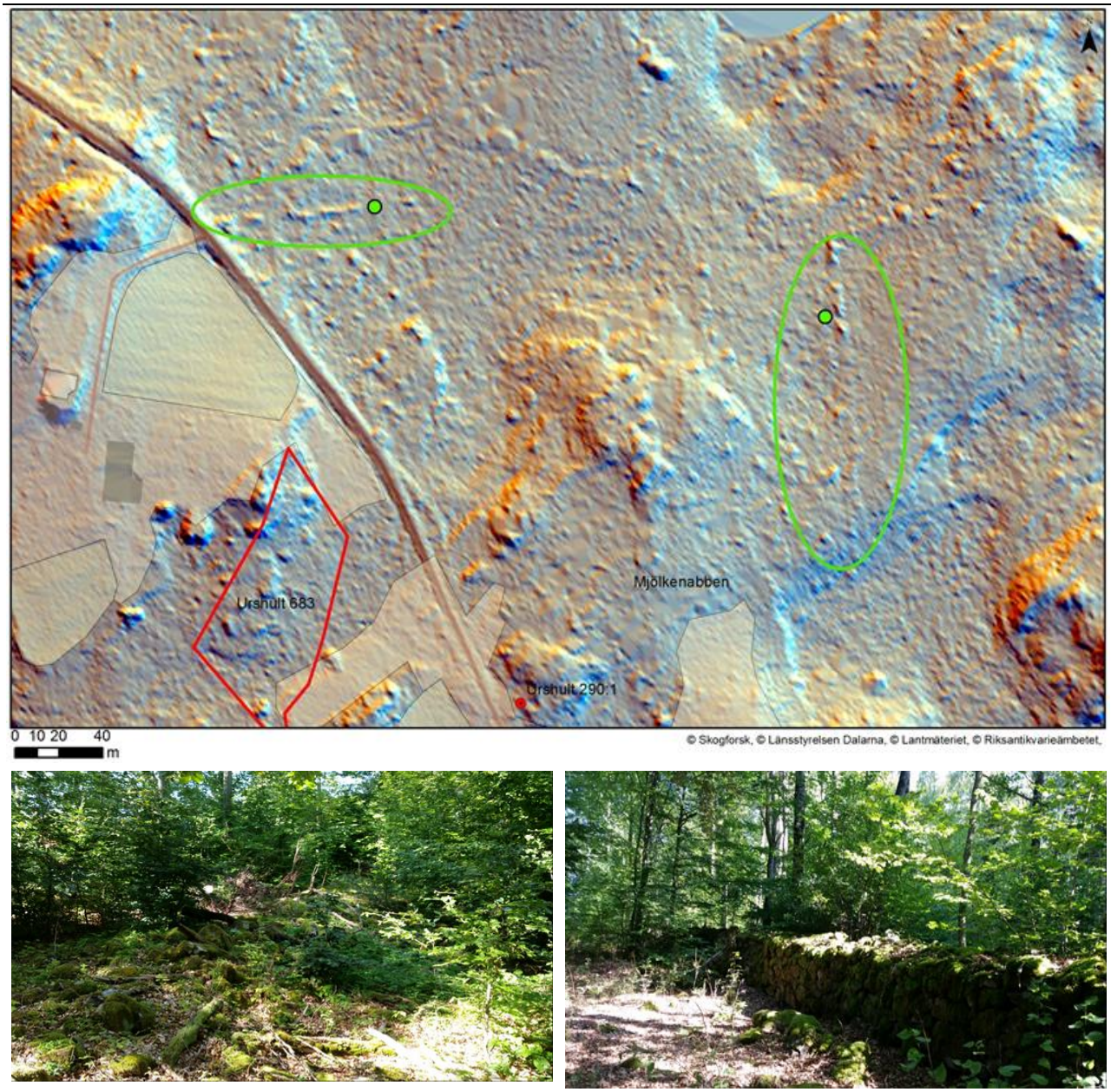

Figure 12. Example showing two dry stone walls in the same landscape, Tingsryd municipality, Kronoberg. The wall in the right hand photograph, marked by the right hand photography point and highlight on the map, is clearly visible from the ground but has been filtered out in the LiDAR data. The collapsed and partially vegetation covered wall to the left is, on the other hand, more clearly visible in the LiDAR data. (This example was produced as part of the Skogforsk project 'Kartering av fornminnen i skogen med fjärranalys". Images from a presentation by Alexander,(2016).

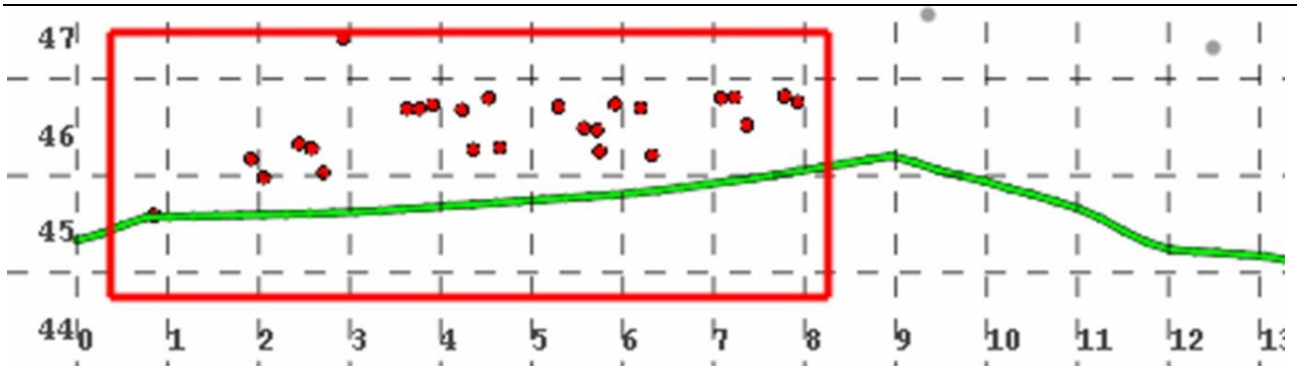

Figure 13. LiDAR points (red) and ground surface model transect from the burial cairn Grundsunda 40:1. The red points are considered by Alexander (2016) as having been incorrectly classified as non-surface, and are most likely reflections from the surface of the cairn. The filtering of points has thus lead to the cairn being less visible in the LiDAR based map. (Image source: Alexander, 2016).

Vertical surfaces, such as the faces of walls or buildings, are problematic for LiDAR as laser pulses transmitted from above are rarely incident on them (a similar problem as for airborne photogrammetry). In a point cloud, therefore, buildings will be seen only as points representing the roofs. Smaller objects with vertical faces, such as dry stone walls, runestones and standing stones, may also be automatically classified as non-ground and thus removed from the ground surface model.

Another common filtering related problem is the automated classification of clearcutting by-products in forestry. Piles of branches and treetops ('*grot*' or '*grenar och toppar*' in Swedish) may be incorrectly classified as ground surface, and subsequently interpreted as archaeological remains such as clearance cairns. Comparison with the Forest Agency's harvesting records and aerial photographs is therefore recommended when interpreting data from forest plantation areas. Similarly, the top of agricultural crops may be classified as the ground surface and thus lead to an incorrectly elevated ground surface in the DEM.

LiDAR has been most frequently used in more open landscapes, but a number of studies have been undertaken to evaluate its potential in woodland and more densely vegetated landscapes (see e.g. Risbøl *et al.* 2013, Krasinski *et al.* 2016, Magnoni *et al.* 2016, Fernandez-Diaz *et al.* 2014). The archaeological potential of a DEM can be improved by varying data collection and post-processing methods. Strategic planning of flight routes in terms of time of year, scanning angle, laser beam divergence and overlap between transects can increase the number of ground returns per square metre (see below).

Return pulses can currently be registered in two different ways. The most common method is by using 'discrete echo scanners', which generate a number of discrete echoes from the intensity of the return pulse. Each pulse often results in 1 to 4 echoes. The alternative to this is full-waveform laser scanning (FW), where the analogue waveform of the return pulse is digitised and considerably more information retrieved. Experiments with FW scanning have shown that the method has potential for allowing a more reliable filtering of ground returns, especially in areas with dense, low, vegetation. The method also appears to be better for detecting very low (down to 20 cm) features (in a study using 8 ppsm and a beam density of 30 cm) (Doneus *et al.* 2008).

From an archaeological perspective, the correct classification of ground surface points is the most important aspect of filtering the point cloud. A number of methods have been developed, and they can be divided into six categories: surface-based, morphology-based, TIN-based, segmentation-based, statistical analysis and multi-scale comparison (Chen *et al.* 2017). For the best possible

results, the choice of method must be made with reference to the study's purpose or research questions and the type of terrain or landscape being scanned (Chen *et al.* 2017, Grilli *et al.* 2017, Fernandez-Diaz *et al.* 2014).

Point density (punkttäthet)

Point density (PD), the number of laser data points per square metre (ppsm), is probably the most important parameter in the use of LiDAR for archaeological purposes. Quite simply, the lower the point density, the more difficult it is to interpret the data. A higher point density may compensate for other problems in identifying ground points, such as the influence of vegetation. The possibilities for producing a high fidelity, high resolution, DEM is thus contingent on the capacity of the data to deliver a high density of filtered ground points. The latter is dependent on the number of laser shots/pulses per square metre (which is dependent on a number of factors, including the laser pulse repetition frequency (PRF), their penetration to the ground and reflection to the detector. Penetration of any single shot is dependent on the scanning angle, intensity and beam divergence (or beam footprint, how much the diameter of the laser beam increases in size with distance from the emitter). In an area of dense vegetation, however, a higher PRF may not necessarily lead to a higher density of ground returns; a lower PRF with a higher intensity per shot and/or a greater beam divergence may prove more useful (Magnoni *et al.* 2016). Overlapping flight transects for data collection also give a higher effective point density, and have the added benefit of illuminating the landscape from different angles and thus increasing the probability of hitting the ground surface (Fernandez-Diaz *et al.* 2014).

In Sweden, the majority of LiDAR based archaeological surveys currently use Lantmäteriets elevation data from the national scanning project. These data are easily accessible, free for non-commercial and state use, and cover almost the entire country at a uniform quality. Although undoubtedly useful, as some of the examples in this report illustrate, these data have a low point density for archaeological purposes, and if better data are available (such as those created within Trafikverkets projects) then they should be used. Lantmäteriet's data generally has a point density of 0.5-1 ppsm, although occasional areas of lower density can be found. Where overlapping transects occur a higher effective point density may be noticed which could improve the possibilities for detecting archaeological features in those areas.

Studies in Norway suggest that a point density of 5 ground ppsm may be optimal for archaeological use in Scandinavia. Risbøl *et al.* (2013) showed a considerable increase in the possibilities for identifying cultural heritage objects and archaeological features by increasing the point density from 1 to 5 ppsm. Increasing density from 5 to 10 ppsm gave no significant improvement, but could allow for the identification of smaller features if they are not covered by vegetation. Improvements were most evident when identifying features with regular forms, whereas irregular objects were still difficult to identify even at high point densities (Risbøl *et al.* 2013).

Interpolation and generation of Digital Elevation Models (DEMs)

A DEM represents a continuous surface generated from point observations. As with other aspects of LiDAR data processing, there are numerous algorithms for converting the point data into a surface. This process is called interpolation, and is a common form of geoprocessing, or spatial statistics, used in many applications from modelling landscapes to analysing and presenting phosphate or magnetic susceptibility data. The algorithms use either an equation to predict the values of spaces between points, or create a model based on the relationships between observed values. The choice of appropriate model will influence the visibility of different features, and depend on terrain type and research questions. However, as a LiDAR survey can be considered as having sampling points almost uniformly distributed over a real world surface, the choice of interpolation method is less

important than when dealing with other more stochastic forms of sampled data (such as soil samples or total station survey points). Interpolation methods may in particular affect the smoothness, accuracy of peaks and troughs, and sharpness of boundaries in a DEM. In a raster model, each and every pixel may or may not represent the exact value of an observed point. The accuracy of such an interpolated surface may be tested by examining its deviation from the observed points. In a simple TIN model, however, every observation is represented by its value, but distinct triangular structures are often visible in the surface.

Agricultural land and ploughed-over buried features

By exaggerating the vertical axis (Z-value), i.e. enhancing the elevation values, of a DEM, more subtle landscape features can often be more easily visualized. This is especially useful in flat, open environments, such as agricultural fields or smoothly rolling landscapes. Some shallow features are not visible in the field, and so exploration of LiDAR data provides a considerable advantage when predicting their location. Additional processing, in terms of experimenting with hillshade settings, using multiple hillshade, and highlighting gradients (slopes) may be necessary in order to reveal small differences in elevation.

