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Article

The Potential of New LiDAR Datasets for Archaeology in Switzerland

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Abstract: LiDAR and its derived elevation models have revolutionized archaeological research in forested areas around the globe. Almost a third of Switzerland is covered in forests. The number of archaeological sites recorded in forests in Switzerland is, however, limited. Given these circumstances, it is surprising how underutilized LiDAR data are in archaeological research in the country. As the Federal Office of Topography swisstopo is finalizing the acquisition of new LiDAR datasets, increasing the covered area and allowing for limited time series analyses, these data should be used to the fullest extent. This article describes the open access datasets and elaborates on their potential for archaeological research and cultural heritage management. By employing LiDAR data on a large scale, Swiss archaeological research would likely substantially increase the number of recorded heritage sites. Additionally, this will have the effect of complementing the palimpsests of past anthropogenic activity throughout the landscape while reducing survey biases in the archaeological record.

Keywords: LiDAR; alpine archaeology; canopy; landscape archaeology; Switzerland; digital elevation models; cultural heritage management

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1. LiDAR in Archaeology

Airborne laser scanning studies have revolutionized our understanding of the archaeological record over the past two decades, in particular in densely forested areas, which are difficult to explore with other remote sensing techniques. Substantial improvements in technology have increased the quality and quantity of the collected data [1]. This has led to a plethora of applications in archaeological research across the world from individual monuments to archaeological landscapes [2–10]. LiDAR technology has arguably had the largest impact on archaeological fields where a substantial portion of the area of interest is veiled by a dense canopy. Entire archaeological landscapes with agricultural and water management systems, urban settlements, and road networks have been revealed [11,12]. Many of these were partially known before, but their real extent remained hidden despite painstaking decade-long survey work and minute mapping activities. Collecting LiDAR data allowed both a detailed and broad-scale look at the extent of anthropogenic activities enabling a multiscalar approach to studying the archaeological heritage of these regions. The data helped immensely in contextualizing the work accomplished by archaeologists in the field and helped direct renewed research efforts. In Belize, a combined remote sensing survey including LiDAR revealed Mayan land-use patterns and their impact on later reforestation [13,14]. The discovery of mound villages, geoglyphs, and road networks begin to change our understanding of southwestern Amazonia and challenge long-held beliefs that the area saw little settlement activity [15]. LiDAR also drives the mapping of Khmer capitals located near Angkor, revealing planned urban landscapes at large scales [16]. In North America, LiDAR data have expanded cultural heritage inventories [17], helped gain a more complete understanding of archaeological and historical landscapes [18,19], and contribute to assess the impact of humans as geomorphic agents [20]. These are but a few regions in which it is not an understatement to call the addition of LiDAR to the archaeologist's toolbox revolutionary.

LiDAR has not been applied for archaeological research on a national scale in Switzerland. While it is integrated into several case studies and is often a part of contextualization for local excavation projects, the data source overall remains underexploited. There are ongoing cantonal (state level) and federal-administration-sponsored LiDAR data acquisition projects, which allow users to access data free of charge and offer derivative products that are easily integrated into existing Geographic Information Systems for cultural heritage management. The data were employed for the small-scale prospection of potential prehistoric settlement sites in Canton Obwalden [21]. A creative application of shallow-depth bathymetry for archaeological research by means of LiDAR was employed by archaeologists in Canton Zug where the researchers re-documented shallow-water mound features [22]. Shallow-water bathymetry played a similar contextualizing role in the documentation of stone mound features in Lake Constance [23]. Canton Bern saw the discovery and documentation of several unknown castle sites in the Emmental [24,25]. Another obvious application of these data lies in the area of surveying and mapping Oppida [26]. The monitoring of glacial archaeological sites in the Alps is so far limited by the time depth of the available data [27,28]. These selected case studies already show that LiDAR data have the potential to substantially complement the known archaeological record in Switzerland both on land as well as in shallow water. Here, the newly produced LiDAR data and their derived products by swisstopo are introduced. Based on several different individual archaeological sites in Switzerland, the potential of these data is elaborated upon.

2. Forested Areas in Switzerland

Switzerland is extensively forested (Figure 1). In 2020, forests cover 31% of the nation's surface area, totaling more than 12,683 km^2 [29]. In the south of the Alps, around 50% of the area is forested, while in the Jura Mountains, ca. 48% of the area is covered in forests. The urban and agriculturally intensively utilized Mittelland and the foothills of the Alps are still covered in 23% and 37% of woods, respectively. In the high mountain terrain, forests cover around 24% of the terrain [30]. The forest line lies at a maximum of 2500 m a.s.l. in the central Alps (particularly in the Valais and Engadin), but it can be lower elsewhere depending on local microclimates [31]. The close correlation between tree growth and temperature suggests that a warming climate will rise both forest and timber lines over the coming decades; however, the decreasing grazing pressure on pastures might also play a role in gradual reforestation [32]. Notably, 8960 km^2, or 71%, of all forests are publicly owned, while the rest remains privately held [29].

