Monitoring cultural heritage by comparing DEMs derived from historical aerial photographs and airborne laser scanning

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Abstract

This paper presents results from a study where identification and documentation of landscape changes using a combination of historical aerial photographs and newer airborne laser scanning (ALS) data were examined. The study was based on remotely sensed data covering a Norwegian protected cultural environment consisting of several pebble-stone built grave cairns. Georeferenced digital elevation models (DEMs) were generated using historical air photographs from the years 1968, 1979 and 1999. In addition ALS datasets from 2008 and 2010 were used in the study. Altogether seven difference models were generated as a result of conducting automated change detections between the different epochs. In this way detailed information about changes that occurred in the landscape and to individual monuments for almost the last 50 years was obtained. Further, the incidents that caused the identified changes were interpreted based on documents from archives. Using this approach the dynamic character of the studied protected site was proven. The study demonstrates the importance of historical aerial photographs as a valuable source that makes possible retrospective monitoring of past landscape changes on a detailed scale.

Keywords

Landscape changes; Automated change detection; Historical aerial photographs; Airborne laser scanning; Photogrammetry; Monitoring; 3D-models; 4D

1. Introduction and research aim

Protection of cultural heritage involves multi-temporal monitoring to detect structural changes and identify potential threats. To identify and document landscape changes retrospectively is important in order to improve the understanding of how continuously changing landscapes have been moulded in the past and why they appear as they do today. Anthropogenic and natural impact in combination causes a continuous change of landscapes which affects not only the everyday landscape but also protected cultural environments and monuments. Generally, landscapes are embedded with traces originating from a combination of long-term natural incidents and human actions, and hence knowledge about how the character of the environment has changed successively is important in order to comprehend how present landscapes appear as a result of long-term processes [1].

Further, how landscapes have developed during recent decades is essential as a backcloth for forward-looking monitoring programmes established to prevent undesirable developments in areas appreciated and protected for their cultural heritage and/or environmental importance. In order to obtain better control over the development of highly-valued cultural landscapes or environments with preferred status, cultural heritage management authorities need suitable methods in order to monitor the development as a basis for taking the actions needed to improve and uphold protection. Given the huge number of sites, this involves suitable and efficient methods, which should be quick, affordable, accurate, and able to identify and document changes on various scales.

The most critical changes to monuments and sites can be detected by monitoring the relief. In recent years, new techniques have been developed to derive dense and accurate digital elevation models (DEM) from airborne laser scanning data (ALS) [2-4] and from aerial photography [5]. The short time needed for data acquisition and the high detail and accuracy of the derived DEMs seem to have the potential to monitor sites and map any occurrence and extent of damage or destruction (see also

[6]). In this study we wanted to explore how historical aerial photographs and actual ALS data sets can be used as a means for identifying and documenting landscape changes within a retrospective context. With this as a background, the following objective was formulated for the study: *How can a combined use of historical aerial photographs and airborne laser scanning data provide information about the rate of surface change in protected landscapes and monuments?*

2. Background

Remote sensing is a suitable approach to identify in an efficient way changes on all scales, from single monuments to entire landscapes [7]. Data used for this purpose are typically satellite images, aerial photographs and (so far to a lesser degree) ALS data, which is the most recent remote sensing method. Multi-temporal satellite imagery has been used for monitoring cultural heritage in landscapes [8], [9], [10] sometimes in combination with aerial photographs [11], [12]. Other monitoring projects are based primarily on aerial photographs , which are repeatedly acquired within pre-defined intervals and combined with register data and field work [13].

Historical aerial photographs from archives offer a valuable, but less exploited, source of information about how landscapes have developed. The fact that aerial photography has been used for more than a hundred years resulting in repeated coverage of entire regions provides an ideal basis for investigations on landscape changes [14]. Even though this is a fairly disregarded approach to landscape studies, good examples exist to indicate the potential information that multi-temporal studies of aerial photographs offer [15], [16], [17].

Most remote sensing based monitoring projects work on a landscape or cultural historic site scale, while monitoring of individual objects is less common. This can partly be explained by the resolution of the data, especially in satellite monitoring which until recently was limited by fairly coarse image resolution [18]. Another vital limiting factor is vegetation cover, which has been a challenge in remote sensing based documentation and monitoring because vegetation obstructs from sight the ground beneath [19]. The emergence about a decade ago of ALS has to a great extent eliminated this obstacle. ALS has found a widespread use in many archaeological communities and is currently used for identifying and documenting cultural monuments and remains from the air [3]. So far this technique has, to a lesser extent, been used by archaeologists as a means of documenting landscape changes despite the fact that this kind of data is suited for this purpose. It is quite a straightforward process to make automated change detections by comparing two ALS datasets with a certain time lag between the data acquisition (as a presumption both data sets have to be provided in the same co-ordinate frame) [20]. The potential for using ALS for monitoring purposes in the management of cultural heritage is mentioned in a few cases [15], [21], [22], but specific projects where ALS data is used for this purpose are so far rare [23], [24]. However, in recent years ALS has been widely used for surveillance in other professional fields, for instance, with the purpose of documenting and monitoring erosion processes and other sedimentation dynamics along coasts and shorelines [25], [26], [27] in addition to glacier monitoring [28].

The absent utilisation of ALS data for monitoring purposes in cultural heritage management so far might be explained by the short period that this kind of data has been available – and that a longer period of time is needed in order to detect substantial changes with impact on cultural heritage.

Documentation of cultural heritage with the use of ALS is increasing, and this widespread collection of data can be seen as a first step in establishing prospective monitoring systems. Thus the ALS data currently collected constitute an essential basis for detection of changes occurring in the landscape. As new second generation ALS campaigns will be conducted in areas which have already been scanned, the repeatedly acquired data sets will provide suitable approaches for using automated change detection algorithms. Unlike the footage of satellite images and aerial photography ALS is an active remote sensing technique and thus enables the collection of topography specific direct 3D information. This makes ALS an especially suitable technique in terms of detecting landscape changes.

Historical aerial photographs are a valuable but geometrically less exploited source of information. These photographs potentially offer radiometric and geometric knowledge about the appearance and changes of past landscapes. Aerial photographs have been available for at least the last century [14]. Photogrammetry has also been used for more than a century to determine the geometric properties from photographs, and with the emergence of new computer-vision techniques like *Structure from motion* (SfM), *Multi-View Stereo* (MVS) and semi-global image matching (SGM) [29] that are stepwise integrated in photogrammetric workflows, it is now possible to generate dense 3D surface models from overlapping 2D images from, for instance, historical aerial photographs [5, 30]. Thus a combined use of historical aerial photographs and ALS data constitutes a new approach to documenting past landscapes and how these have changed – a use based on semi-automated examinations of these data sets.

However, these computer vision based approaches do not consider any available information that is given by the present fiducial marks and the camera calibration protocols, which are needed to guarantee highly accurate results. Therefore, in order to guaranty the high calibrated geometric accuracy potential of the images taken with calibrated large sized metric cameras, the orientation and dense matching of the historical imagery is here based on a standard photogrammetric workflow with a software package that has already integrated some of the new computer vision techniques (further details are provided in section 3).