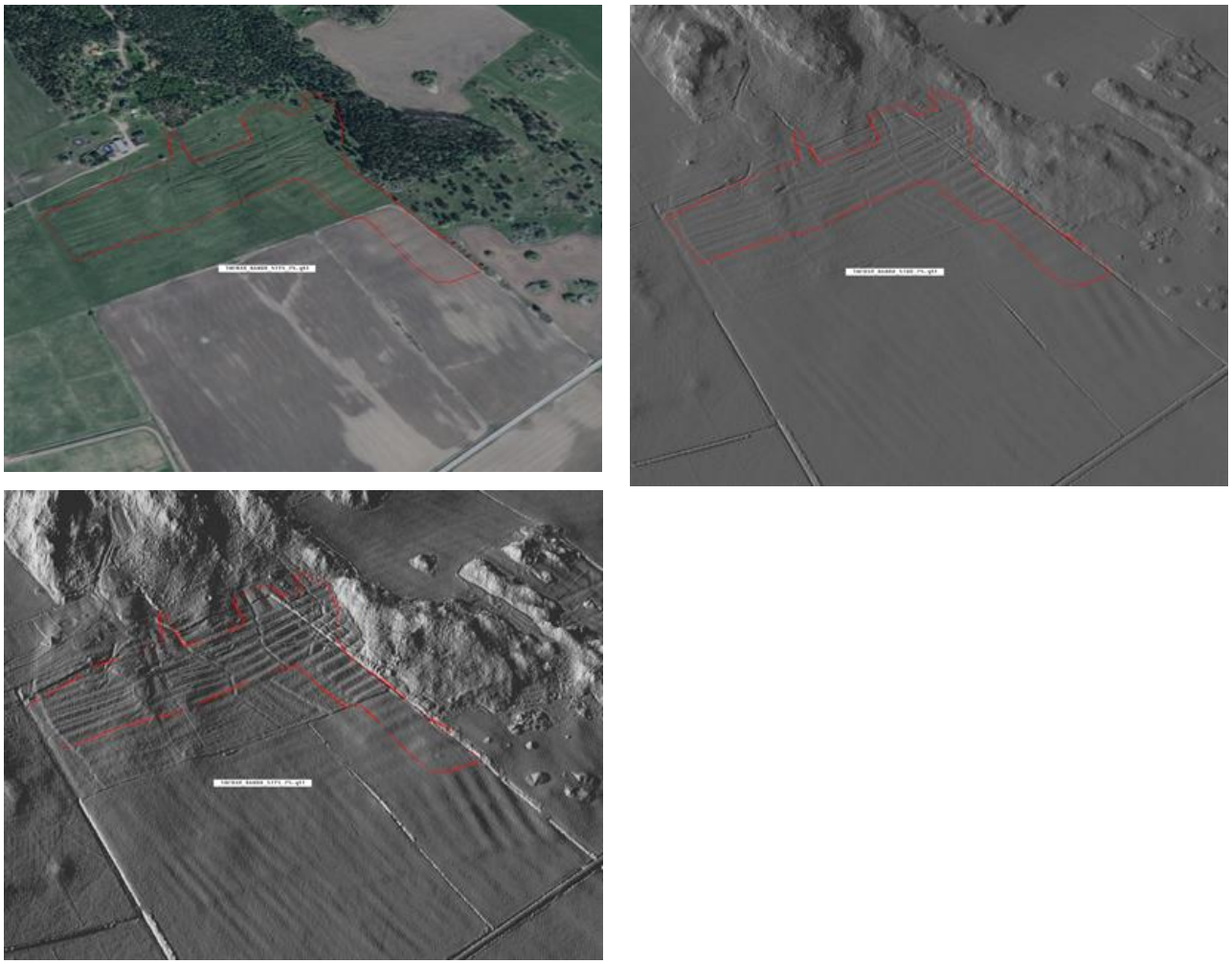

Figure 14. Säby 92:1: Ancient field system shown as orthophoto (top left), hillshade with Z-value = 1 (top right) and Z-value = 5 (bottom left). The ridge and furrow plough marks are between 0.2-0.3 m deep. The red border demarcates the extent of the registered archaeological site, but the higher z-value clearly shows a larger extent of fields. The area is now used as pasture, but trenches from military training have damaged the site in the northwest (Alexander, 2014a)

This can be exemplified by looking at the area of ancient fields represented by the site Säby 92:1 in Hallstahammar, Västmanland (Figure 14). When enhancing the vertical axis it becomes clear that the extent of the cultural remains is greater than that which has been registered as a result of field survey. Similar examples can be found throughout Sweden, and it is even possibly to detect areas of historical agriculture in lands that are no longer considered productive. On Gotland and Öland, for example, large areas of prehistoric agriculture from the Bronze and Iron Age are registered, besides which can be found traces of settlement sites, graves and farmsteads.

Intensity values in LiDAR data may also be a useful source of information, especially in agricultural land (Figure 15). Intensity is the strength of the return (reflected) pulse, and it can provide useful clues to the character of the reflecting surface. Harder surfaces tend to be represented as higher values (often shown as lighter shades) than softer surfaces. Intensity is affected by soil type and soil moisture content, variations in which are often caused by buried or ploughed over features such as ditches, graves, fields, pathways and palaeochannels. Palaeochannels, the traces of past stream or river channels, may provide a variety of important archaeological and geological information. Their location, which can often be seen through variation in vegetation or depressions in the landscape, informs on the character and hydrology of past landscapes, but also helps provide information on the archaeological potential of an area. Past settlements may have been located along the edges of these water sources, but any organic sediments may also provide important sources of palaeoenvironmental data for environmental archaeological analyses such as pollen or insect analysis (see 'Other potentially useful geodata...' below). The usefulness of intensity data, however, varies considerably between situations and interpretation may have variable levels of success.

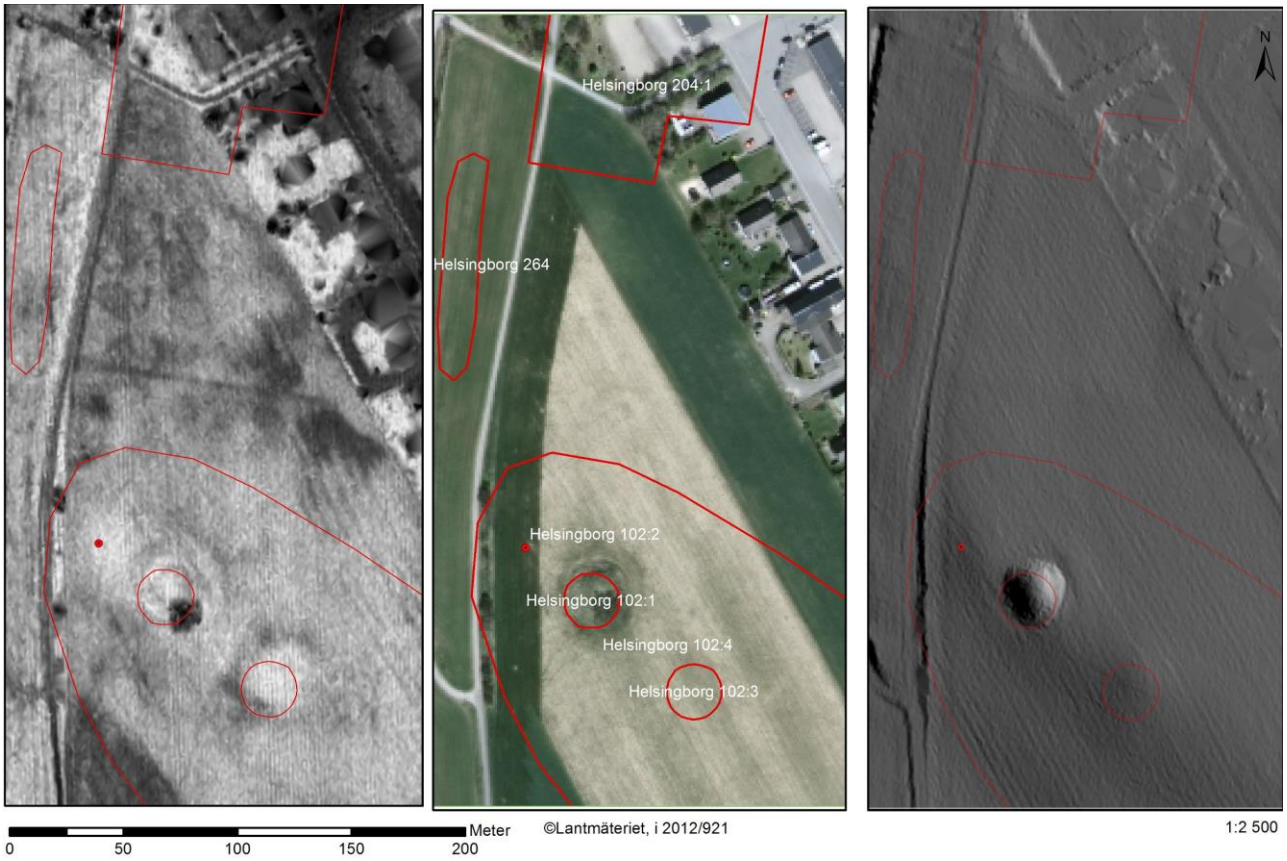

Figure 15. Intensity data (left) compared with orthophoto (middle) and DEM (right). Two of the grave mounds at Helsingborg 102 have been ploughed over, and are visible as lighter patches in the intensity data, even though one of them (102:3) is not at all visible in the orthophoto. To the north of the mounds can be seen intensity variation which could quite probably represent other buried archaeological remains (Alexander, B 2014a).

Automatic and semi-automatic methods

Denser laser scanning can enable the use of automated, or more often semi-automated (guided) interpretation tools for improving the efficiency of locating archaeological features. These tools work best with features which are uniform in terms of size and shape, such as the circular remains of charcoal production sites (see examples below). Although it is very unlikely that they will eliminate the need for expert archaeological knowledge and experience, automated tools form a useful addition to the archaeologist's toolkit. The computational power and storage requirements will vary with dataset size and type, complexity of algorithms or approach, and research application.

A number of experiments with the automated identification of cultural and archaeological remains in laser data have been undertaken in Norway. Research at the Norwegian Computing Center (Norsk Regnesentral) has been a driving force behind developments (see https://www.nr.no/en/projects/cultsearcher), and (semi-)automated detection is used for assisting in the identification of features in Vestfold and Oppland counties. Currently available methods are still considered problematic, even with base data which is considerably higher resolution than that which is generally available in Sweden. Trier and Pilø (2012) found that an increase in point density from 0.5 to 2 ppsm increased the success of automated charcoal production site identification from 54% to 81%.

Both Krasinski *et al.* (2016) and Trier *et al.* (2015:161) recommend a point density of at least 5 ppsm, and the latter scanning when there are no leaves on the trees. Using pattern recognition algorithms, better results were achieved for features standing out from the surrounding terrain, and which could not be confused with naturally occurring structures. Charcoal production sites and hunting pits were reasonably successfully identified, whereas grave mounds were more easily confused with natural geomorphology. In an experiment with 469 grave mounds in a grave field, 304 (65%) could be identified automatically. The method successfully identified 10 previously unknown grave mounds, but a further 11 were discovered during subsequent field survey which had not been automatically detected. Better results were achieved for larger aggregations of similar features, such as grave fields, than lone or smaller groups of features in the landscape (Trier *et al.* 2015).

There is a danger of over representation of features in landscapes that are easier to scan. Trier *et al.* (2015) discovered, for example, that proportionally more charcoal production sites were detected on alluvial and glacial flood plains with sparse vegetation, even though similar remains were present in less favourable environments such as woodland. Recently developed techniques however, such as 'deep learning', appear to at least preliminarily, give more successful results (see e.g. https://www.nr.no/en/node/849).

Examples of recent LiDAR use in archaeological survey

Below follow a few examples of the many recent Swedish archaeological investigations in which the use of LiDAR has been integrated.

In 2014, LiDAR data was used as the basis for interpretation in an archaeological survey in Jämtland (Olofsson, 2015). The survey area was investigated by two archaeologists, on two different occasions. After the subsequent field survey, approximately every second object identified in the LiDAR data had resulted in the registration of an archaeological site. A positive side effect of the field survey was also the discovery of further new sites which had not been identified in the laser data or by previous field surveys. A previously unknown iron bloomery site (*blästplats*, a type of iron production site), for example, was discovered whilst investigating a suspected charcoal production site which was identified in the LiDAR data. Whilst many charcoal production sites and pitfall traps

(also called hunting pits or deadfall traps) would have most likely been discovered during a field survey, it would have been considerably more time consuming than the LiDAR based evaluation. However, the author warns that other types of remains, such as bloomery iron production sites and house foundations, would be more successfully located through traditional field survey. Olofsson also noted that interpretation undertaken by an archaeologist with more experience of reading laser based data led to a higher proportion of successfully identified remains in the field. The report concludes that a traditional field survey, supported by LiDAR data, is a very efficient method for locating sites. The author stresses, however, that there is a need for improvements in the methodology of LiDAR data interpretation, in combination with field survey, to avoid incorrect results. Further education of archaeologists in the interpretation of LiDAR data is also needed. Archaeological survey in Jämtland has continued to use laser scanning in subsequent years (Olofsson, 2015).