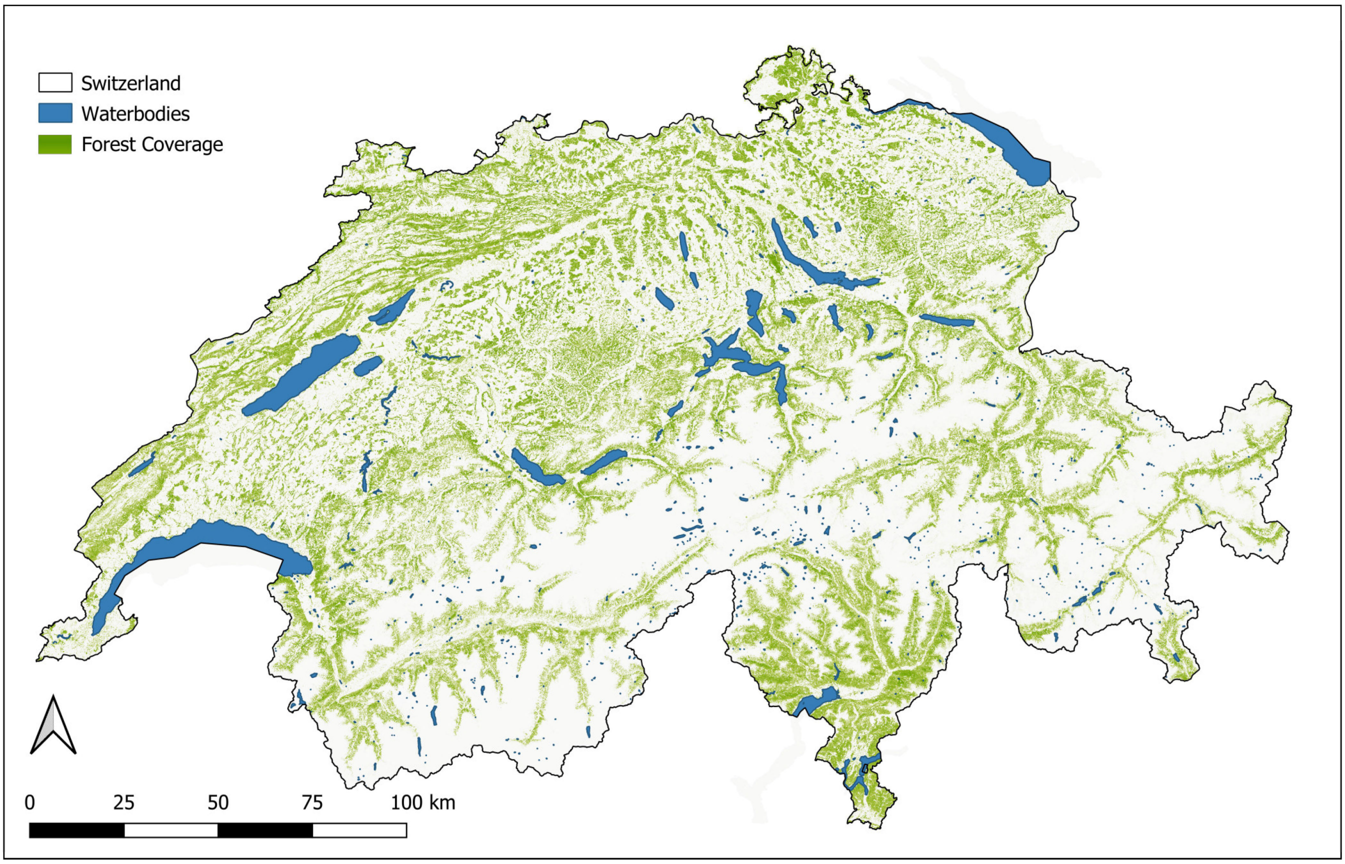

Figure 1. Areas of Switzerland covered in forests based on a vegetation height model from 2019 by Ginzler and Hobi [33]. Adapted with permission from [33], 2015, Ginzler and Hobi.

Roughly, a third of Switzerland cannot be comprehensively surveyed by means of remote sensing if not for LiDAR data. While some sites in forests are well known and have been excavated, it is very likely that there is a significant bias toward recording sites in open terrain. In many areas of Switzerland, cultural heritage law is intricately linked to building legislation and thus enforces the recording of sites more often in urban contexts, namely during construction activities. As forested areas are generally not part of the land that is cleared for construction, this leads to a situation where sites in forested areas are less often recorded, there is only infrequent demand to excavate them, and thus fewer resources are available for their documentation. Figure 2 shows part of the inventory of archaeological sites of the Canton of Bern correlated with the areas of the canton covered in forest. The ground cover shapefiles of the swissTLM3D data collection are used to separate forests from agricultural and urbanized areas [34]. Out of 4225 entries in the database, 1221 lie within the borders of these polygons and are thus situated in or at the very least close to forests. The heterogeneous nature of the cultural heritage database has to be taken into account. Point features include settlement sites, individual buildings such as churches, individual burials, and burial sites with multiple archaeological features, as well as chance finds. This shows that a significant portion of cultural heritage sites in Switzerland are lying in forested areas and are thus difficult to detect with remote sensing methods other than LiDAR. Certain areas show a strong bias toward sites in non-forested areas such as the western parts of the Canton of Bern. It is reasonable to assume that there is significant potential in exploring these areas with LiDAR, surveying what lies beneath the canopy.