3. Materials and methods

The data used in this study are from a protected archaeological site called Mølen in Vestfold County, Norway (Fig. 1). Mølen is a pebble-stone beach with more than 200 cairns dating from the Roman Iron Age period to the late Iron Age (0 – A.D. 1000). The site holds 16 large round cairns with a diameter of up to 30 m and a height of between 1 and 3 m; one 44 m long and 10 m wide cairn which is 1.5 – 2 m high; one boat-shaped cairn with a length of 20 m; and a total of 192

smaller round cairns measuring between 0.5 to 2 m in diameter (

Fig. 2,

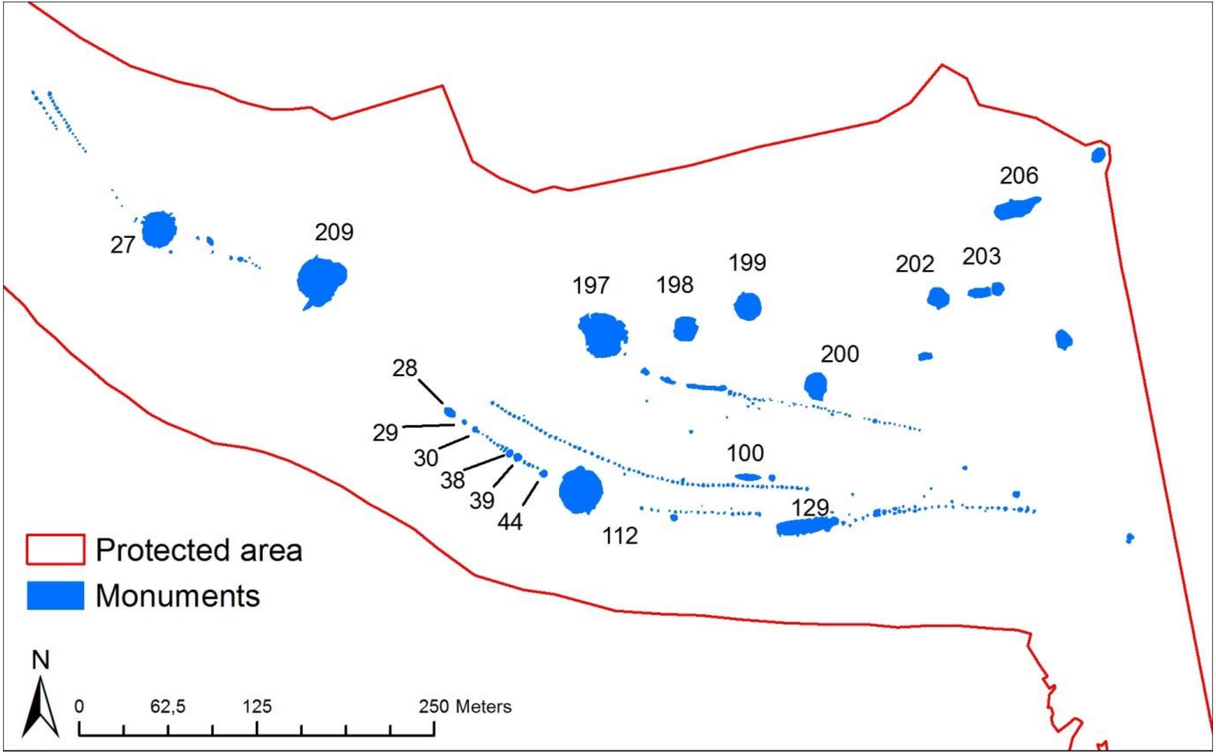


Fig. 3). All these features are built with pebble stones which are not covered by sediments making the site extremely vulnerable to changes and alterations. Even though Mølen has been protected by law for decades, this vulnerable site has been continuously exposed to changes and alterations mainly due to human activity. Stones have been moved, carried away, new features built, prehistoric

ones re-built, and old and new stone constructions altered, making Mølen both a vulnerable and dynamic heritage site.

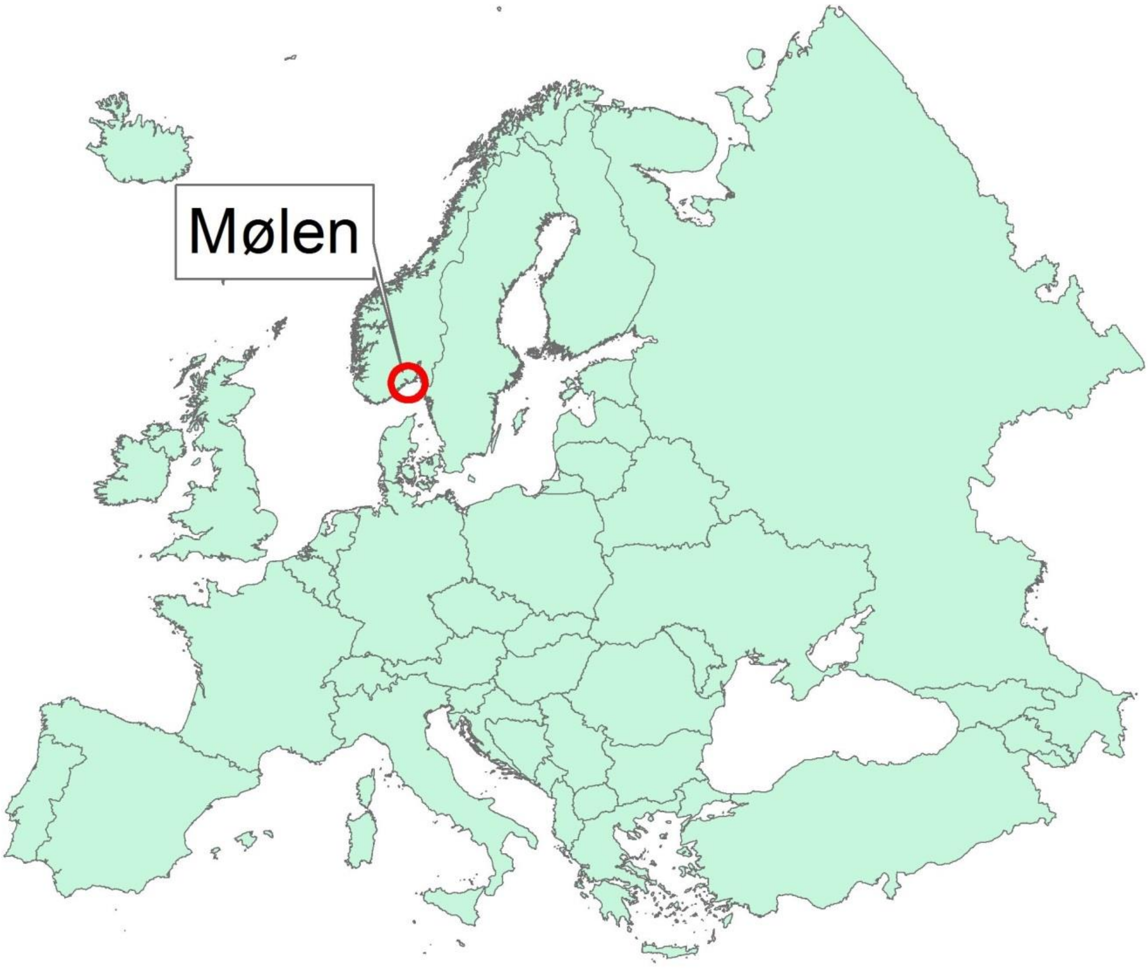


Fig. 1. The geographical location of Mølen in Vestfold County, Norway.