LiDAR data was used as the basis for a survey of Skogs parish undertaken by Gävleborg County Museum. Using hillshading on the Swedish National Elevation Model (which is based on LiDAR data with a point density of between 0.25 and 1 point per square metre), Ulfhielm and Björck (2016) undertook a desktop (computer) based identification of sites. This was followed by ground truthing in the field, and although almost 100% of the charcoal production sites identified by LiDAR were confirmed as correctly identified in the field, additional sites of the same type were found which were not visible in the laser data. Approximately half of the features interpreted as hunting or charcoal production pits were confirmed as correct in the field. Pit house features on raised beaches (*boplatslämningar i klapperstensfält*) were considered easy to spot in the LiDAR data, but some prominently protruding blocks were misinterpreted as pits. The identification of settlement remains and water related archaeology were not successful (Ulfhielm & Björck, 2016).

In a project undertaken by Skogforsk (the central research body for the Swedish forestry sector), LiDAR data was used as the basis for mapping cultural heritage sites with an aim towards reducing the amount of damage caused by forestry. The results demonstrated good possibilities for identifying commonly occurring types of remains, but that others were difficult to detect and that there were problems in blocky terrain (Willén & Mohtashami, 2017).

Västerbotten County Museum has undertaken a number of investigations using maps based on LiDAR data. In the SKAIK project (*Skogens Kulturarv i Kvarkenregionen*), in collaboration with Österbotten in Finland, hillshade was used to identify potential archaeological remains. Of 129 objects identified in the LiDAR data, 75% were found to be archaeological remains after checking them in the field. Amongst the most easily identified remains were pitfall traps and tar and charcoal production sites. Building foundations (*husgrundar*) were not visible in the LiDAR data, but nearby clearance cairns (*röjningsrösen*) were. Smaller features such as cooking pits and hearths were not revealed by the LiDAR data used in this investigation, and field survey often revealed additional features close by to those that were identified in the LiDAR data (Andersson, 2012).

Figure 16 to Figure 21 show examples to illustrate the importance of increased point density on the visibility of archaeological remains.

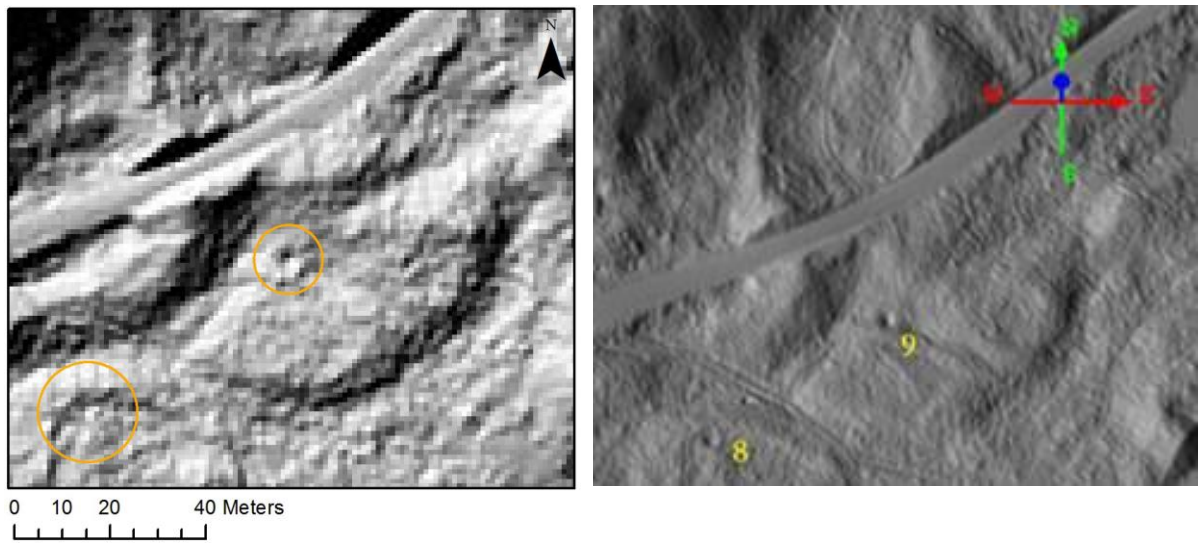

Figure 16. Two hunting pits Älvdalen 617 (point 8 and photograph) and Älvdalen 619 (point 9), in hilly terrain. Älvdalen 617 is not visible in Lantmäteriets national elevation model (left panel, 0.5-1 ppsm), but is visible in a model with higher point density (11 ppsm) undertaken for forestry. Lantmäteriets image has a resolution of 1 metre per pixel, whereas the forestry image 0.3 metres per pixel (Alexander, 2014a)

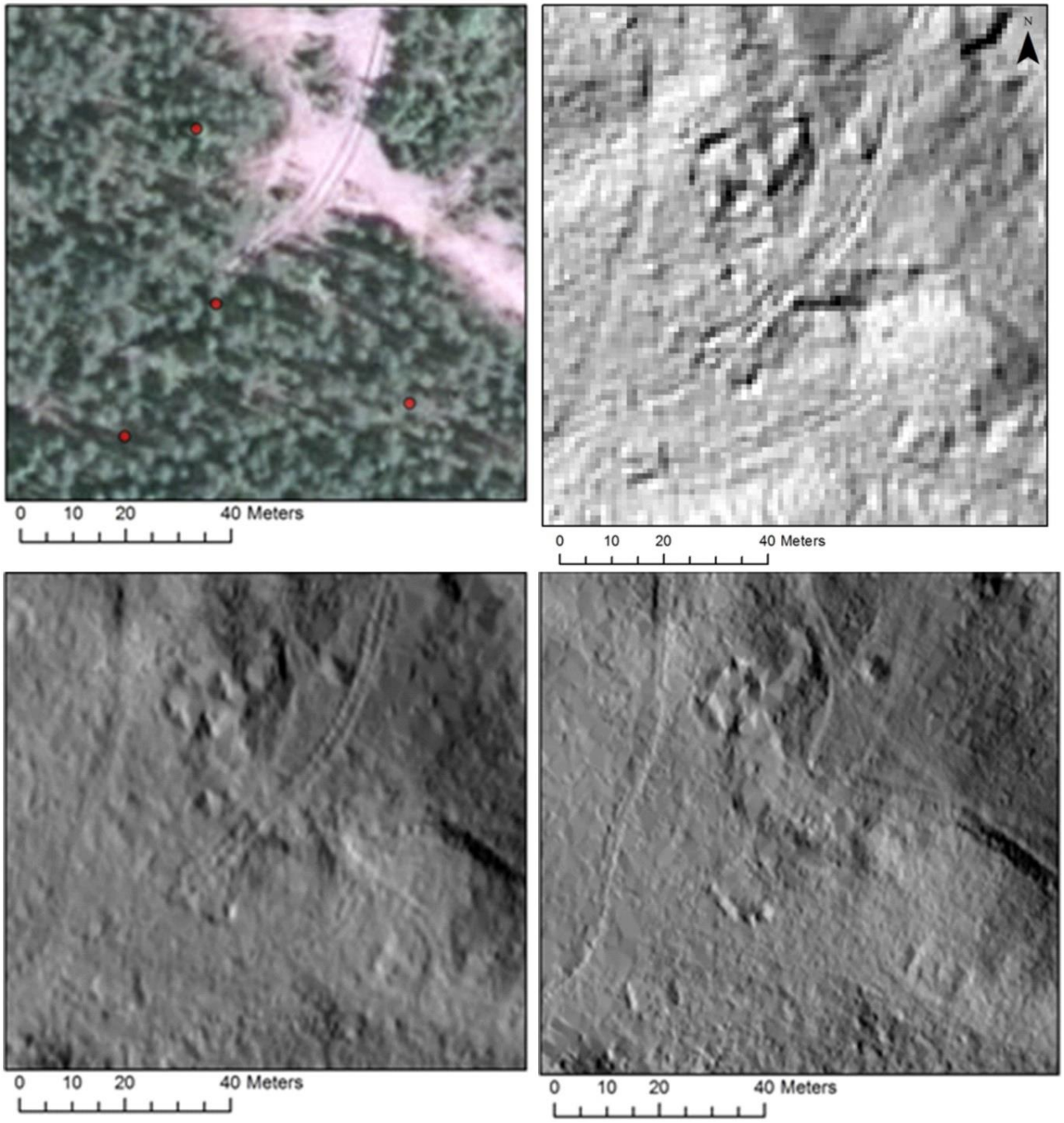

Figure 17. Four charcoal production sites (Floda 658, 660, 661 and Floda 665), marked with circles on the orthophoto (top left), in Floda parish, Gagnef municipality, Dalarna county. The top right panel shows the same area in Lantmäteriets viewing service for the national elevation model (scanned June 2010 at 0.5-1 ppsm) with 1 m resolution (i.e. 1 m per pixel) and 2x vertical exaggeration. Bottom left is the same data but at 0.5 m resolution and no vertical exaggeration. Bottom right shows data created in connection with a forest consolidation survey (scanned August 2009 at 5 ppsm) at 0.3 m resolution, which shows much more detail. Since these scans were made, three of these sites have been damaged by forestry activities (Alexander, 2014a).

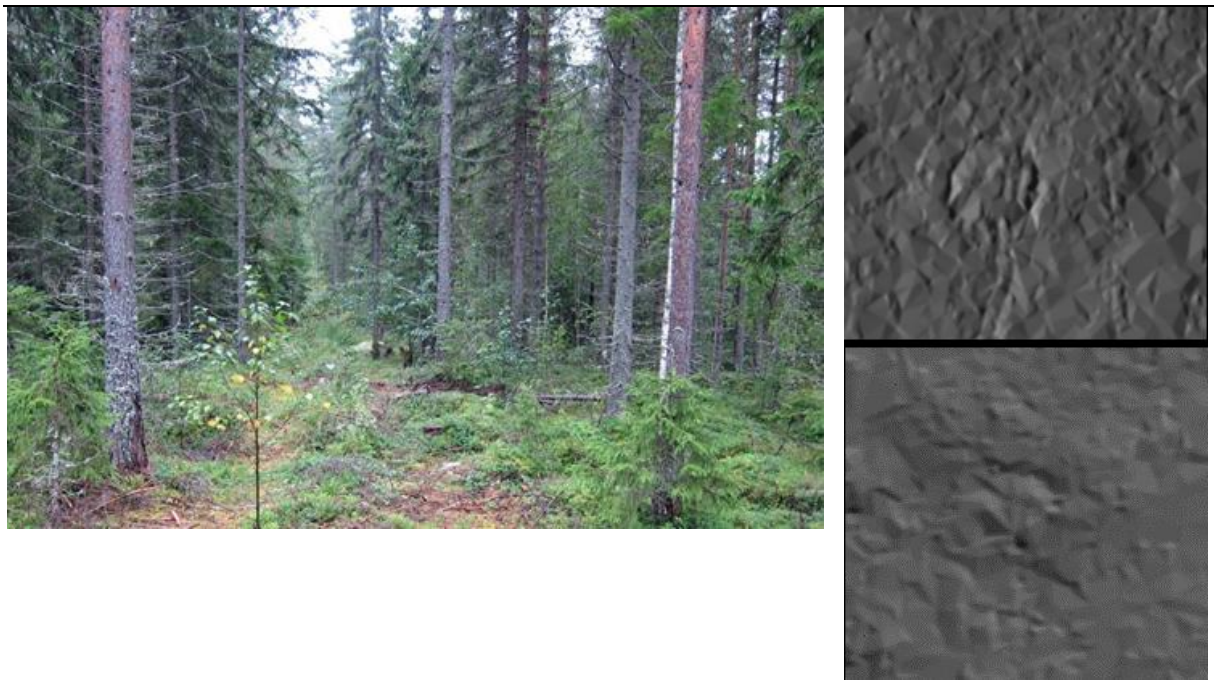

Figure 18. A charcoal production site in Floda, Dalarna, damaged by forestry machinery. The feature is 11 m in diameter and 0.2-0.6 m tall, overgrown with six pines and some small deciduous trees. The panels to the right show a DEM in TIN format, with the upper image derived from a local scanning and data with a point density of 1.45 ppsm, and the lower image from 0.3 ppsm data in the national scanning. The higher point density clearly makes the feature easier to see. (Note also the triangular pattern in the DEM caused by the TIN interpolation method). (Alexander, 2011).