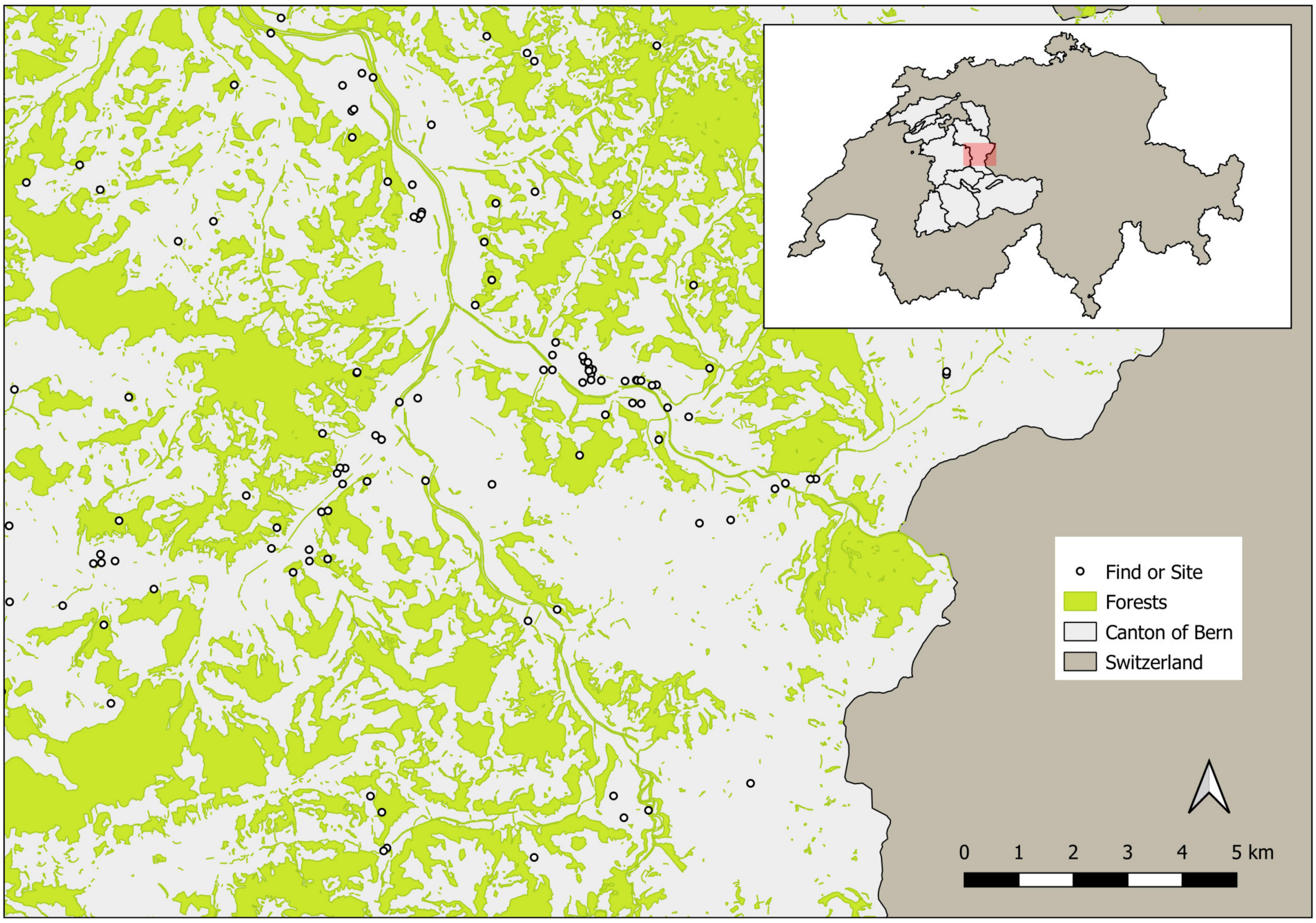

Figure 2. The inventory of archaeological sites of the Canton of Bern combined with forest ground cover shapefiles from the swissTLM3D data collection. A bias toward site locations in non-forested areas is apparent in this area.

3. The Swisstopo Data Collection

The current LiDAR acquisition campaign started in 2017 and will be finalized in 2024. Data for northeastern Switzerland were generated in 2017–2018. From 2018 to 2019, LiDAR data for western Switzerland were created. Central Switzerland and the Ticino were covered in 2019–2020. From 2020 to 2021, the Grisons and from 2021 to 2022 the Valais and Jura were covered by the campaign. Gaps remain, particularly for the Canton of Bern, Solothurn, as well as Basel Stadt and Basel Landschaft, with a planned end of the data acquisition in 2023. All data from the campaign will be published by the end of 2024. A new LiDAR campaign is already in the planning stage, ultimately allowing for several LiDAR datasets to be available with roughly a six-year gap in between. The national LiDAR campaign is supplemented with data provided by various cantons if they match the quality criteria [35].

Swisstopo aims to publish datasets with a minimum of 5 pts/m^2 and an average of 15–20 pts/m^2. LiDAR campaigns are planned so that there is minimal snow and foliage coverage. Datasets have a location accuracy of 0.2 m (1σ) and an elevation accuracy of 0.1 m (1σ) [35]. Several LiDAR-derived datasets are created by swisstopo and made available to the public free of charge (Figure 3).