Fig. 2. The pebble-stone beach at Mølen. The long cairn (ID 129) in the foreground and one large round cairn (ID 112) in the background. Photo: NIKU.

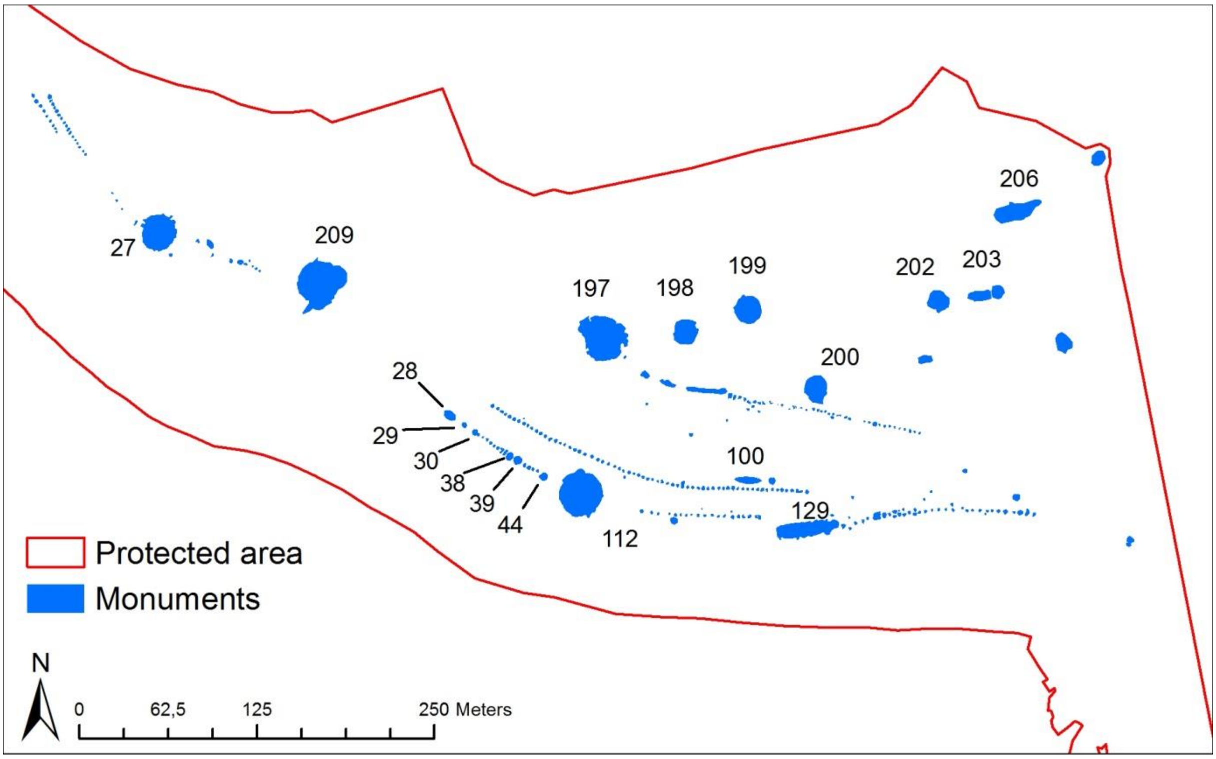


Fig. 3. An overview of the Mølen site and the monuments.

Mølen has been documented by ALS twice – in 2008 and 2010. The parameters of both flight campaigns used in this study are shown in Table 1.

Table 1. ALS parameters used at the 2008 and 2010 scanning.

Time of data acquisition	May 2008	June 2010
Platform	Helicopter	Helicopter
Instrument	Leica ALS50-II	TopEye system S7N 700
Point density per m^2	Minimum 10	Minimum 10
Scanner type	Discrete echo	Full-waveform
Scan angle	40°	45°
Flying height above ground	500 m	450 m
Speed of aircraft	30 m/s	30 m/s
Laser pulse rate	140 000 Hz	120 000 Hz

Based on these ALS data an automated change detection was conducted a few years ago indicating the dynamic nature of the site [23]. The automated change detection provided a great deal of information about recent incidents at Mølen. Since the interval between both laser scans was very short, an extension of the change detection further back in time was desirable. For that purpose, a series of vertical aerial photographs were acquired from archives held by the Norwegian Mapping Authorities whose archive holds series of vertical photos from 20 flights covering Mølen and distributed through the period 1947-1999. These images were acquired as part of the national mapping campaign and were taken with calibrated metric cameras for photogrammetric purposes. For our purpose, coverages from 1968 (two at scale 1:6.000), 1979 (three at scale 1:15.000) and 1999 (seven at scale 1:5.000) were chosen (Fig. 4). Other photographs were also considered but only the chosen ones fulfilled our needs concerning quality, resolution and an appropriate time span covering roughly the last 50 years. In addition to an appropriate ground sampling distance (GSD) the image texture must be sufficient as well as the general rules in photography and photogrammetry must be fulfilled (sufficient overlap, appropriate lighting condition and short exposure time to mention the most important). A combination of appropriate scale and good imaging quality was most decisive for the selection of the photographs used in this study. Visual inspection of the photographs showed that the quality of the photographs improved with the development of cameras and lenses irrespective of scale. Therefore, it is worth noticing that photographs taken at different epochs at an equal scale can have quite different quality.

The chosen aerial photographs were used for the creation of digital elevation models (DEMs). Next to the relative georeferencing of the images per epoch, an adequate absolute georeferencing had to be performed. In the first step, we manually measured control points (more than 15) on the building roofs in the ALS DEM from the epoch 2010 for an approximate georeferencing of the image data. Based on these control points the image data was approximately, relatively and absolutely georeferenced with the photogrammetric software Match-AT [31]. Subsequently, the software Match-T DSM [32] was used in order to generate a dense point cloud from the images per epoch. Owing to the limited manual digitisation accuracy (approx. 0.5m in all co-ordinate directions) and the inhomogeneous distribution of the control points in the area of interest (only a few old buildings could be identified), a subsequent fine-georeferencing of the point clouds was essential in order to improve the absolute georeferencing. For the subsequent second step for the final georeferencing of the multi-temporal point clouds, least squares matching (LSM) [33] was utilised. Within LSM an affine transformation between two epochs could be determined. Within the epoch-wise LSM determination, a mask was used in order to exclude large areas with significant changes within the epochs (e.g. along the coast line and in vegetation) and the ALS flight mission from 2010 acted as fixed reference for all other epochs. The final digital surface models (0.25m grid) were interpolated with the software OPALS utilizing the interpolation method *moving planes* (see [34]).

LSM allows correcting planar and vertical errors by the minimisation of height differences as long as sufficient inclined surfaces are available. In the project area systematic planar as well as vertical errors could be removed. The resulting difference models (Figures 6-10) show that the differences are quite small in temporal stable areas, as well as in inclined areas like roofs of buildings. The height accuracy for the 1968 data set in respect to the 2010 ALS data was estimated to be approx. 0.16 m, while the respective height accuracies for those of 1979, 1999, and 2008 (ALS) were approx. 0.19 m, 0.10 m, and 0.05 m. Subsequently, the matched points were transformed and a digital elevation model with a grid width of 0.25m was generated. Finally, automated change detections were carried out. This was done by creating and visualising difference models with a 0.1 and 0.2 m threshold. Altogether, seven difference models were calculated (Table 2), which consequently was used for interpreting changes on a landscape scale as well as on individual monuments. Where ALS-derived data were involved, the unfiltered digital surface model (DSM) was used.