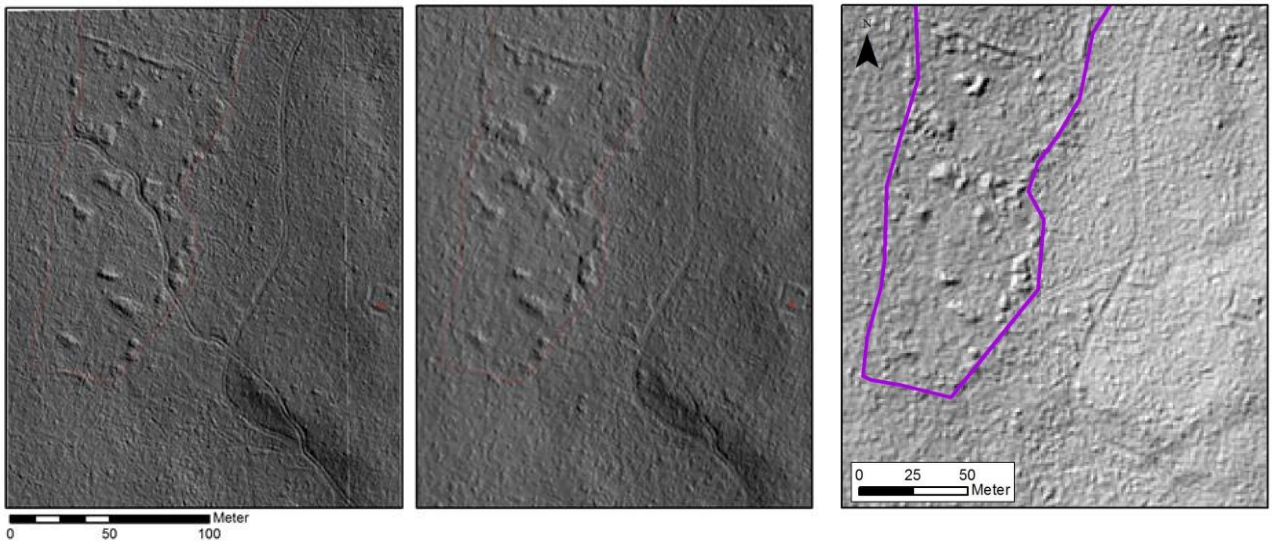

Figure 19. Southern part of the ancient fields system Floda 487 in Dalarna. The clearance cairns are between 3-15x2-8 m across and 0.5-1.4 m tall, and the dry stone walls are 19-72 m long, 1.5-3 m wide and 0.6-0.8 m tall. The three images show, from left to right, local scanning at 2.52 ppsm, processed national data at 0.57 ppsm, and the area viewed in Lantmäteriets viewing service with hillshade. The area has been damaged by a track which is only visible with the higher point density (left) (Alexander, 2013b).

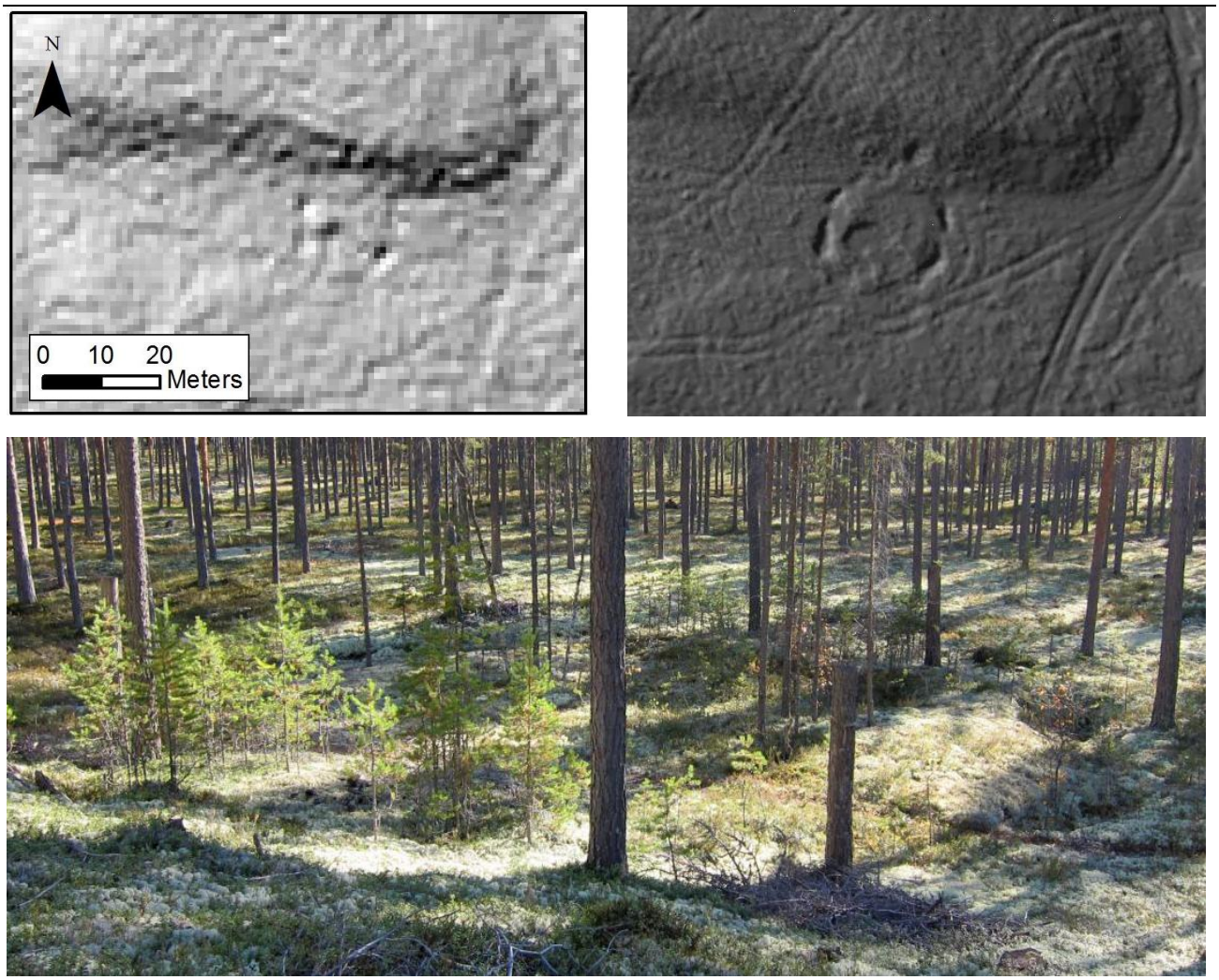

Figure 20. Särna 277, a post 16th century charcoal production site, 15 m in diameter and up to 0.4 m tall and surrounded by ditches. The site is barely visible in Lantmäteriet's viewing service at 1 m resolution and with a point density of 0.5-1 ppsm (left), but clearly identifiable in the right hand image with 0.3 m resolution and 11 ppsm. (Working material from an unpublished report for Dalarna County Administrative Board, Alexander, 2009).

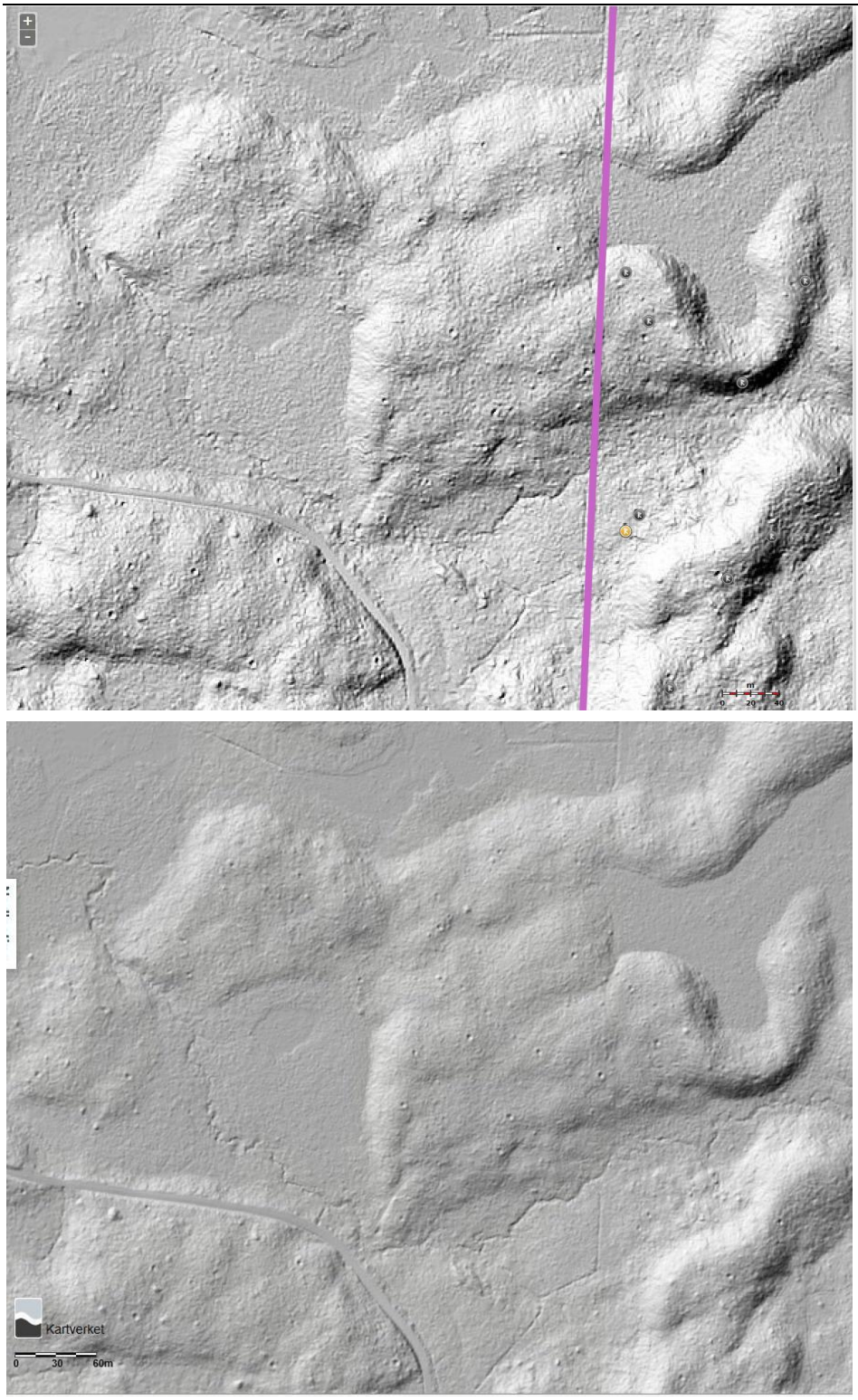

Figure 21. A patch of wooded land at the Swedish-Norwegian border, in two different LiDAR images. Scattered charcoal production sites are seen as small circular features. The upper image shows the Swedish national elevation model with 0.5-1 ppsm, as shown in the Swedish National Heritage database Fornsök (http://www.fmis.raa.se/cocoon/fornsok/search.html). The lower image shows the same area at 2 ppms from the Norwegian Kartverk (Hoydedata.no), in which the features are considerably easier to spot. Maps copyright © Lantmäteriet & Kartverket.

The Swedish Transport Administration's Toolbox

Below are discussed some of the most frequently used prospection and analysis methods, as well as data sources, during the initial stages of Trafikverket's road and rail projects. These tools are most often employed in the planning stage where a small number of alternative routes are to be chosen between, and physical and environmental data collected along them. A detailed understanding of the archaeological and cultural heritage status of the areas potentially affected by these routes is thus needed, and archaeological survey and prospection methods are routinely applied in such investigations. The following section of this report is primarily based on data delivered by Trafikverket, in the light of information on the methods provide above. It provides an overview of the possibilities for archaeological survey inherent in data collected for other purposes, including potential further requirements that archaeological and cultural heritage value assessment may have in terms of data quality or specifications. Specific details relating to the individual file types provided for evaluation are listed in Appendix 1.

Error margins are not explicitly discussed in the information below, but must be considered when using any of the data as the basis for archaeological survey planning or predictive modelling. Much of the geodata is based on the digitization of older maps, for which error margins may be between 50-70 m (see SGU documentation for data type for details). Maps based on the interpretation of aerial photographs and ground survey may have up to 200 m error margins. Transitional zones are seldom distinguished from sharp boundaries, and SGU advises that a 50 m zone around any border (e.g. boundary between soil types) should be considered when using the data. Data based on more modern maps may have a 25 m error margin due to the use of 25 m grid based surveys, but exact information on the source of data for any area is not always readily available or provided with geodata as standard. We therefore advise the use of caution and at least 50 m buffering when using borders in these data as the basis for delimiting areas of investigation. The accuracy of basemaps will influence the accuracy with which sampling strategies can be devised. For example, if the base data underestimates the blockiness of an area that is targeted for sampling for soil chemistry prospection, a planned regular sampling grid may not be feasible. In a worst case scenario the relevant sediments may not be present for sampling, and the field trip will have been wasted.

Evaluation data coverage

Example data was provided by Trafikverket from the North Bothnia Line rail project (*Norrbotniabanan*), including Umeå, Skellefteå och Robertsfors municipalities (Figure 22). Note that the purpose of this report is to evaluate and exemplify rather than present actionable results from the data provided. Any examples of interpretation provided below should be investigated as part of further research and evaluation and not be used to guide sampling or development without further discussion.