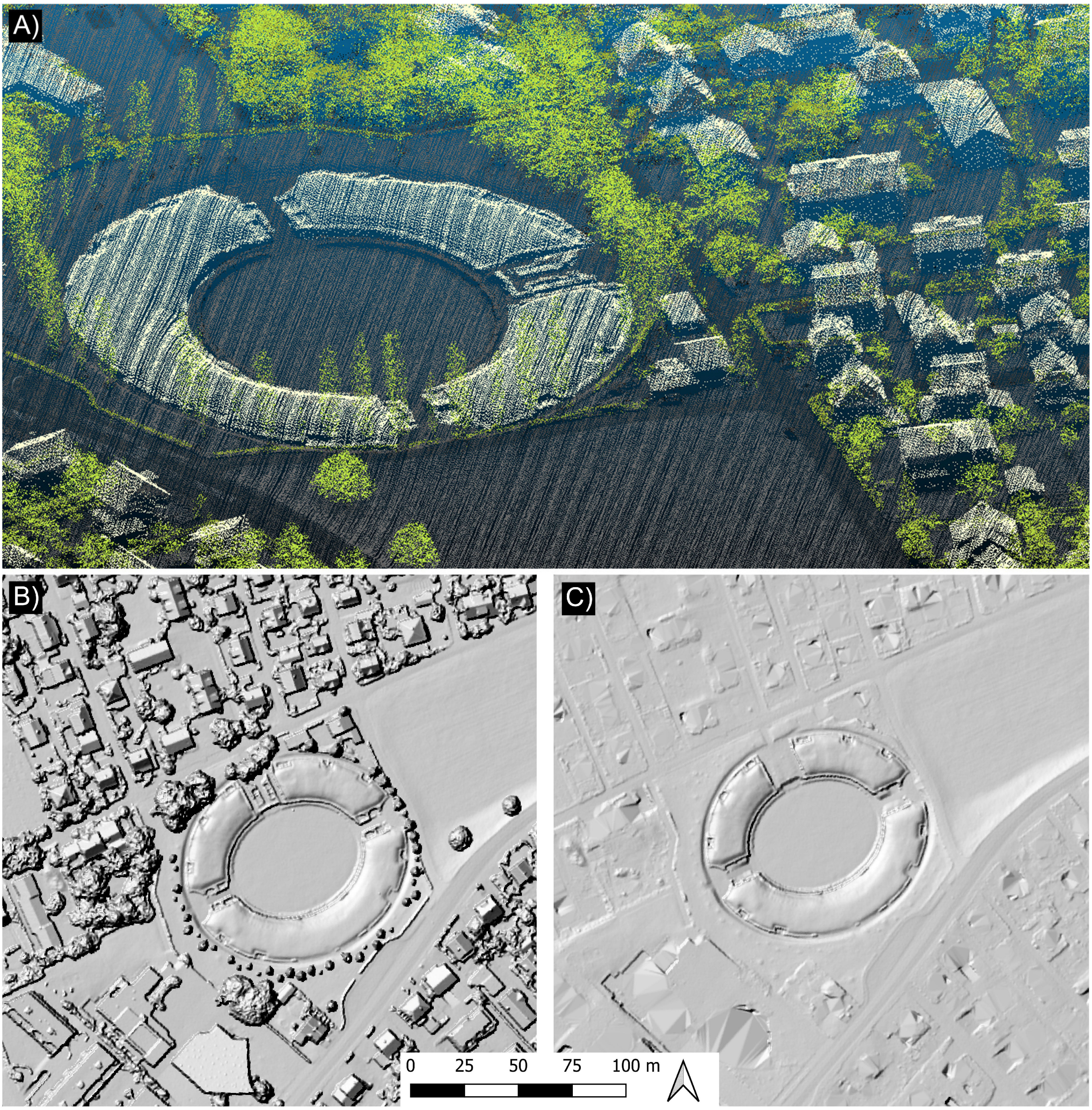

Figure 3. The different LiDAR-derived open access datasets provided by swisstopo side by side covering the Roman amphitheater in Vindonissa/Windisch (Canton Aargau): (**A**) swissSURFACE^{3D} Point Cloud; (**B**) hillshade of LiDAR-derived swissSURFACE^{3D} Raster; (**C**) hillshade of LiDAR-derived swissALTI3D (©swisstopo).

3.1. swissSURFACE^{3D} Point Cloud

The swissSURFACE^{3D} product is a classified point cloud that is supplied in a LAS format in tiles of 1 km^2 [36]. The classification follows the American Society for Photogrammetry and Remote Sensing (ASPRS) standards for LiDAR point cloud classification [37,38] but makes small modifications. The datasets are classified into six classes, which are displayed in Table 1. The dataset was cleaned of noise. Swisstopo is working with private companies to generate LiDAR datasets. Slightly different processing techniques and points in time for the acquisition can lead to varying point densities and aberrations within the product.

Table 1. ASPRS classes and therein included types of objects for the swissSURFACE^{3D} product [36].

Class	Type of Object	ASPRS Nomenclature
1	temporary or unclassified objects	unclassified
2	ground	ground
3	vegetation including low, medium, and high	low vegetation
6	buildings	buildings
9	water	water
17	bridges, overpasses, and viaducts	bridge deck

3.2. LiDAR-Derived swissSURFACE^{3D} Raster

The swissSURFACE^{3D} Raster is a LiDAR-derived digital surface model (DSM) with a resolution of 0.5 m [39]. Poles and power lines are excluded from the DSM generation while using classes 2, 3, 6, 9, and 17 of the processed LiDAR point cloud (see Table 1). Water bodies are calculated separately, and the interpolation of the point cloud is accomplished by using a "spike-free algorithm"—possibly following the article by Khosravipour et al. [40], but it is not clearly specified which algorithm is used. The product is iteratively generated as new LiDAR data become available. The raster is supplied as a cloud-optimized GeoTIFF. As of early 2023, eastern and central Switzerland, the Grisons, and the Ticino, as well as western Switzerland including the Canton of Vaud, Geneva, Fribourg, Neuchâtel, and Jura, are available for download in 1 km^2 tiles. The LiDAR coverage of the Valais, Canton of Bern, and Solothurn, as well as Basel Stadt and Basel Landschaft, are still to be created. The product is scheduled to be completed in 2025 [39].