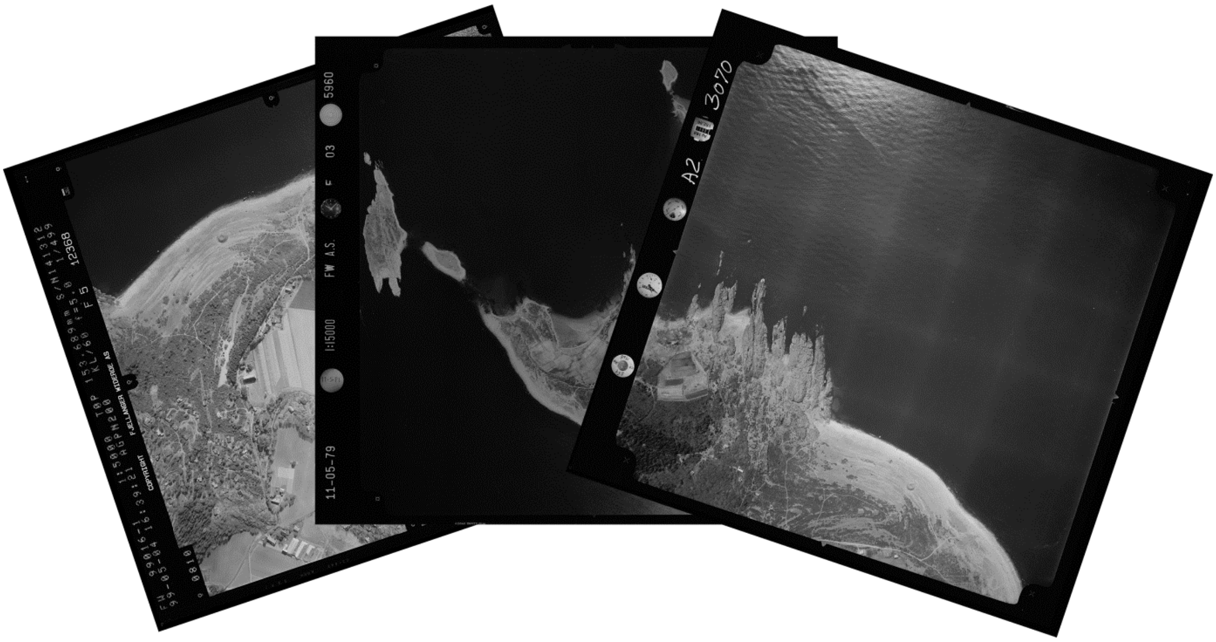


Fig. 4. The vertical aerial photographs used in the study (Copyright: Norwegian Mapping Authority).

Table 2. An overview of the difference maps used in the study. The figures in the second column indicate the resolution of the models used in the study, i.e. if the number is 10, all elevation changes that exceed 10 centimetres are detected and visualised.

Time period	Resolution (centimetre)
1968 – 1979	10, 20
1968 – 2010	10, 20
1979 – 1999	10, 20
1979 – 2010	10, 20
1999 – 2008	10, 20
1999 – 2010	10, 20
2008 – 2010	5

Various documents related to Mølen and held in archives at The Cultural Historical Museum and at Vestfold County Authorities were examined in order to be able to interpret changes identified on the difference models. In addition the digital 2D-images of the historical aerial photographs were frequently studied as part of the interpretation process, as well as the ortophotos generated for each epoch.

4. Results

The generation of DEMs for each of the years 1968, 1979 and 1999 gave a fitted basis for creating difference models. During interpretation of the results, the ALS generated DEMs from 2008 and 2010 were imported into 3D-modelling software, which allowed real-time studies of the landscape in 3D (Fig. 5). Such software allows the user to move around in 3D and study the model from different angles and perspectives, providing a better understanding of landscape changes.

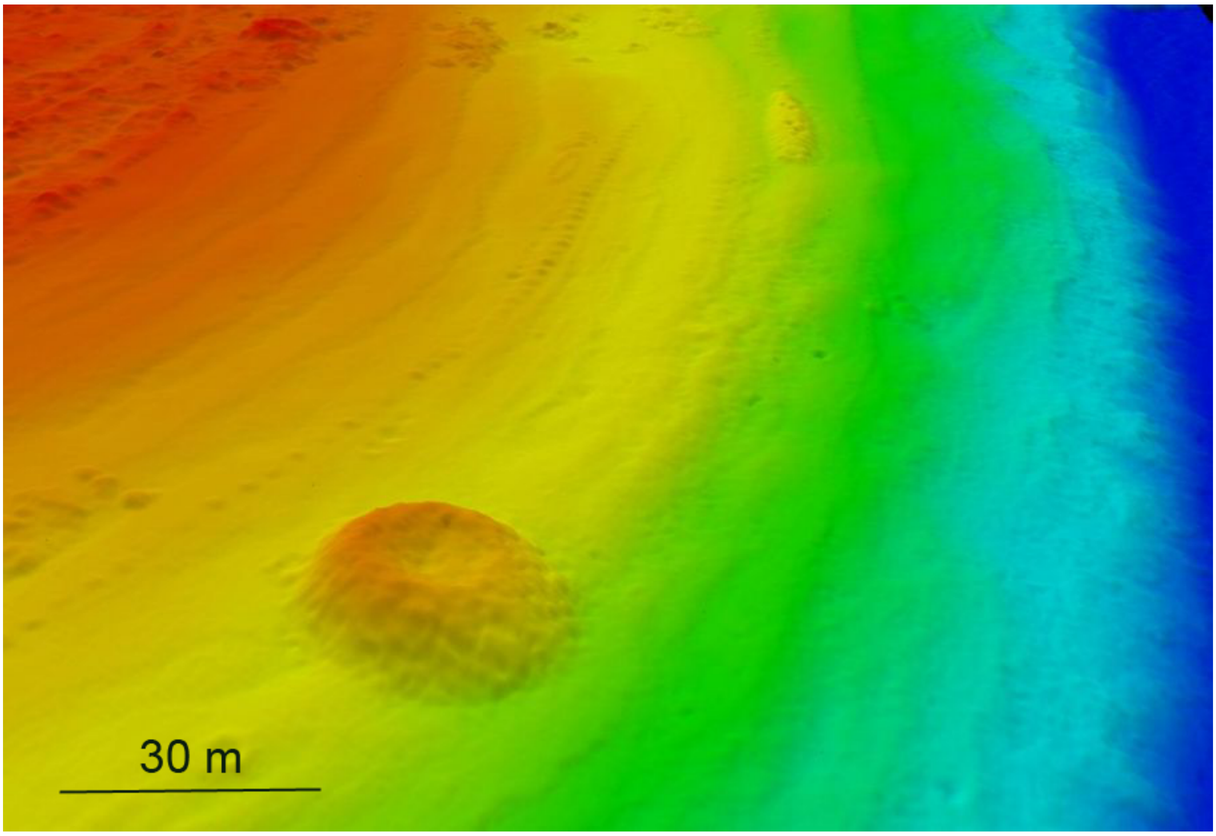


Fig. 5. A DTM generated from the 2010 ALS data.