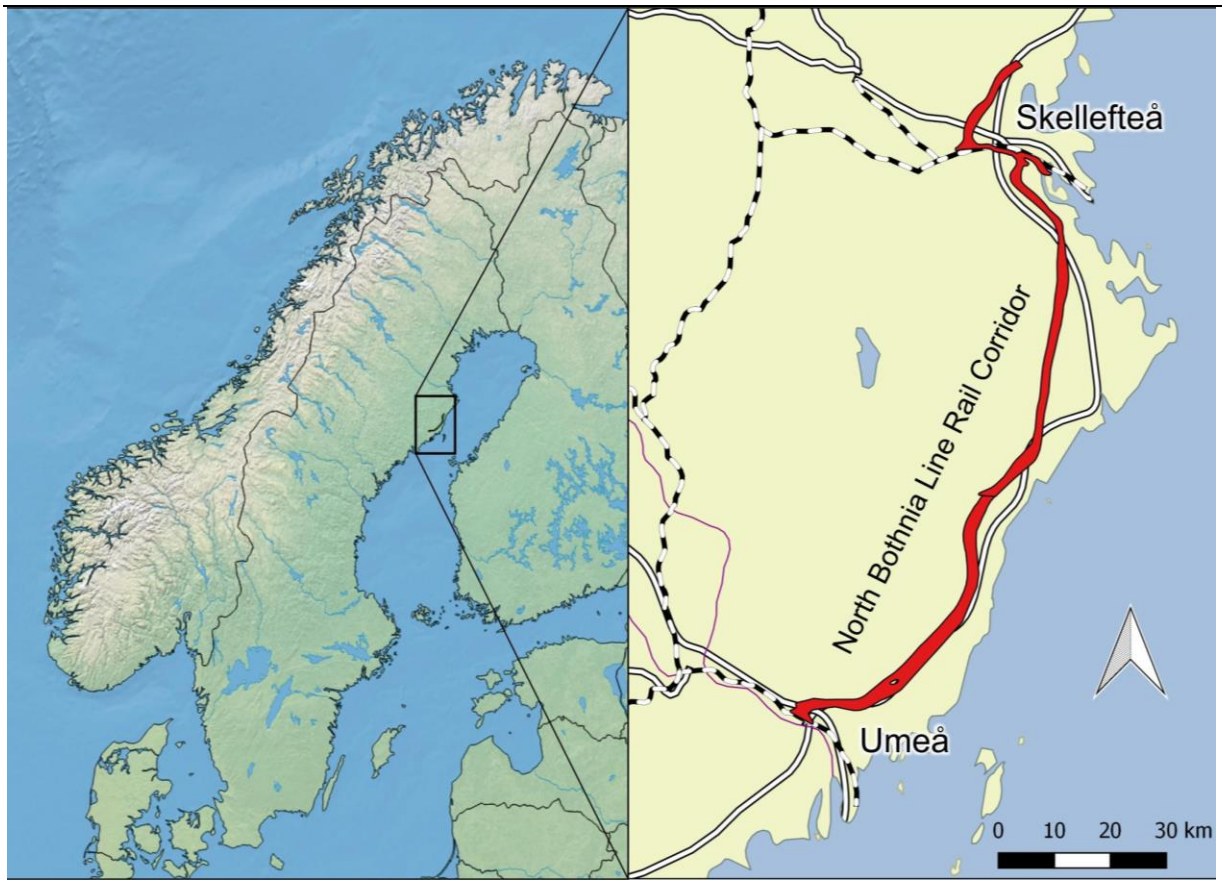

Figure 22. Location and coverage of the example data provided by Trafikverket for this investigation. (Data from Natural Earth and Trafikverket).

Geotechnical data

Bedrock (berggrund)

Human land-use has always been directly tied to the possibilities afforded by different types of terrain, many aspects of which are heavily influenced by the underlying bedrock. Different bedrock types provide potential access to different materials (e.g. flint, quartz, and quartzite) which may have been useful to past peoples, as well as influence the nature of sediments above and around them. The development of modern soils in many locations has been the product of a combination of natural processes and human activities (e.g. block clearance, ploughing, manuring) over hundreds to thousands of years.

Geographical data on the spatial location, form and type of bedrock can provide information of importance to archaeological survey, prospection and research. Stone tools are one of the most important and frequent prehistoric finds in Scandinavia, and the location of potential source areas for quarrying or mining raw materials for their production is of considerable importance for the understanding of resource use, movement and trade in the Stone Age. Bedrock geology may also provide explanations for patterns or inconsistencies in soil geochemical survey results (e.g. over deformation zones) as well as the boundaries of different vegetation types or land uses.

Bedrock outcrops not only provide easily accessible material sources, but should also be inspected for rock art (paintings or carvings). Maps indicating their location are useful when planning field surveys. Burials may also be encountered in caves or recesses in outcrops.

Soil types (jordarter) - primarily Quaternary geology

Modern soils are the result of thousands of years of natural processes acting in combination with more recent human activity. The latter varies from the recent impacts of modern forestry (e.g. increasing erosion and nutrient circulation) to hundreds or thousands of years of build-up of organic material through ploughing and manuring since the Late Stone Age. Soils may thus contain a considerable amount of geoarchaeological information on the nature of past landuse, and soil maps thus provide an important starting point for archaeological survey. Critical information on the archaeological potential of an area may be provided by soil/sediment type classifications. Soil type information may also be critical to the choice of remote sensing or sample based prospection methods viable for an area.

Geomorphology/Landforms (landform)

Geomorphology, the spatial distribution of topographic features or landforms, is an important factor in influencing human decisions on the placement of settlement or activity. Past peoples would have read the landscape when planning a route just as we do today, and the location of ridges and valleys would have formed important transportation routes. Much of the Swedish landscape is made up of features created by or as a result of the last glaciation, and the location of moraine ridges and drumlins is essential information for predicting the location of communication routes (which often have archaeological sites close by) and settlement sites, which tend to be located on raised, dry topography. Geomorphology maps may also help in the interpretation of LiDAR data by identifying natural features and boundaries.

Surface blockiness (blockighet i markytan)

Blocky moraines and blocky raised beaches are common landscape elements in northern Sweden. Whilst some blocky terrain is difficult to survey on foot, there are a number of archaeological remains which are commonly found in them. The mapping of the location of blocky areas provides an important source for predicting possible locations of these sites, and important information for planning field surveys and soil sampling projects.

Soil types (SGU category: jordarter)

Soil type data is provided by SGU at four levels:

1. Thin or non-contiguous upper surface layer
2. Thin or non-contiguous surface layer
3. Shallow layer
4. Deep layer

Information on the sediments closest to the surface provides an indication of natural processes of archaeological importance as well as the results of past human activities. Deeper sediments provide information on older landscapes or human activities and processes that have acted over a longer period of time.

General grain size descriptions (sand, silt and clay) provide some indication of the archaeological potential of a sediments. An archaeologist may use this information to assess the archaeological potential of an area and an environmental archaeologist may use it to help decide on the most

appropriate sampling technique for geoarchaeological prospection and mapping (e.g. phosphate mapping, see below).

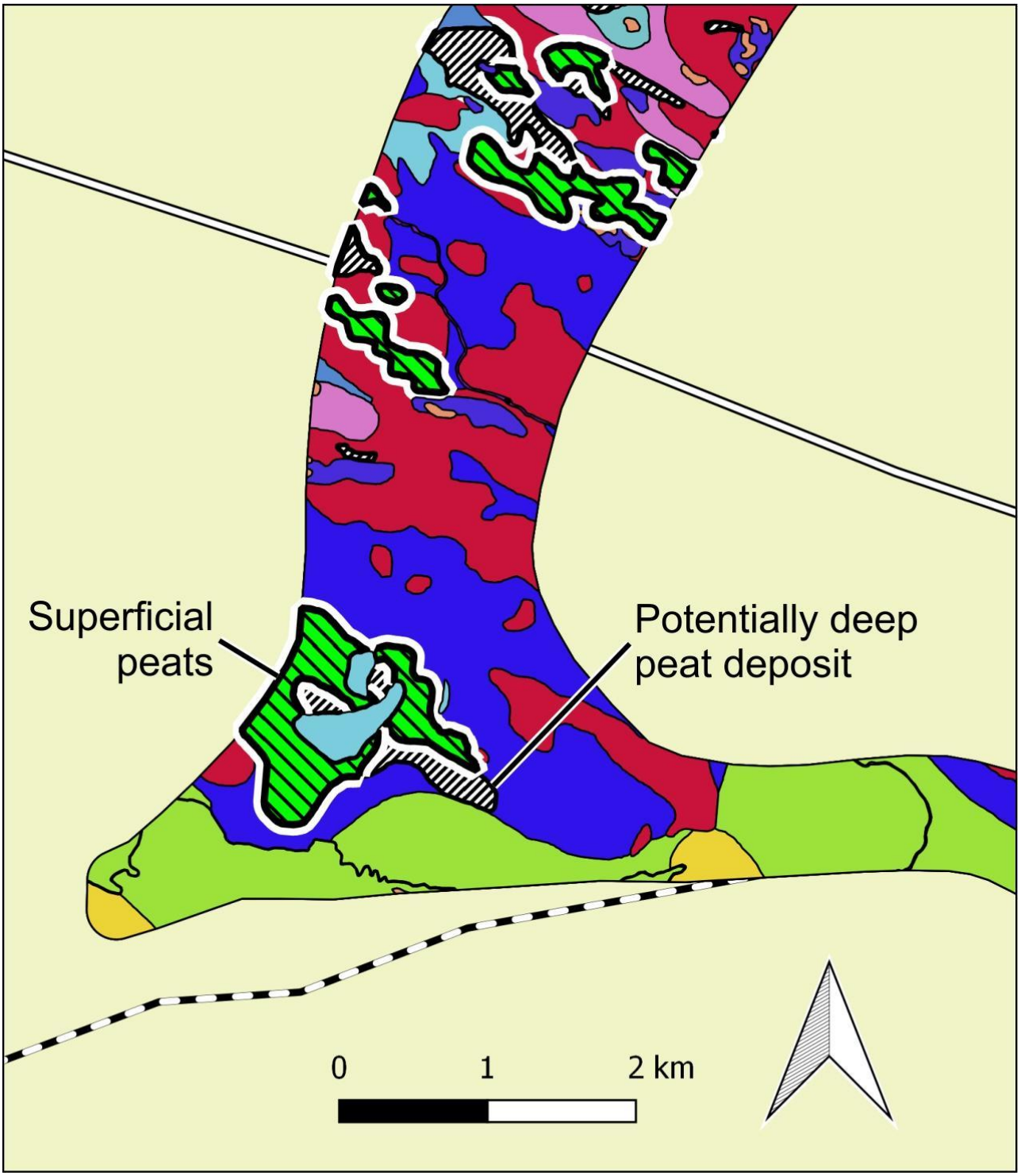

Figure 23. Soil types map with the distribution of peat deposits highlighted (striped pattern). Potentially deep deposits can be differentiated in the SGU data from more superficial/shallow peats by selecting the appropriate classification categories. This can be used as a guide when planning coring or sampling projects so as to increase the probability of obtaining material of the required age. Shallow peats tend to be younger than deeper ones or provide evidence of peat mining.

Information on the location of peat at the surface can act as a guide for locating potential coring/stratigraphic sampling sites for palaeoecological analyses (in combination with other data below). These analyses provide a picture of past landscape and vegetation change, and often

climate change, in a region. They can also often help detect the presence of past human activities which impacted the landscape in terms of vegetation change (e.g. deforestation, agriculture) or other forms of landscape management (e.g. burning, ploughing). Information on the presence and depth of peats may provide useful information on peat ages and historical use: If peats are present at the surface, but not the underlying 'shallow layers', then it could be assumed that they are of a relatively young age or have been mined (Figure 23). Peat bogs also sometimes produce bog bodies, platform dwellings, fishing technology or other covered site remains.

Information on the distribution of windblown sands may be useful in current and former coastal zones, or arid regions, for identifying areas where archaeological remains may have been covered after abandonment. Raised beaches (former coastlines, former lake shores), are a classic target for archaeological field survey due to a common assumption that past human activities are most likely to have been concentrated around water sources (fresh water for consumption and domestic activities, in addition to transport and fishing for both fresh and saltwater). This assumption has biased archaeological survey in Sweden considerably, but these areas do hold good potential for finding remains, as do many others.

The age of surface sediments provides a potential maximum age for archaeological sites upon them. Glacial sediments, for example, could potentially support archaeological sites which are older than those which could be found on post-glacial sediments. The location of kettle holes (*dödisgroppar*) is useful when locating potential palaeoenvironmental sampling sites, as well as trying to understand the landscape made available for colonisation at the end of the last Ice Age.

Soil depth (jorddjup)

Soil depth data provides complementary information on soil types as well as valuable information on the potential amount of sediment covering archaeological remains. When combined with Quaternary geological information on the types of sediments or soils, the data may help predict the probability of remains being covered by alluvial (river, delta or other flowing water deposited) sediments, sand dunes (recent or ancient) or as a result of other geological processes such as landslides. It may also be useful for modelling past areas where erosion may have removed archaeological remains and either destroyed or redeposited them (such information is important for helping to understand and predict the location of sites in the landscape). Human activity, such as ploughing, quarrying and mining, both modern and past may also have led to the large scale movement of sediments from uplands to lowlands. Archaeological remains younger than 2 000 years old have been found under over 16 metres of sediment in Northern France, and post Bronze Age colluvial sediments in Skania are often more than three metres deep.

These data are best explored in combination with the other geodata within GIS rather than as separate images.

Gridded soil depth model (raster)

SGU's soil depth data are based on interpolation between boreholes and other point sources, with the interpolation guided by references to soil type data. The accuracy of the soil depth model at any point should therefore be considered with respect to the density of boreholes in the area (i.e. less boreholes means that there could be anomalies or variations present which are not reflected in the model, see Figure 24). The accuracy of the model where soil type maps have been used to aid interpolation varies according to the accuracy of the maps used.