3.3. LiDAR-Derived swissALTI3D

The swissALTI3D product is a digital terrain model mostly based on LiDAR data. The data can be downloaded in a resolution of 0.5 m, 2.0 m, 5.0 m, and 10.0 m in tiles of 1 km^2 as a cloud-optimized GeoTIFF [41]. Due to the heterogeneous data sources, swissALTI3D does not have consistent accuracy. The 0.5 m resolution raster data, which are most relevant for archaeological applications, have an accuracy of 0.3 m for LiDAR-derived parts of the dataset, 0.5 m accuracy for photogrammetrically created parts of the dataset below 2000 m a.s.l., and 1.0–3.0 m accuracy for photogrammetrically covered areas above 2000 m a.s.l. [41]. The swissALTI3D product is constantly being developed, and swisstopo pushes for one to two updates per year. Specific changes are documented in detail in [42].

4. Surveying

The introductory paragraph on vegetation coverage in Switzerland has already shown that roughly one-third of the country is forested, and thus there is significant potential for the discovery of new archaeological features. While the visual interpretation of hillshades and LiDAR-derived terrain models will likely remain the standard for some time, the consistent coverage of the country with relatively homogeneous data makes it ideal for machine learning applications.

Recent years have seen rapid growth in the number of applications of automatic detection in archaeological remote sensing, particularly in the subcategory of deep learning [43–48]. Given sufficient training data, convolutional neural networks have been shown to be especially promising in centering on actual archaeological sites while diminishing the number of false-positive detections. Nonetheless, there has been an ongoing debate about their usefulness in archaeology, largely due to the significant resources required for the implementation of these models, including large volumes of training data and specialized expertise [49]. The rarity of archaeological sites can make it difficult to gather enough data to train a deep learning model effectively. This appears to be a problem that can be overcome by pooling resources from various cantonal archaeological entities for the acquisition of training data for largely homogeneous categories of sites. As the jurisdiction over archaeological heritage is rooted in cantonal legislation, and resources are thus potentially unevenly distributed, such an approach might run into considerable bureaucratic hurdles.

Nonetheless, a limited approach through visual interpretation can also improve and complement the inventories of cantonal heritage administrations. On-ground archaeological surveys in forests are difficult even during times of the year when there is little to no foliage (Figure 4). The subtle terrain differences through which archaeological sites can be recognized are easily obscured by trees, dense shrubs, and undergrowth. Figure 4 shows a large grave mound with 30.1 m east–west and 27.4 m north–south diameter. What is easily recognizable using LiDAR data looks much different with vegetation in the way. This sizeable monument is hidden quite well from the view of passers-by. Smaller monuments can be almost impossible to recognize when covered in ground shrubs, dead branches, and leaves. It is therefore instrumental for surveys in woodlands to utilize the available LiDAR data to not only contextualize but also recognize archaeological sites in the first place. There is little doubt that the number of recorded sites in forested areas would increase if systematic remote sensing surveys based on LiDAR data were performed. Cost arguments that hold true for many places in which LiDAR data have to be paid for or have to be generated in the first place have little validity in the context of Swiss archaeology.

Figure 4. Limited visibility even of large monuments is a defining hurdle for woodland surveys. This burial mound is not easily recognized until a survey participant essentially stands on top of it recognizing its shape. Contextualizing LiDAR data make the recognition much easier (©swisstopo).

5. Re-Documentation

Diverse archaeological sites in Switzerland were first documented in the 19th and 20th centuries with hand-drawn plans and limited cartographic accuracy. The LiDAR datasets by swisstopo allow for a relatively quick, resource-efficient, and highly accurate re-documentation of archaeological heritage sites. These LiDAR datasets also provide a common minimum standard for documentation. This renders the cross-comparison of larger architectural sites easier and supports the analytical processes archaeologists use to understand landscapes.

The forested plateau located above the confluence of the rivers Saane and Glâne in Posieux (Canton Fribourg), for example, first came to the attention of archaeologists in 1861, when a defensive wall and large limestone blocks were noted. Prehistoric artifacts, including a Neolithic axehead and a Bronze Age socketed axe, were discovered. It was not until 1973 that the significance of the site of Châtillon-sur-Glâne was recognized as a hilltop settlement dating to the Iron Age. The site is now known for its rich finds of imports, including shards of Greek black-figured ware, pseudo-Ionian pottery from southern France, amphorae from Marseilles, and other items from the Mediterranean. This has led to a recognition of Châtillon-sur-Glâne as an important node in the north–south oriented trading networks between the Mediterranean and the peoples north of the Alps. Extensive excavations started in 1974, leading to the discovery of domestic architecture [50,51].

Georeferencing previously published maps over the highly accurate LiDAR-derived digital elevation model (DEM) is a simple way to cross-check documentations, detect changes, map additional structures, and determine potential inaccuracies (Figure 5). An ambient occlusion algorithm by Z. Čučković [52], which simulates scattered diffuse light bouncing off of surfaces, was applied to the data in QGIS (further information regarding visualization is elaborated upon in [7]). This results in an image of the terrain that is easily legible and looks softer than the metallic high-contrast result of a hillshade calculation. The site map of the 1983 publication [51] was then overlaid in multiply mode in QGIS. The multiply mode creates the pixel product of the values of the upper layer with those of the layer below it and then divides the result by 255. This leads to white pixels vanishing and dark pixels remaining visible, effectively isolating the lines and writing on the overlaid map. This is a simple and effective tool to compare different records of the same site and allows for a comparison between sites without the potential visual confusion different map styles and documentation standards create.