Fig. 6 shows all changes that occurred in the area throughout the whole period under investigation (from 1968 to 2010), based on an analysis of the earliest aerial images and the most recent ALS data. Red colour indicates areas that were elevated since 1968, and blue and green colours the lowered areas. The vast red areas in the northern and eastern part of the image are mainly due to growth in vegetation. The blue areas near some of the grave cairns situated within the vegetated areas can be explained by clearance of vegetation around monuments carried out by the regional cultural heritage authority as part of a caretaking plan. The red line at the bottom of the image indicate the shoreline and we can ignore the off-shore data as well as the near-shore data where the shown differences relate to tide and waves and is thus irrelevant information in this context. What the difference map also shows is a concentration of both blue and red colours on some of the monuments, indicating that their shape has been changed at least on one occasion throughout the last 50 years.

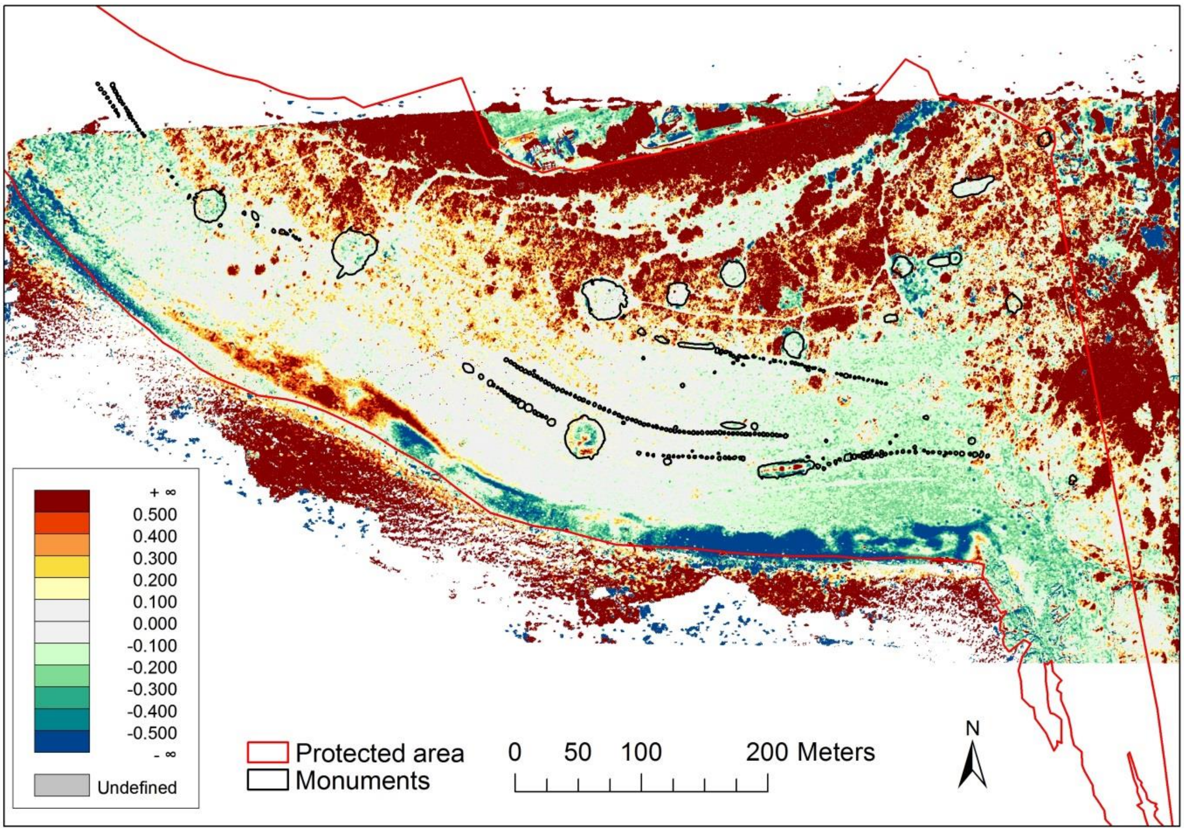
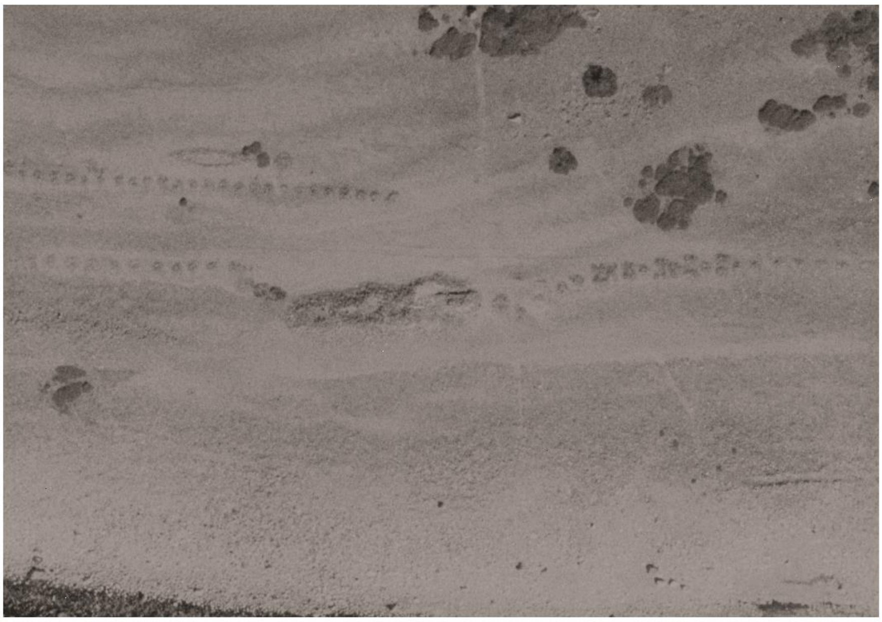


Fig. 6. A difference model showing the time period 1968 – 2010.

A closer study of the long cairn (ID 129), for instance, resulted in detailed information about this monument. A comparison of the 1968 and 1979 images revealed only few changes to the long cairn and its nearest neighbourhood (Fig. 7). A visual study of the aerial photographs from this period revealed that the minor differences are caused by changes of vegetation as well as constructions and removal of small heaps of stones. A comparison of the 1979 image to the one from 1999, on the other hand, indicates major modifications of the long cairn at a certain time in this period, where the