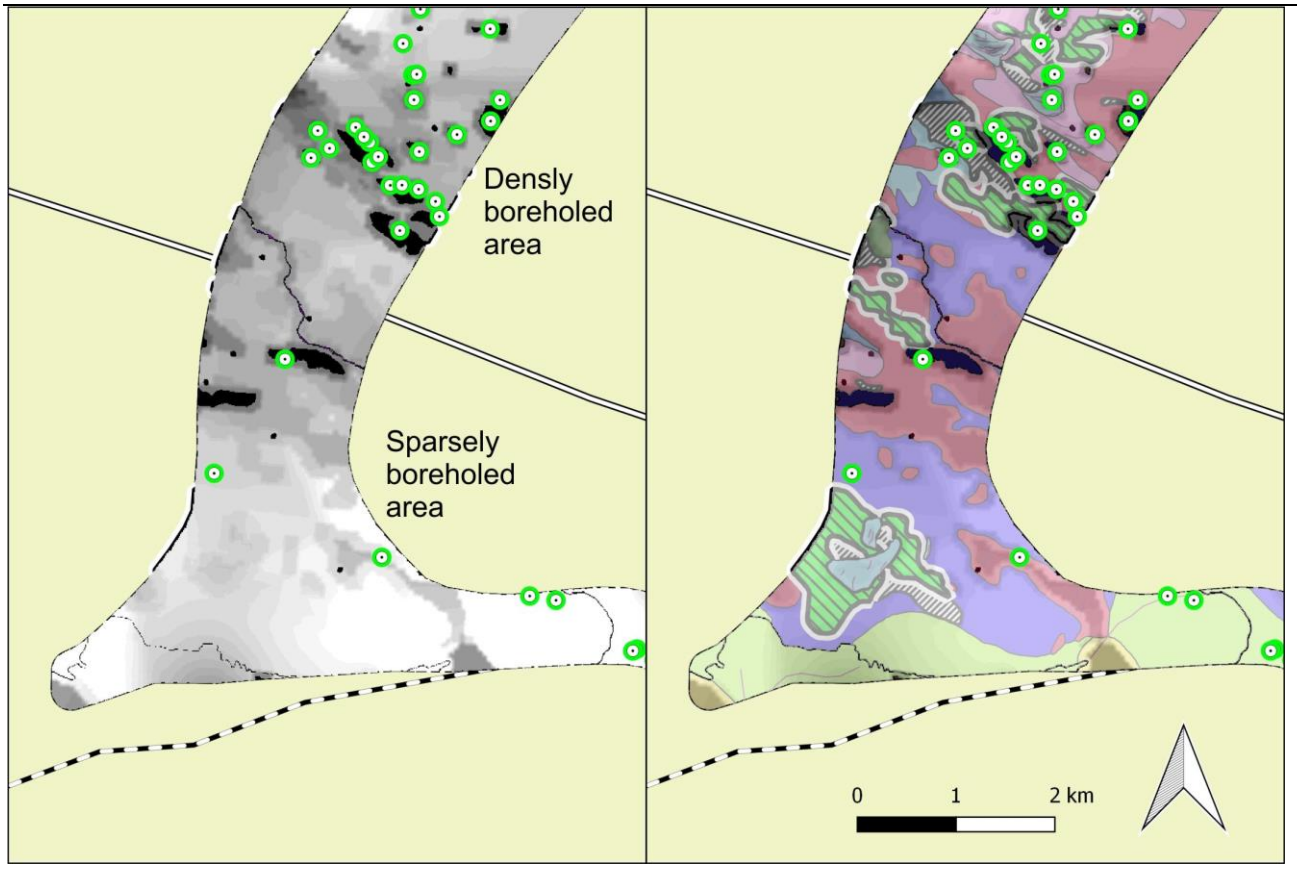

Figure 24. Left: Soil depth map showing deeper of soil ranging from 0-29 m as black to white. The location of reference boreholes are shown as points. Right: Soil depth model overlaid on soil type polygons to illustrate a useful combination of layers for interpreting soil data.

In theory, based on test trenching, boreholes and dating, it could be possible to use these data to calculate the expected depth and volume of sediment which would need to be removed to reach a particular sediment age. This would be useful information when costing an archaeological excavation, if used in combination with remote sensing and prospection methods to locate the areas and depths at which remains are most likely to be found.

Although these data are provided as both depth and interval layers, the evaluation datasets did not appear to differ in content. These data may have different implications in other contexts and will require re-evaluation.

Gridded bedrock elevation model (raster)

The elevation of the bedrock surface in metres above Lantäteriet's GSD-Höjd Grid2+ elevation model (https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/Hojddata/GSD-Hojddata-grid-2/). Bedrock elevation data may be useful for modelling the potential location of archaeological sites in related to later sediment movements that may have covered them. This type of analysis is currently, however, rare in archaeological research and generally requires more research time than consultancy projects allow for. There is certainly room to investigate the potential of these data for their use in archaeological settlement modelling.

Modelled in 50x50 m squares (1 pixel = 50 m), these data are of considerably lower resolution than other raster data provided in the evaluation dataset. Similar accuracy concerns should be considered to when using the soil depth data.

Reference data (underlag)

The location of reference points, and the information obtained from them (e.g. if the borehole reached the bedrock, the source of observation data), are important when evaluating the reliability of the soil and bedrock depth data above. It should also be noted that the reference data for observations and assumptions include a number of other databases (e.g. *Torvdataarkivet*) for which the accuracy and origin should be assessed before conclusions are drawn.

Ground penetrating radar (GPR, geo-/markradar)

Evaluation material was provided in the form of a report containing a number of transect/profile radargram images with notes on identified probable subsurface features. Horizontal (plan) figures from multiple depths would be required in order to be able to evaluate the nature and spatial extent of any buried remains. Radargrams are a specialised image form and most likely not interpretable by the majority of archaeologist (with the exception of those trained in or with experience of geophysics). The notes provided are of limited archaeological significance apart from comments on the location and depth of potential surfaces and infilling which could indicate buried or excavated features. Follow-up test trenching would be required to evaluate the archaeological potential of these.

When undertaken using archaeological prerequisites, and under the right circumstances, GPR can be an extremely useful information source for identifying the extent and depth of potential remains. It is especially effective for high-contrast situations, such as finding stone (or wood) in soft sediments, or ditches or pits in harder sediments. It may be useful for locating features now overgrown by peat growth, but more experimental work is necessary in this field.

GPR is an advanced technique which is difficult to apply in archaeological contexts without specific knowledge of the specifications, interpretative tools and knowledge required in these contexts. We therefore only recommend the commissioning of GPR projects to companies with a proven successful track record of archaeological applications, and where geotechnically trained archaeological staff are included in the project from the design stage.

Nature conservation survey (naturvärdesinventering)

There is a strong relationship between the structure of the modern landscape and past human activities. In fact, outside of the upper mountain regions, Sweden has very few truly natural environments surviving (the few old growth forests are at most only a few hundred years old, which is not long from an archaeological perspective). Past human activities have thus strongly influenced the biodiversity of most areas, and the landscape character or conservation value of an area may often be explained in terms of past landuse (Figure 25). Conversely, nature conservation surveys can thus provide much information of use in cultural heritage and archaeological surveys, and may provide a point of departure for cultural heritage surveys. It should be noted, however, that a nature conservation survey does not necessarily include all areas of potential archaeological interest as highly cultivated or urban areas may be avoided due to their low conservation value.

Spatial data from nature conservation surveys are therefore of interest in archaeological field survey in that they may provide information on the location and extent of past human activities. In order to do this efficiently, the archaeologist needs access to the GIS data resulting from the survey, including the base data underlying any maps and reports.

The evaluation data provided in this project was preliminary and incomplete, and a number of areas discussed in the report were not present in the GIS data. The GIS data in its preliminary form also did not include sufficient data to be able to efficiently connect the numbered descriptions provided in the report to specific objects in the shapefiles. Connection could have been performed by visual comparison of the maps in the report with the GIS data, but this would take more time. It could be advantageous to run the archaeological/cultural heritage survey in parallel with the nature conservation survey and ensure knowledge exchange between the groups. It is apparent that coordination and timing of different survey types must be considered to ensure an efficient transfer pathways for data production and sharing. These factors should perhaps be integrated into Trafikverkets project workflows to maximise the efficiency of data use and consultancy time.

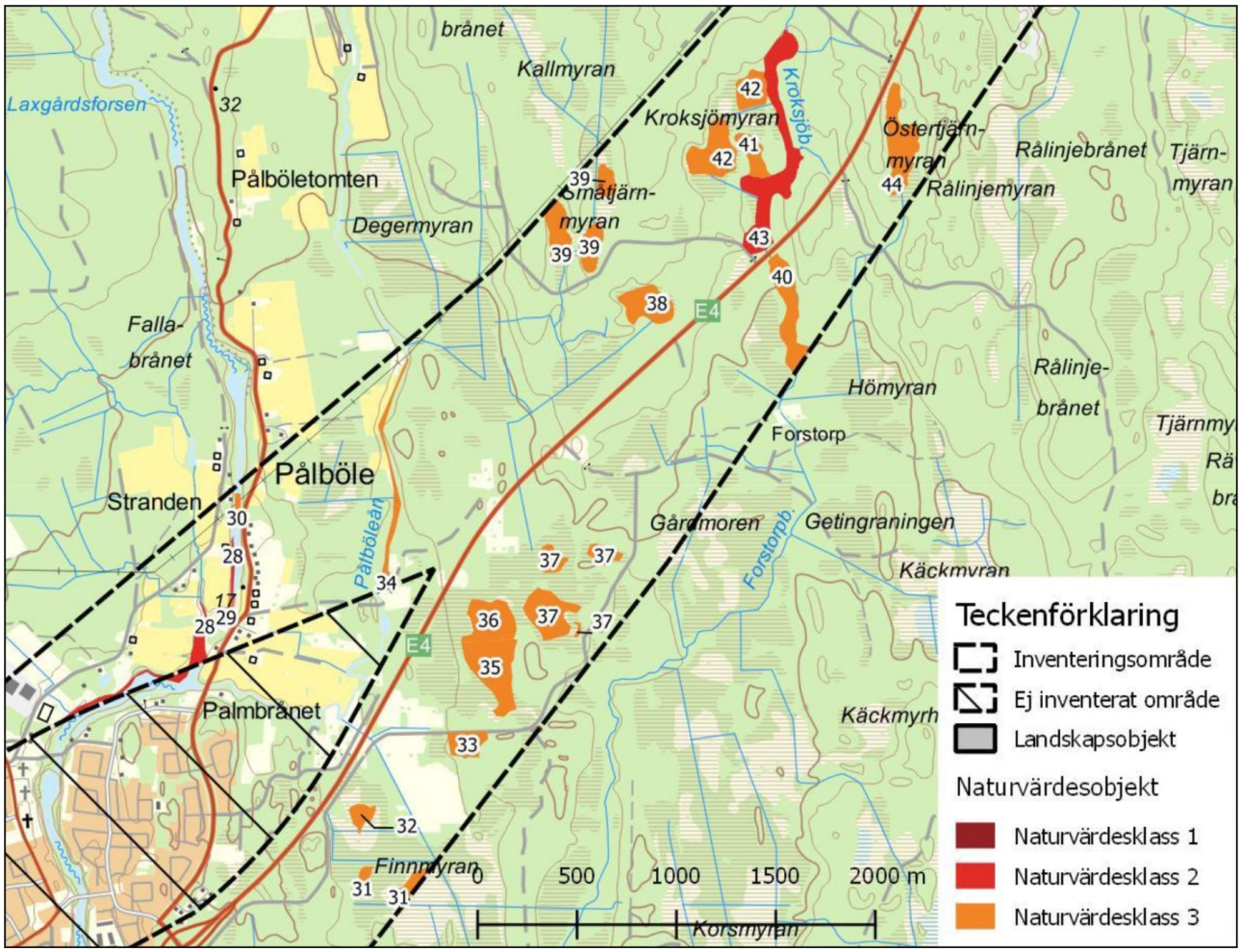

*Figure 25. Map showing areas of nature conservation interest, ranked 1 (highest) to 3 (least high) in terms of value. A number of these areas (e.g. nr. 28 and 30) are the result of secondary woodland growing in areas previously cultivated or otherwise manipulated by people (*kulturmark*). (Map source: Figure 19, p.36 in Rommell* et al. *2016).*

LiDAR (laserscanning)

The great potential for the use of LiDAR data is described in detail above, and will be summarised here with respect to the evaluation data. LiDAR surveys are a cost-effective method for collecting terrain data from a large area, but must be used in combination with field surveys for the evaluation of features identified in the data. For best results (i.e. maximum successful discovery of remains), data collection and processing should be undertaken according to specifications designed for the landscape to be surveyed and the expected types of archaeological features. In designing a LiDAR

scan, a point density of at least 5 points per square metre should be used. Involvement of an archaeologist with skills in interpreting LiDAR data is essential throughout the workflow.