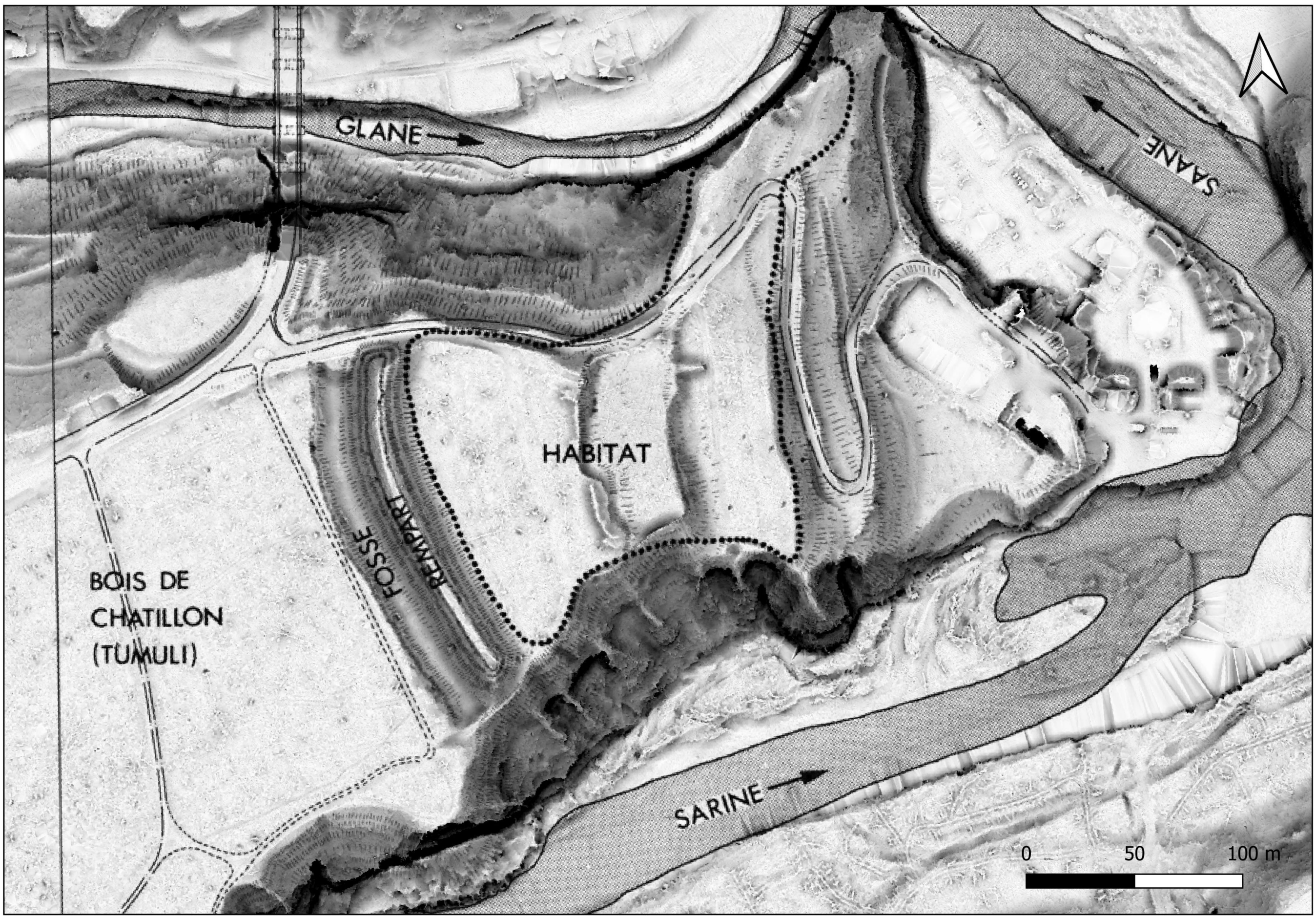

Figure 5. An overlay in multiply mode of the 1983 map of Châtillon-sur-Glâne [51] on the ambient occlusion map derived from the LiDAR-based swissSURFACE^{3D} Raster (©swisstopo). This map is turned 4° west to accommodate for the slight deviation of the north arrow on the 1983 map.

6. Monitoring and Protection

It is obvious that knowing what archaeological sites exist is a first step toward protecting them from destructive anthropogenic activities. Looting is not as much of a problem in Switzerland as it is in less politically stable areas of the world, cf. [53–56], but occasional incidents are known. In the case of the bronze hand of Prêles (Canton of Bern), detectorists recovered the so far earliest part of a human bronze sculpture in Central Europe [57]. Even though the find was made in 2017, it was hailed as one of 2018′s top 10 discoveries by the magazine *Archaeology* and received significant public attention [58]. Residues of the adhesive between bronze hand and gold wristband were dated to around 3500 years ago. Possible additional artifacts might have vanished from the site before it could be archaeologically investigated [57]. This obscured the context of an extremely rare archaeological item and shows that even in the limited number of cases of looting in Switzerland, significant damage can be inflicted on our knowledge of the past. However, arguably a larger danger to cultural heritage in Switzerland is the destruction through unmonitored construction activities. The establishment of a more complete inventory of archaeological sites would certainly increase the efficiency and effectiveness of archaeological heritage protection.

During the research for this paper, several mound structures were found. At the time of the writing of this paper, many of them are not part of the publicly accessible database of archaeological heritage sites in their respective cantons. It can thus be assumed that these sites, which are lying under forest canopies, have so far not been properly recorded. Figure 6 shows a double-mound structure that has been recently and severely impacted by forest operations. Based on the LiDAR data, the western mound measures 16.1 m east–west and 18.2 m north–south. The eastern mound measures 18.3 m east–west and 19.5 m north–south. The eastern mound exhibits traces of heavy forest machinery. The tracks leading right over the mound are up to 0.3 m deep. The weight and compression of the soil might have caused irreparable damage to archaeological artifacts and human remains inside the mound. Of course, foresters cannot be expected to recognize mound structures as archaeological monuments. However, an updated inventory of archaeological heritage sites in forested areas and communication between the cantonal and communal administration might have prevented the damage and preserved the monument in its pristine state.