southern part of the cairn was lowered and the central part elevated (



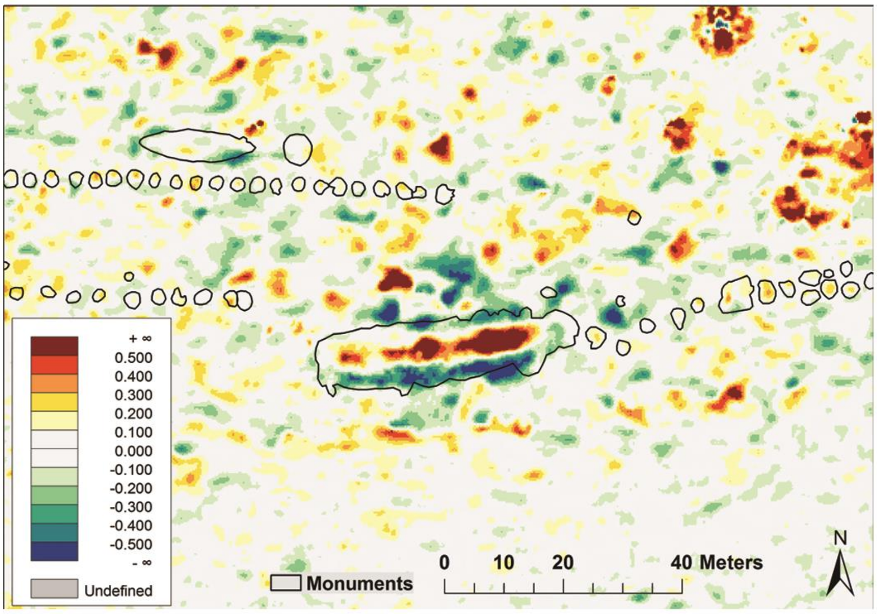

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Fig. 8, A-C). The archival studies unveiled that the long cairn has been subjected to damage several times, and that the most severe change occurred during the Second World War where pits were dug into the cairn to serve as nests for machine guns. In 1980 a restoration campaign was carried out by the Cultural Historical Museum where stones apparently were moved from the southern part and placed in the centre of the cairn in order to fill in the machine gun nests. This incident is documented on the difference model by dark blue and dark red colours respectively. The restoration campaign also reconstructed some of the small features lying on lines more or less parallel with the shore. These were originally small cairns, but at some point in recent history stones were removed from the centre of many of these, apparently in order to examine if they were prehistoric graves. Prior to 1980 most of these features appeared as small stone circles and the restoration campaign reconstructed several of these as cairns by re-allocating the removed stones. This explains the red colouring in the centre of several of these. In the period from 1999 to 2010 the most conspicuous changes documented by the difference map are the ones connected to the removal of vegetation as part of a caretaking plan (

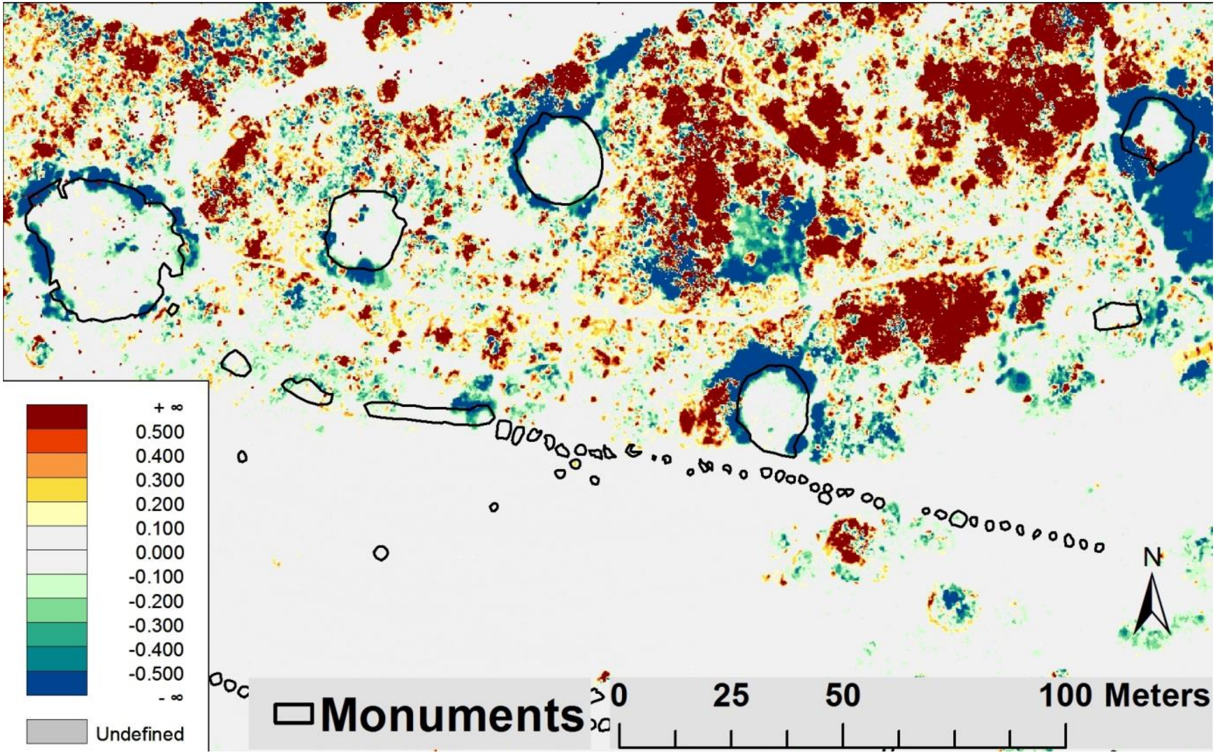

Fig. 9).

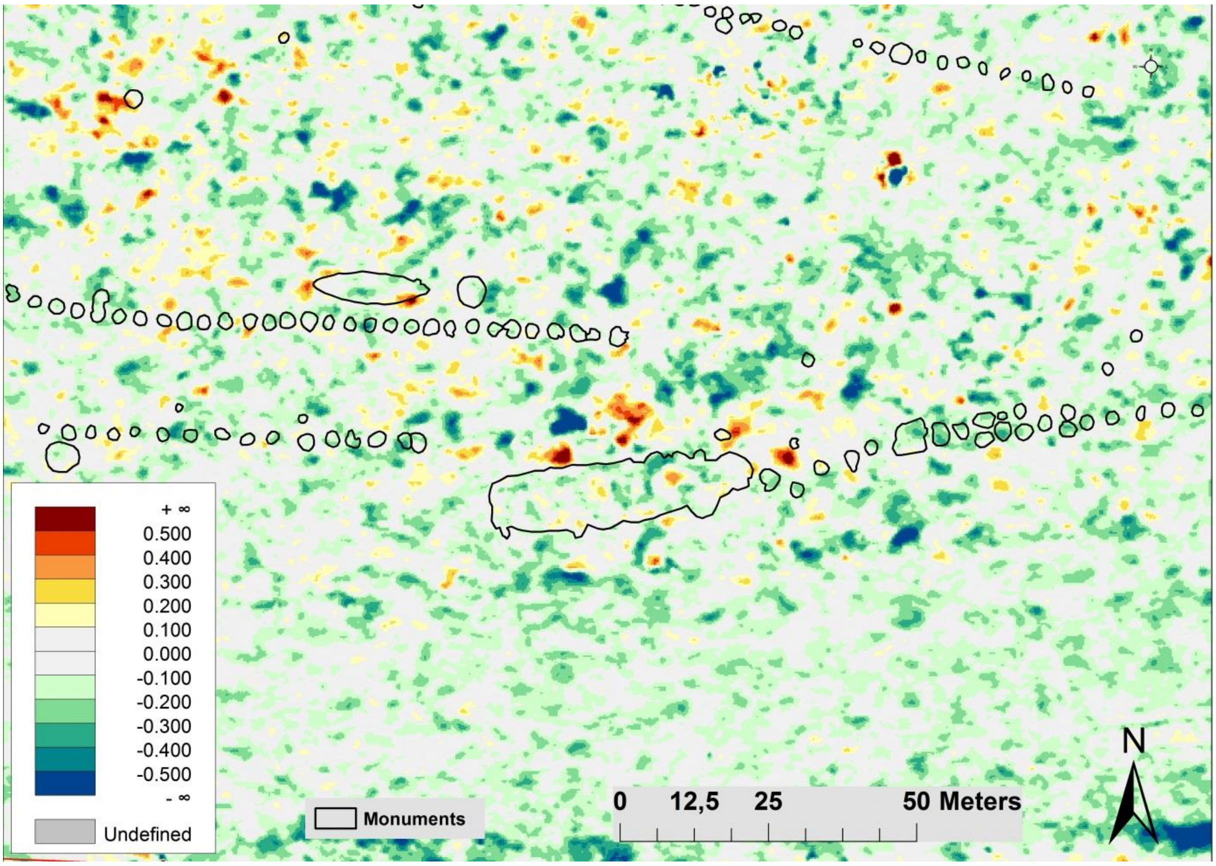

Fig. 7. A section of the difference model 1968 – 1979 showing the long cairn (ID 129) and its nearest surroundings.