Data should be delivered to most archaeologists in a format that is easy to use in GIS, such as a raster or TIN based DEM. Raster is usually preferable, in GeoTIFF format and as high a resolution as possible from the underlying point data. For more detailed studies, more advanced users may prefer to also receive the raw data in LAS-format and undertake their own post-processing so as to ensure optimal configuration for the situation at hand. CAD data formats (e.g. DWG) are generally not useful for archaeologists. Lyr and shp files do not support this kind of data. Data provided online (e.g. as a WMS service) may be a useful solution for delivering large amounts of data for office based work, but raster files will always be needed for field survey and offline use. It is probably most efficient to provide all the potentially required data on a memory stick from the start.

Complete information on the data collection and processing process is essential (e.g. point density, scanning angle and altitude, overlap, point classification, filtering and interpolation method details). This will allow the expert to assess the relative probability of detecting different types of feature in the data. The evaluation data provided here did not include sufficient metadata to make these evaluations, and we could not assess whether or how the point data had been classified or filtered. Further discussion may be necessary to examine these files in more detail.

Semi-automated tools for the detection of regular, relatively large remains, are becoming available and could be employed to speed up the detection of features. These are, however, not always useful where sites such as charcoal production features and pitfall traps are uncommon. There are, as yet, no off the shelf systems available for performing these tasks and semi-automated detection is most often undertaken within research projects (although see notes on Norwegian projects in LiDAR section above).

Laser scanning technology and interpretation methodology is advancing rapidly, and frequent re-evaluation of the best and most cost effective set of tools is advised.

Orthophotos (5 cm per pixel), Skellefteå kommun

These are very high resolution orthophotos that allow for the detection of archaeological features that would not be visible at lower resolutions. Their use is, however, extremely processor intensive and slightly lower resolution should be evaluated in parallel to see whether the performance gains outway the loss of fidelity. 10 cm/pixel and 25 cm/pixel should be also compared for the same area, perhaps using LiDAR data as an additional source for locating features. Information on the date and time of photographing should be provided to help ensure a correct interpretation.

The orthophotos, at high resolution, provide:

- A landscape overview and details which provide background material for field survey, including the identification of potential archaeological sites. If taken at the right time of year, cropmarks may be used to locate sites under arable crops (this will vary by year and conditions and expert advice should be sought). They are best combined with LiDAR data and examined prior to fieldwork. They also allow archaeologists to see suitable access routes and plan fieldwork.
- In combination with older orthophotos, they allow for the identification of historical landuse changes, which helps in the interpretation of the recent landscape. It also allows the archaeologist to separate recent and older changes in the landscape, and identify potential

historical remains. It also allows for the identification of more recent landuse's effects on the cultural landscape.

- Potentially an indication of past cultivation structures (e.g. fields, drainage), and possibly even ownership structures (e.g. boundaries), in the structure or differences in vegetation at former boundaries.
- The location and, to an extent, type of peat bogs which could potentially be used for palaeoecological analyses. Potential bogs can be marked on the photos and test-cored to see if they provide suitably preserved and aged organic remains for the reconstruction of past vegetation and environmental conditions (see below).
- Vegetation forms and patterns which can be interpreted in terms of their potential for supporting biological and/or cultural landscape diversity, as a consequence of past settlement activities. In combination with historical maps, they could allow older historical landuse changes to be more precisely dated by the age structure of current vegetation.
- Information to support and refine the details of geological and soil type maps and thus help the archaeologist interpret the landscape in terms of past human activities.

Other potentially useful geodata and prospection methods

There are a number of other geodata layers available through SGU which are of use in archaeological planning, field survey and excavation. The most important of these are briefly listed below. SGU also provides a variety of layers which are of use in heritage management and risk assessment (such as landslide and erosion risk), these are, however considered outside the scope of this report (but see Karlsson, 2018 for examples).

Historical coastlines data (historiska strandlinjer) (SGU)

These are useful for estimating the oldest potential age of a site, based on the calculated emergence of an area with isostatic rebound. It also provides data for creating terrain models for different periods in the past, which accurately include the relationship between landscapes, sites and coastal environments for locations below the highest coast line (and thus younger than a certain age). Coastal resources are an important concept in archaeological reconstructions, providing both transportation routes and food.

Highest coastline data (högsta kustlinjen) (SGU)

The highest coastline in any area of land uplift provides an estimated maximum age for sites below this line (i.e. the most recent date at which land uplift pushed the area over sea level). It is thus useful when dating finds or predicting the location of archaeological sites of a particular age or type.

Soils data (jordmån)

http://www-markinfo.slu.se/sve/mark/jman/jmdom.html

Although these maps are of poor resolution, they are useful for planning sampling and analysis strategy based on the probability of encountering particular soil types.

Magnetometer surveys

Although little used in Sweden, (fluxgate-)magnetometer surveys are a common part of the archaeological prospection toolkit in many parts of the world. The method relies on the different magnetic properties of sediments and materials to produce a map of anomalies. It is especially good

for locating buried walls, ditches or other modifications to materials. The method works best in uniform sediments such as arable soils where there is little variation in soil moisture content.

Magnetic susceptibility prospection and surveys

Magnetic susceptibility (MS) surveys may be undertaken using a field probe or by sampling and laboratory analyses. They work using the magnetic properties of the sediments, and are useful for locating areas which have previously been heated (such as hearths or industrial wastes).

Phosphate surveys

Human activity tends to increase soil phosphate through the deposition of organic waste. Sampling followed by laboratory analyses allow the method to identify areas of higher activity in the past, and thus target areas for excavation. The results also help interpret the activities which have occurred on almost any archaeological site.

Resistivity surveys

Also little used in Sweden, resistivity surveys measure variation in the conductivity of sediments between a transmitter and receiver to build a map of buried features. The method is useful for identifying similar types of feature to magnetometer surveys. It also works best in uniform sediments such as arable soils where there is little variation in soil moisture content and where there is little natural ferromagnetic material scattering.

Pollen, insect and plant macrofossil prospection and analysis

Peat bogs and lake sediments often store a record of the environmental and climate changes that have occurred around them (see The Swedish Context above) as their sediments accumulate. By sampling these sediments, processing and analysing them in the laboratory, we can often find out both broad and specific details on past landscape and climate changes in an area. These investigations are best conducted in combination with field surveys and can be undertaken in detail along with archaeological excavations to build a more comprehensive picture of an area's past.

Radiocarbon dating of cores (and charcoal from fireplaces)

Our capacity to understanding the past is highly dependent on our ability to date past events. Radiocarbon dating of peat and lake cores allows us to isolate (human or natural) events that may have changed the vegetation in an area, and ensure that analyses are focussed on the time period of interest. Dating of charcoal from archaeological hearths helps establish their date of the final phase of use.

Summary and way forward

The methods and data types investigated in this report have great potential for providing useful information when planning archaeological and cultural heritage surveys. Routinely making all of the data types described above available to archaeologists will improve the efficiency with which they can locate features of interest and/or plan for excavations. Different requirements on collection, documentation and processing may exist for the use of the methods and data for archaeological and cultural heritage tasks to those of other purposes.

Early involvement of archaeologists in the planning around and interpretation of these data will help ensure that valuable cultural environments can be avoided early in the planning stage, and the potential need for expensive excavations reduced. Well planned prospection will also help to ensure any necessary fieldwork and excavations are efficiently focussed on the most promising locations. Fieldwork time is expensive, especially in areas where the current state of knowledge is poor (especially large parts of Sweden's forested lands and Norrland). By combining an investigation of high-resolution orthophotos, LiDAR based DEMs in raster format, and geodata in shapefiles, areas of high archaeological potential can be identified. Semi-automated methods for the detection of certain archaeological feature types may also be employed under expert supervision, but these are as yet not commonly available. Together, these data and tools may be used by archaeologists trained in their use to target field survey based on what can be identified on the computer.

Early evaluation of these data will also ensure that the location of potentially useful organic deposits are located early. These analyses take time, and starting analyses early would allow the results of palaeoenvironmental reconstructions to be integrated into archaeological reports rather than being delivered separately later or appended to reports (as is more common).

Person (2010) has expounded, for Jämtland and Västernorrland, a method for the analysis of multiple data layers including soil types, place names, the distribution of out-of-context archaeological finds and historical monuments. These layers are used to predict and locate areas of potential cultural environments. Lindholm *et al.* (2015) have also proposed a more integrated approach to landscape analysis using GIS. Models which are based on the known distribution of sites and artefacts are, however, potentially biased towards the types of areas which have been the focus of previous field surveys. For many areas, this generally means an over emphasis on the types of areas which have been extensively developed over the past 200 years. To a large extent, these areas include agricultural lands, coastal areas and along the edges of hydroelectric power regulated lakes and rivers. A number of student theses (e.g. Hultgren, 2016; Olsson, 2006) have looked into evaluating these biases, with varying degrees of success, and it would be worth synthesising the results into a more robust research project orientated towards Trafikverkets workflow and objectives. Further research is needed to develop more innovative methods which avoid this tendency to perpetuate an older antiquarian tradition and increase the probability of predicting the location of cultural remains throughout the landscape.

Methods using various combinations of advanced techniques to gather and integrate data still require the skills of a trained archaeologist to identify and interpret features. In other words, even though much of the data may be gathered by technicians, geologists and digital specialists, archaeologists are still required to use them in cultural heritage studies. However, the latter requires that the archaeologist is informed about, or has access to information on, the data collection process, most especially in order to limit the potential for incorrect interpretation of digital collection and processing artefacts. A similar caveat follows for the use of any maps produced from survey data (e.g. geological or vegetation maps), as information on the error margins of both the maps and the original collection data is essential to assessing the reliability of the product for locating archaeological features. Ideally, the various specialists required in this process chain should work together to ensure a reliable understanding of the landscape throughout time and depth. Alternatively, a common metadata format could be used for communicating methods and accuracy data between partners.

It must also be stressed that a thorough understanding can only be obtained by combining remote sensing methods with field observations, and that excavation will almost always be necessary at some stage in an investigation on the cultural heritage of an area which risks destruction due to development. It should also be stressed that training and experience in the archaeological use and

interpretation of the methods detailed above is essential. Little, if any, of the interpretative process can be safely undertaken without this, although some data preparation, if properly documented, may be undertaken by technicians with appropriate technical skills. We would also like to point out that the interpretation of data from different landscapes requires different knowledge and training, as different types of archaeology and requirements are involved (e.g. an agricultural landscape in Scania has different types of remains, which are visible through different methods compared to a wooded landscape in Västerbotten). If there is sufficient demand, it may be possible to persuade universities to offer vocational courses (*uppdragsutbildningar*) to increase archaeological competences in other sectors and allow technicians (or other groups) to partake more comprehensively in the preparation of data for archaeological use.

Suggestions for efficient use of methods and data

Below are a number of summary points to help in the planning and coordination of infrastructure projects with respect to archaeological and cultural heritage surveys.

Combining and preparing data for archaeological and cultural heritage use

- Geodata may be advantageously combined into a single GIS project.
- Any categorical vector data (e.g. soil types) should be styled so as to differentiate between categories. This applies to point, line and polygon data.
- If any symbology standards are preferred or to be adhered to for publication maps, these themes should be applied before the delivery of the data.
- Raster layers should have a symbology showing a colour or grey scale gradient from maximum to minimum values.
- These tasks may be undertaken by a technician without archaeological knowledge.
- All data preparation stages should be documented and the documentation should follow the data.

Geodata

- Geodata from SGU of the type evaluated in this report (bedrock, soil types, soil depth) could be used more extensively in the archaeological and cultural heritage survey process. These data can help locate areas of greater archaeological potential for different periods and types of remains, help understand modern vegetation in terms of human activity or natural processes and provide valuable information for planning fieldwork and sampling.
- These data should be provided as routine to archaeologists to help them plan fieldwork and predict areas of cultural heritage or archaeological interest.

Nature conservation survey

- Data and results from nature conservation surveys should be provided to archaeologists to assist in their interpretation of past landscapes.

- As any modern landscape is a product of past activities and processes, a discussion between those undertaking conservation surveys and the archaeologists would help ensure a more holistic understanding of the modern and past landscape.
- Nature conservation reports could include more detail on past landuse activities in areas of high or low biodiversity resulting from human activity, by referring to the work of archaeologists. They currently lack detail in their time depth and tend to simplify cultural history information which could be expressed in more detail for a richer view of the landscape.

Orthrophotos

- Orthophotos are an important source of landscape information for archaeologists and should be provided as routine. They provide information which can help in field survey and the location and interpretation of features. Their use as an analysis material, rather than just as background images, should be specified at the tender stage.
- High resolution photographs (<25cm/pixel) provide considerably more information that low resolution (>1m/pixel) and should be provided where available.
- More work is needed to assess the relative advantages of very high resolutions (<10cm/pixel) in relation to the difficulties caused by large file sizes (although as computing power increases this will become less of a problem).
- High resolution orthophotos may be used in combination with geodata for the identification of landscape elements affected by cultural activities. They may also be used to help in the identification of wetlands for palaeoenvironmental sampling.
- Orthophotos should always be provided with LiDAR data.