It is likely that many other important monuments are being damaged through forest operations, but estimating the damage incurred is not possible due to a lack of survey efforts underneath the canopy of Swiss forests. The awareness of archaeological heritage in forested regions is low. While the limited visibility of monuments in forests might protect them from other anthropogenic disturbances, it makes them prone to damage caused by forest operations. Monuments in forests are often in excellent condition, because they have less often been impacted by agricultural activities such as plowing, but the use of heavy machinery for timber harvesting changes this. A more complete inventory of archaeological sites in forests could raise awareness and allow timber-harvest planning to take into account the vulnerability of archaeological heritage.

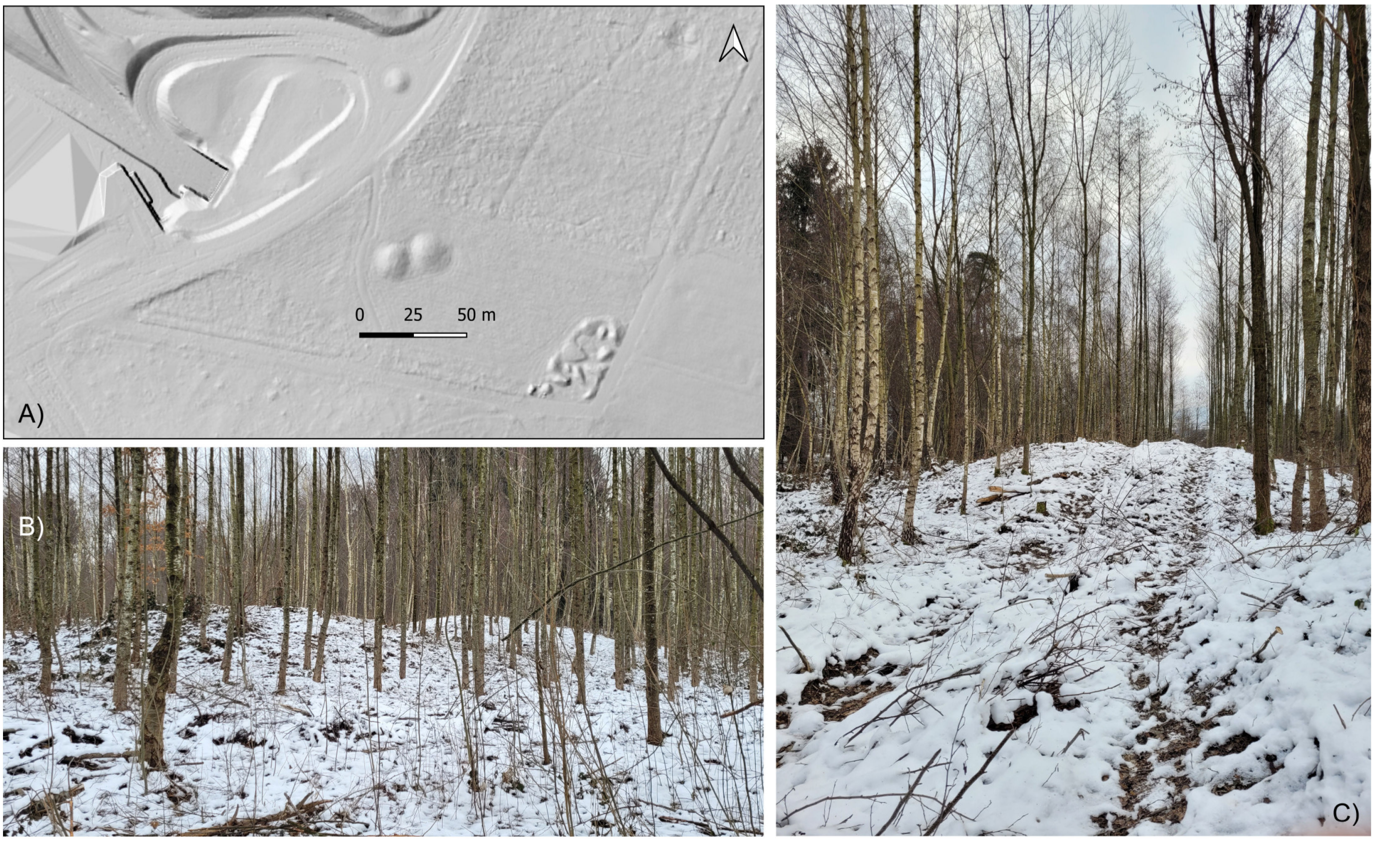

Figure 6. (**A**) The double-mound structure in a LiDAR-derived DEM (©swisstopo); (**B**) mound structures are currently not in the publicly accessible inventory of sites of the Canton of Bern; (**C**) the eastern mound has been heavily impacted by forest operations.

Further opportunities for the monitoring of archaeological sites in forests will arise with the renewed acquisition of LiDAR data by swisstopo. Swiss mapping authorities will continue the data collection efforts across the entire country with a time interval of approximately six years [35]. This will provide time depth to the dataset and allow for monitoring the changes in the terrain surrounding archaeological sites. The temporally diverging datasets will allow researchers to track larger movements of soil through both natural erosion and anthropogenic activities and thus help to assess the state of archaeological sites underneath the canopy.