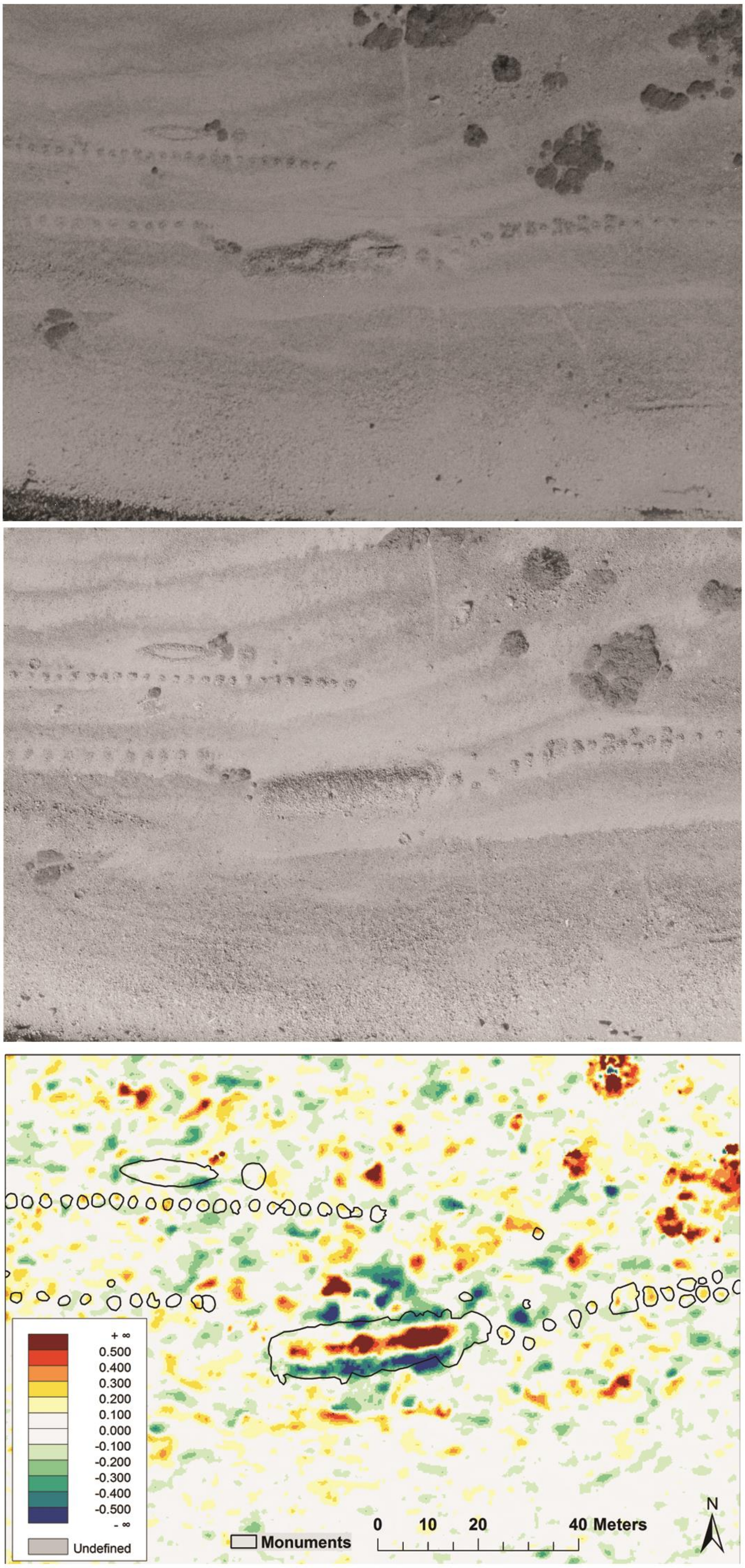
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Fig. 8. A section of the vertical aerial photo from 1979 (A) and 1999 (B) showing the long cairn (ID 129) and its nearest surrounding, plus the same section as a difference model 1979 – 1999 (C).

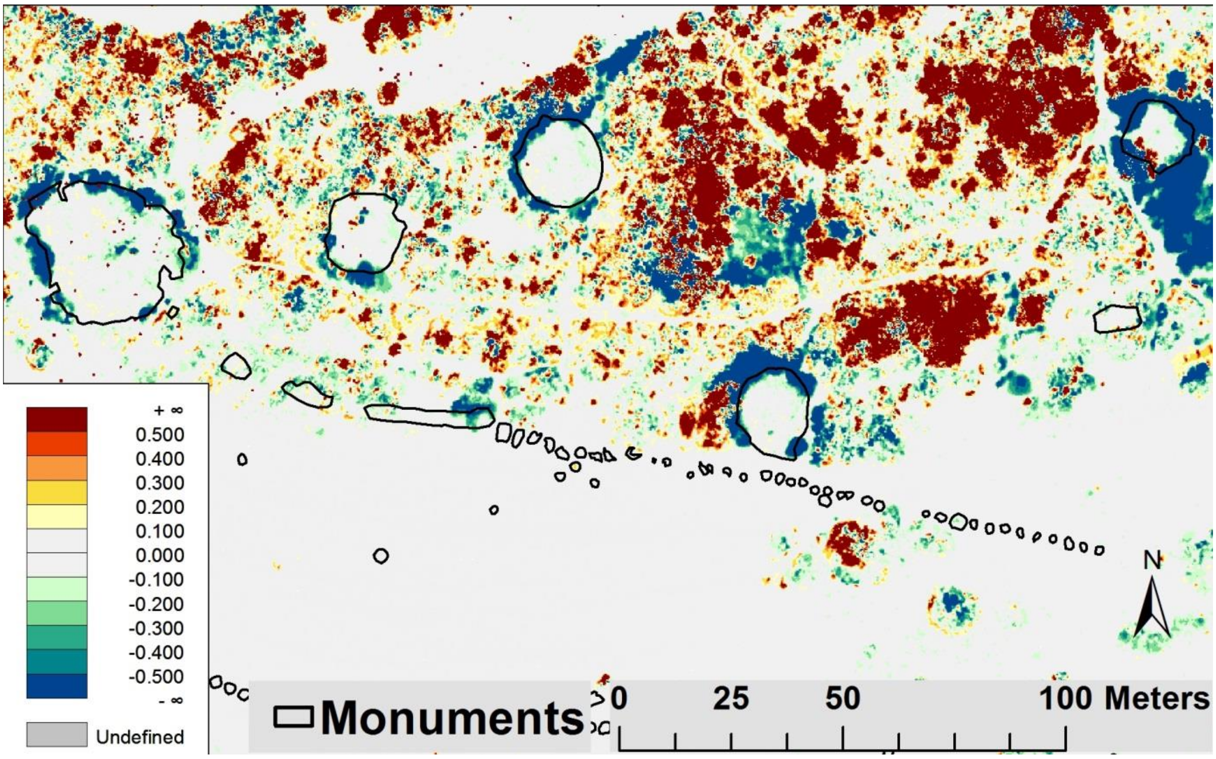

Fig. 9. A section of the difference model showing the time period 1999 – 2010. The solid blue areas are a result of vegetation removal around grave cairns.