LiDAR/laser scanning

- LiDAR surveys can be used advantageously for a number of tasks in archaeological and cultural heritage survey. This includes as a data source in assessing the potential impact of planned development on areas of cultural heritage value. LiDAR data can be used for quality control of existing cultural heritage records (many of which are incorrectly located in the National Heritage database).
- They also provide useful data for visualization and presentation and may help when communicating and discussing project information between sectors.
- LiDAR data may be used in combination with field survey to improve the detection rate of archaeological sites (over just field survey).
- Access to LiDAR data early in the project is essential for interpreting the landscape and planning field survey. This will help ensure time schedules are met by increasing the probability of locating cultural heritage objects early.
- Their use requires an archaeologist trained the use and interpretation of these data. If available and relevant for the area studied, semi-automated identification tools may be employed by these experts, but these skills cannot be replaced by non-archaeologist technical staff.

- Local high density laser scanning is much preferable to using data from the national elevation model (Lantmäteriet) as the latter is scanned at too poor a point density for reliable archaeological use. The national model's processed data also filters out some archaeological features.

- Laser scanning should be undertaken, if possible, with a point density of ca. 5 points per square metre. Scanning between 2-5 ppsm is acceptable, but lower point densities mean less reliable identification of remains and more time in the field. Scanning with >5 ppsm provides useful data, but may not improve the reliability of interpretation and is currently not considered cost effective. However, higher densities may be useful for semi-automated processing techniques which are currently under development. Low resolution data may be sufficient for quality control of the location of some existing cultural heritage data.

- Scanning should preferably be undertaken during the spring, after snow has melted, whilst last year's vegetation is compressed, and before new vegetation has started to grow or develop leaves. Excess surface water may reduce the reliability of LiDAR data and scanning of excessively wet ground should be avoided. Autumn, after deciduous trees have dropped their leaves is acceptable as second choice. Some environments, such as open pine heaths or bare ground, may also be scanned effectively during the summer.

- Provision of the data as appropriate file types (DEM) is essential for efficient workflow. Required file types should be established as early as possible and data delivered on a memory stick or harddrive. A LiDAR competent archaeologist will most likely prefer the data as LAS files and DEM files (raster/TIFF). It may also be useful to provide processed raster data such as hillshade and/or multiple hillshade images. Preparation of these files could probably be undertaken by a technician according to archaeological directions, but further discussion is necessary.

- All information on the scanning process and processing (point categorization, filtering, interpolation method) of files must accompany any data to ensure correct interpretation.

- The advantages of using Trafikverkets own data should be investigated more thoroughly with the help of archaeological LiDAR and field survey experts.

- In any project, we recommend a comparison of existing data on archaeological sites in the National Heritage database and Forestry Agency's 'Forest and History' database with results from an analysis of LiDAR data for the same region. This will help assess the detection efficiency of using the LiDAR data for different environments and vegetation types.

GPR/Georadar

- GPR surveys should be undertaken by contractors *with published experience of georadar for archaeological prospection* and the interpretation of GPR data with respect to buried archaeological features.

- The archaeological interpretation of georadargrams cannot be undertaken by technicians without training in the archaeological use of the method and its interpretation.

- Tendering information should include close parallel scans and the production of 3D data from which horizontal and vertical transects and plans can be extracted for an assessment

of the extent and depth of potential archaeological remains. Interpretation must include an archaeological assessment of the GPR results if it is to be useful to archaeologists.

Other prospection methods

- Geoarchaeological prospection should always be used to delineate areas which have the highest probability of containing buried archaeological remains *prior* to any form of excavation. This should be followed by test trenching to obtain more details on the results and finally full excavation if required.
- The appropriate choice of prospection methods (e.g. soil chemistry, resistivity, magnetometer, magnetic susceptibility etc.) will depend on the type of soils, depth of sediments, rockiness and vegetation cover. Providing access to geodata at the archaeological project tendering stage will help archaeologists assess the most appropriate set of methods and provide a more accurate budget.
- Pollen, plant macrofossil and fossil insect analyses can be used to reconstruct past environments and climates. They may provide information on how a landscape has been manipulated by people in the past and are essential for the interpretation of any archaeological site's place in the landscape. By test analysing potential organic deposits at the prospection stage, it may be possible to reduce the time needed for locating suitable deposits in a later archaeological project, and lead to a more rapid delivery of integrated results.
- The results of all of these prospection methods, especially those with spatial sampling, can be integrated through GIS and help in final analyses.

Field survey

- Although the use of LiDAR and orthophotos can improve the efficiency of archaeological and cultural heritage survey, they cannot remove the need for field survey to ensure the correct classification of all relevant features in an area.

Other useful data which could be provided

Other data sources, not covered in the evaluation material, may be useful for several purposes in the evaluation of cultural and environmental impact of a planned project.

- Historical orthophotos provide information on recent landscape change and historical landuse. Their provision helps in the analysis of modern orthophotos, and the identification of modern versus earlier landscape changes.
- Historical coastline data is important for understanding the landscape context of any site below the highest prehistoric coastline. They should be provided as shapefiles for the area to be investigated.

Suggestions for efficient use of other data, sampling and analysis

In preparing this report a number of processes and data types were identified which should be investigated further. These should be evaluated in terms of the feasibility of using the material or data retrieved for other purposes in order to improve the efficiency of the complete project. This may entail changes to tendering processes and order information.

- Workflow models should be designed which include data collection, processing and type requirements specification and sharing between consultancy groups (e.g. archaeologists and nature conservation). This will reduce the need for different groups to retrieve data themselves and save time throughout the project.

- Boreholes or cores which provide organic sediments (peats, organic silts and clays) could be used for palaeoenvironmental prospection. I.e. retrieved organic sediments could be tested for the presence of preserved and identifiable (sub)fossil plant and animal parts (e.g. pollen, insects and seeds). Information on preservation allows the sediments to be assess as to their viability as sources for palaeoenvironmental or climate reconstruction. Initial radiocarbon dates could be obtained from this material to help in the interpretation of archaeological features and landscapes in the area.
  Discussion on appropriate coring machinery should be initiated to ensure the retrieval of useful, uncontaminated material from known depths. Some motorised coring equipment does not produce stratigraphically intact cores and may not be appropriate for this type of use.
  Sediments used for this purpose must be handled so as to avoid contamination with other organic sediments or modern material. They must be sampled, described, bagged and labelled as quickly as possible after extraction. They must never be allowed to dry out and should not be rehydrated if dried.
  Further research should be undertaken to test the feasibility of the above concept and identify any recommendations for future project planning.

- Boreholes or cores which retrieve stratigraphically intact sediments could be used to describe the late Quaternary geology of the area, and thus provide valuable data on past sediment movements and landuse.

- Results from the analysis of some of the data covered in this report could be fed back to government authorities (e.g. SGU, Board of Agriculture) to improve the publically available national data on soils, peats and Quaternary sediments.

- Further information from the Forestry Administration on the age of woodland may prove useful when interpreting LiDAR data and orthophotos in terms of modern versus historical landuse.

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Appendixes

Appendix 1. Technical description of archaeological relevance of files

Specific details of the potential for archaeological and cultural heritage survey of the individual files provided by the Transport Administration. The files are grouped as they were delivered to MAL for analysis, which more or less mirrors the categories used for the delivery of geographical data from SGU and other sources. For complete lists of SGU's layers, and data classifications within them, see https://www.sgu.se/produkter/geologiska-data/vara-data-per-amnesomrade/.

Geotechnical data

Bedrock (SGU category: berggrund)

Bedrock information is particularly useful when planning field surveys or conducting archaeological research. The resolution and accuracy of the data will affect the potential for accurate planning, although this is more important for sampling strategies than field survey.

Bedrock (berggrund)

Shapefile: [berggrundsytor], polygon

- Useful for identifying potential, or lack of locally available, stone material sources (e.g. diabase/dolerite, slates, soapstone, asbestos).
- May explain patterns in geoarchaeological data and vegetation or landuse (e.g. over deformation zones or faults).

Outcrops (Hällar)

Shapefile: [hallar], polygon

- Provides information on potential stone resource sites.
- Information on potential sites for rock/outcrop bound site sypes (e.g. rock art and some burial types).

Soil types and geomorphology (SGU category: jordarter)

Geomorphology/Landforms (Landform)

Shapefile: [jordart_25_100k_lf/Landform], polygon

- Includes location of geomorphological features (e.g. drumlins, moraine ridges) of importance in locating and understanding archaeological sites and landscapes.
- Especially important for predicting the location of prehistoric settlements when surveying.

Surface blockiness (Blockighet i markytan)

Shapefile: [jordart_25_100k_bl], polygon

- Important background information for field survey of raised beaches (e.g. *boplatsgrop i klapperstensfält*).
- Provides information on the accessibility of an area for field walking and soil sampling

Soil types

Soil type data are potentially extremely useful in archaeology. Data were provided in four layers:

1. Soil type in thin or non-contiguous upper surface layer (Jordart i tunt eller osammanhängande översta ytlager):

Shapefile: [jordart_25_100k_jy0], polygon (upper surface layer)

2. Soil type in thin or non-contiguous surface layer (Jordart i tunt eller osammanhängande ytlager):

Shapefile: [jordart_25_100k_jy1], polygon

3. Soil type in shallow layers (Jordart i grundlager):

Shapefile: [jordart_25_100k_jg2], polygon

4. Soil types in deep layers (Jordart i djuplager):

Shapefile: [jordart_25_100k_jd3], polygon

- Surface layers provide similar information to shallow layers, but for more recent or superposed deposits.
- Presence of peat in different layers provides potentially useful information on peat ages and cultural use: If peats are present in surface but not the deeper layers, they may be assumed to be young or have been mined.
- General grain size information is useful for prospection and designing research strategies.
- Identifying areas where sites may have been covered by windblown sands (aeolian), river sediments (alluvium) or other transported sediments (colluvium).
- Locating peats which could be tested for palaeoecological coring or bulk sampling (e.g. pollen, plant macrofossils, insects) potential.
- Locating raised beaches (former coastlines, lake shores), which are often targeted for archaeological survey and frequently produce archaeological sites.
- Distinguishing between glacial and postglacial sediments can give an indication of the potential age of sites.
- Lakes and rivers are classified and thus easily marked in maps (Fields JG2=91, JG2-TX="Vatten").
- May be used to help predict potential for sediments containing cultural information
- May be used to help interpret traces of older landuse.
- May help in the identification of sediment movement (mass wasting) and potentially covered or eroded sites.
- The location of kettle holes (*dödisgropar*) may help when looking for good palaeoenvironmental coring sites.

Soil Depth (Jorddjup)

Shapefiles: bergyta (50x50m raster - m over sea level), jorddjup (10x10m, 1m z)

- Useful for estimating potential for burial of archaeological remains (e.g. under sand dunes, river deposits or peats).
- Useful for planning soil sampling and coring.
- Used together with soil type map layers (jy, jg, jd).
- Difference in usage possibilities between soil depth and soil depth as interval is unclear in the evaluation context.

Shapefile: jorddjup underlag (points)

- Shows points from which soil depth is interpolated.
- Useful for quality control/error evaluation of soil depth data, and looking for explanations where archaeological and soil depth data may disagree.

Nature conservation evaluation (Naturvärdesinventering)

Shapefile: Hedkammen (polygon)
Shapefile: Naturvärdesobjekt (polygon)
Report: NVI Norrbotniabanan.pdf

- Preliminary data provided - objects and data keys missing. Cursory evaluation possible, but not linking of objects to other layers and information in report.
- Good for providing a holistic overview of natural and cultural heritage in an area.
- Possibilities for synergies with archaeology, as some cultural landscape elements and their biodiversity can be explained by their archaeology.

Laserscanning SE

Files: Dwg, xyz and kmz-filer

- LiDAR is an extremely useful information source for archaeological survey. The usefulness is highly dependent on: scanning point density and reliability (e.g. season and purpose of scan), filtering and processing used, resolution of DEM, type of terrain and landscape (e.g. woodland or open fields) and the types of remains to be looked for.
- Combined archaeological and LiDAR interpretation skills and experience is essential for using these data.
- Difficult for most archaeologists to use DWG files due to lack of access to CAD software. Processing and use of these files is also suboptimal for archaeological purposes.
- XYZ data (point cloud) may be useful for some archaeologists but is not ideal except for advanced analyses and along with other formats.
- LAS format raw data, TIFF format raster interpolated DEM data are ideal for archaeological use

Ortofoto (5 cm) (Skellefteå kommun)

Tiff & tfw-files

- Excellent detail for archaeological purposes, but large file size difficult to handle. Lower resolution (10cm/pixel?) might be more efficient but this needs to be investigated.
- Provides a landscape overview, background for maps and allows for potential to see cropmarks and other cultural remains.
- Ecw - format files are not generally useful for archaeologists who use traditional image formats more often.
- Multispectral data from the same areas would also be useful

Ground Penetrating Radar, GPR (Markradar)

Provided as technical report.

- GPR has great potential in some types of sediment and landscape, but not others.
- Provided material was of little archaeological use. Anomalies were not described in a useful way for helping archaeological interpretation of buried features.
- Future work should be undertaken by a company with proven, published track record of archaeological GPR use and interpretation.
- Excavation is always necessary to evaluate identified features (if they are to be disturbed).

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