7. Visualization

The opportunities for displaying LiDAR data are immense and can be adapted for the specific situation with a large degree of creative freedom. Basic DEM visualization by means of relief shading and other techniques is covered in [59]. Some have found that the often-applied hillshade calculations are in some cases not the ideal way to visualize archaeological features in LiDAR data and that a multimethod visualization yields better results [60]. A number of more recent case studies introduce additional visualization algorithms and discuss them in detail [61–64]. It is important to point out that the selection from the wide choice of visualization techniques should be informed by the purpose for which the visualization is needed. An archaeological researcher who would like to map faint structures underneath the canopy will likely make a different choice than a science communicator who wants to illustrate the architectural history of a medieval castle. This paper merely presents a visualization example, showing the potential of utilizing the swisstopo open access LiDAR datasets for a wide range of applications in archaeology.

The Castle Laufen was constructed on an outcrop overlooking the Rhine Falls. It is a Swiss heritage site of national significance located in the municipality of Laufen–Uhwiesen in the Canton of Zürich. The castle was first mentioned in written sources in 858 AD. In 1449 AD, it was besieged during the Old Zürich War and acquired by the City of Zürich in 1544, which lead to additional construction, including a curtain wall, gate tower, and the draw bridge. With the invasion of Napoleon in the late 18th century, the feudal order came to an end, and the castle ultimately ended up in private hands. In 1941, the City of Zürich reacquired the castle and subsequently renovated it.

For visualization, the swissSURFACE^{3D} Point Cloud dataset was downloaded as a LAS file. The point cloud was imported into the open source software CloudCompare v2.13 alpha ($\approx$13.5 million points). The dataset was split along the previously defined point classes (see Table 1) in order to allow for independent selection and coloration (Figure 7). Custom color ranges were created for the Rhine Falls, which are displayed through the ScanAngleRank field. As the areas around the castle are overgrown by vegetation and a full view of the architecture is thus not possible during most times of the year, the points associated with the vegetation were isolated and removed. Bare ground was colorized using greyscale color on the NumberOfReturns field. The bridge and buildings were colorized along a yellow-brown gradient using the Intensity field.

Figure 7. Top: Copper engraving of the Castle Laufen by D. Herrliberger, 1750. **Bottom**: Example of a visualization of the swissSURFACE^{3D} Point Cloud dataset (©swisstopo) in the open source software Cloud Compare.

8. The Potential of New LiDAR Datasets for Swiss Archaeology

With the acquisition of new LiDAR data over the course of the coming years, the coverage and the time depth of the open access dataset in Switzerland are increasing. Considering the easy access and the free-of-charge availability of the data, LiDAR remains surprisingly underutilized in Swiss archaeology. The fact that large areas of Switzerland are forested is a key factor in increasing the potential of LiDAR data for usage in Swiss archaeology. The archaeology of woodlands is relatively inaccessible by means of remote sensing methods other than LiDAR. Additionally, traditional on-ground archaeological surveys in forested areas are time-consuming, resource-intensive, and face difficulties due to the vegetation-induced limitations of visibility. This might be a reason why archaeological records in many areas of Switzerland are biased toward sites in open landscapes.

The advent of machine learning models for archaeological purposes has brought with it an immense reduction in the workload required for large-scale remote sensing surveys, and having access to homogeneous high-resolution datasets over large areas is an ideal precondition for employing them. The problem is that convolutional neural networks in particular need significant volumes of training data and expertise, which is not necessarily available at government agencies dealing with cultural heritage. However, even in a less involved form of utilization, LiDAR data and their derivatives can substantially contribute to the documentation of new sites and thus their entry into cantonal registries. While dealing with large point clouds requires some expertise and dedicated software, the swissALTI3D product by swisstopo allows for the simple exploitation of LiDAR data in the form of a tiled raster. These can be easily integrated into existing infrastructure at cantonal archaeological heritage management.

The increased documentation of archaeological heritage sites in forests is a precondition to preserving archaeological documentation. Employing LiDAR data in exploratory surveys quickly reveals that the current archaeological records are incomplete. This can in the worst case lead to the destruction of otherwise well-preserved ancient monuments through forest operations and other anthropogenic activities. The re-documentation of previously surveyed sites could help to increase the quality of comparative studies in Swiss archaeology and monitor changes in the landscape. The continued acquisition of new data by swisstopo will in the future provide several LiDAR datasets for the same location and thus provide a time series basis for monitoring and protecting sites.

The potential of LiDAR data for visualization from archaeological research to science communication is gargantuan and currently barely used. The readily delivered high-resolution DEMs are intuitively understandable by a lay audience when improved through simple visualization techniques. This would, for example, make it possible to engage citizen scientists in archaeological surveys. Local residents interested in history and archaeology can be incorporated into the efforts to protect cultural heritage through discovering and mapping, as well as reporting newly found archaeological sites. Such an approach would need to be conducted in conjunction with cantonal cultural heritage management agencies but has the potential to alleviate some of the resource constraints while simultaneously engaging the public in a positive manner and leaving room for science communication. Earth observation, in combination with citizen science, has been found to be promising [65,66], and first pilot studies in archaeology have been conducted elsewhere [67,68].

As a free and high-quality resource, LiDAR data currently remain underexploited in Swiss archaeology. Despite widespread use and groundbreaking case studies elsewhere, these types of data have yet to reach their full potential in Switzerland, both with regard to academic as well as practical applications. While some preliminary attempts have been made, it is hoped that this article will help broaden the utilization and increase the incorporation of LiDAR data and their derivatives into archaeological theory and practice in the country.

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