A comparison of the 2008 data set with the one from 2010 documented incidents occurring within this period of time (Fig. 10). The six cairns (28, 29, 30, 38, 39 and 44) were subjected to archaeological excavations in 2009. Prior to the excavations these features appeared as heaps of stone with a pit in the centre but were subsequently reconstructed as convex cairns. The two red dots at the top of the image (marked by a blue circle) are the result of the building of new cairns by visitors piling stones on top of each other – an incident that often occurs in this area where stones are moved so easily.

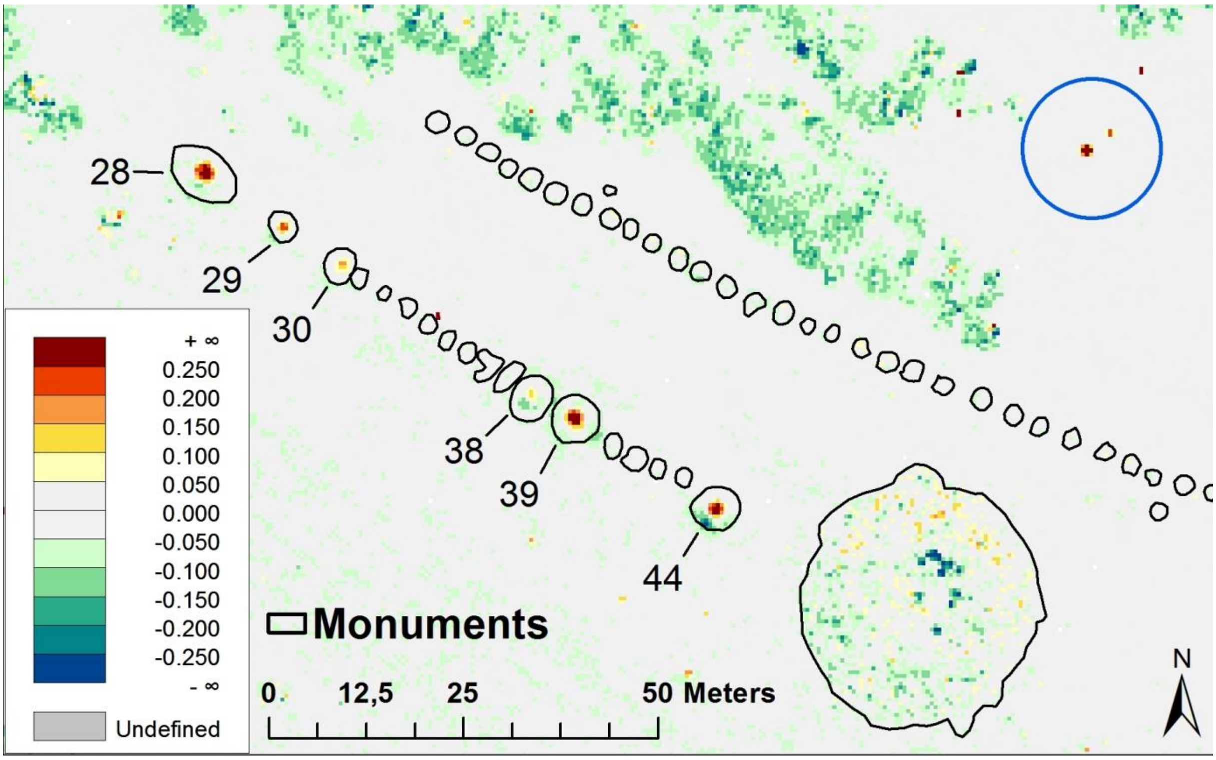

Fig. 10. A section of the difference model showing the time period 2008 – 2010. Reconstructed cairns and construction of new ones are visible as red dots.

5. Discussion

Difference models were generated from historical aerial photographs and ALS data used as basis for detecting and documenting changes to a protected cultural environment. With this approach new information about the dynamic character of the site was proven. The resolution of remote sensing data is often a limiting factor in terms of detecting small-scale changes in landscapes, an assertion which especially applies to older remote sensing data. However, the approach used in this study enables detailed examinations on a decimetre level of images from the 1960s and onwards. Using more recent data collected by ALS makes studies possible on an even more detailed level.

Thus the difference maps constitute suitable visual representations for the identification of changes to landscape and features in the landscape, but knowledge of the areas studied and their cultural history is a prerequisite in terms of understanding the identified changes. Also, it is essential to ask what the colour gradations really represent. It is important critically to study whether they represent real changes in the landscape or are caused by different sensor properties (e.g. the different sensing of vegetation by ALS sensors (penetration capability through small gaps in the canopy) compared with image matching data (mixed pixels in vegetated areas) significantly differs) and remaining relative and absolute georeferencing errors. While systematic georeferencing errors for the complete scene could be reduced within this study by LSM matching to less than 0.05 up to 0.2 m, local differences have to be studied in respect of remaining local errors or deformation sources. Thus co-operation between people with technical skills on the one hand and experts on cultural heritage and landscape development on the other is important in order to achieve the best possible results.

6. Conclusion

The study presented here shows how new knowledge about landscape changes can be obtained by generating digital elevation models from historical aerial photographs and creating models showing differences from one epoch to the next. Furthermore, a comparison can be made between the air-photo based models and ALS-generated digital elevation models. Depending on the scale of the photographs and the resolution of the ALS data, this approach provides information both on a landscape and a detailed scale. This clearly demonstrates the importance of historical aerial photographs as a valuable source of information. Next to radiometric information, these historical aerial photographs can be used to estimate a dense geometric model of the scene. Based on both information sources, an orthophoto (which represents the radiometric information at the correct 2D location) can be determined.

Using the approach presented in this paper, changes on different scales from whole landscapes to single monuments and remains could be investigated in a retrospective context. The resulting maps also provide documentation of the development of natural features, like vegetation and topography, which is of importance in understanding landscape and how it has changed within a cultural historical context. Furthermore, retrospective difference models are useable for detecting and visualising landscape changes as a backcloth for future monitoring programmes and, thus, are a basis for improved management to avoid undesired development of protected sites.

As mentioned, the difference models are suitable for identifying vegetation development and how this affects the visual character of the landscape. However, vegetation also represents a hindrance when it comes to mapping the bare ground beneath. One of the most important success factors behind the widespread and increasing use of ALS data for cultural heritage purposes is the ability to make high-resolution 3D digital terrain models (DTMs) of the ground – even in areas covered with vegetation. In contrast, when generating 3D information based on 2D images like historical aerial photographs only DSMs can be produced, which is a limiting factor in vegetated areas where the character of the bare ground still must remain in obscurity.

Using photogrammetry based on historical aerial photographs in combination with ALS generated DEMs, multi-temporal landscape changes within the last 50 years have been identified and documented. The results of the study are considered to have transfer value to other cultural environments and landscapes where multi-temporal knowledge is needed in order to document landscape changes for improving understanding, protection and management of cultural heritage at all scales, from single monuments to entire landscapes.

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