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Identifying areas of archaeological potential in the Swiss Alps using satellite-derived time-series of snow cover estimates

Camille Cornut[a], Sylvain Ozainne[b], Charlotte Poussin[a,c], Romain Andenmatten[b], Gregory Giuliani[a,c,*]

[a] University of Geneva, Institute for Environmental Sciences, EnviroSPACE lab., 66 Boulevard Carl-Vogt, 1205, Geneva, Switzerland
[b] Office cantonal d'Archéologie, Canton du Valais, route de la Piscine 10, 1950, Sion, Switzerland
[c] University of Geneva, Institute for Environmental Sciences, GRID-Geneva, Bd Carl-Vogt 66, CH-1211, Geneva, Switzerland

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ABSTRACT

The Alps have historically been crossed by populations moving between northern and southern Europe for various purposes. Testimonies of such human presence were long preserved from decomposition being covered and protected by perennial ice and snow. However, with ongoing climate change, large portion of these permanent snowed and frozen areas are being freed up exposing artifacts to rapid deterioration. Consequently, archaeologists are requiring new methods to monitor the cryosphere enabling them to efficiently identify potential areas of conservation and protection of archaeological remains. Herein, we used a 34-year satellite-derived time-series of snow cover estimates to identify potential zones for conservation of archaeological remains in the Valais alpine region (Switzerland). Findings suggest that over the considered analysis period (1984–2018), snow cover has declined of about 15% during the summer maximum melting season releasing a surface of approximately 45 km^2 in the study area. Moreover, crossing snow probabilities with Topographic Position Index (TPI) and slope data allowed to compute an Archaeological Potential (AP) map to derive zones with high potential of current or imminent release of archaeological remains. Combining this map with density of wood artifacts found on the field in a test area showed that 92.5% are inside identified receding snow/ice areas. Results of this analysis demonstrate that the proposed methodology can be a valid approach to monitor snow/ice minimum extension and identify perennial snowed and iced fields with archaeological potential. It provides the basis for defining new archaeological protection areas, preventing the loss of threatened ancient organic remains and enhances future field research campaigns in mountainous regions.

1. Introduction

Often perceived as a hostile and lifeless environment, mountainous high reliefs and remote areas covered by snow and ice have nevertheless been valuable thoroughfare for past populations. The Alps, which separate northern and southern Europe, are not an exception. They have long been crossed by people for migration, military, trade, raw material collection, hunting or agropastoral purposes. Covered and protected by ice and snow, testimonies of human presence were then preserved from decomposition. The cryosphere, the frozen water part of the Earth System, includes glaciers, snow covered areas and perennial ice fields that can preserve organic artifacts over several millennia. As they are characterized by favorable conditions of altitude and climate, the Swiss Alps have

* Corresponding author. University of Geneva, Institute for Environmental Sciences, EnviroSPACE lab., 66 Boulevard Carl-Vogt, 1205, Geneva, Switzerland.
E-mail address: gregory.giuliani@unige.ch (G. Giuliani).

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proved a great potential for conservation of such archaeological remains (Curdy and Nicod 2019). Notable locations encompass Graubünden (Kaufmann 1996), Bern (Hafner 2012), and Valais/Wallis (Andenmatten & Aberson 2019; Eschmann Richon et al., 2016) cantons, where numerous discoveries of organic objects or human bones revealed a regular presence on alpine ridges from the Neolithic period to modern times (Grosjean et al., 2007; Rogers et al. 2014).

Mountains are among the most sensitive and affected by climate change (Mountain Research Initiative EDW Working Group, 2015). Various studies show evidences that warming rates are amplified at high altitude with related reduction of glaciers' mass and snow cover extension as well as duration and quantity (Beniston et al., 2018; Adler et al., 2018). As a consequence of ongoing climate change, permanent snow covered areas have significantly decreased over the Alps during the last decades and large portion of the alpine cryosphere are being freed up (Giuliani et al., 2020; Poussin et al., 2019; Dhu et al., 2019). Since artifacts released from glaciers or ice fields are exposed to rapid deterioration, they must be collected shortly after the melting of ice or snow (Andrews, 2012; Rogers et al. 2014). Artifacts discoveries remain rare, as they mainly occur during field surveys campaigns or follow occasional reports by hikers. Therefore, archaeologists have a strong interest for innovative methods and tools helping them to monitor the cryosphere and identify potential areas of interest for investigation.

Remote sensing is increasingly used in archaeology to obtain data and information that is not possible with traditional archaeological investigation techniques (Luo et al., 2019; Bassier et al., 2018; Alexakis et al., 2012). However, to our knowledge, only few researches are conducted to identify potential zones of investigation related to decrease of snow in mountainous areas (Andrews, 2012). With the advent of high-performance computing and satellite imagery available under open data licenses it is now possible to efficiently analyze large volume of satellite Earth Observations (EO) data (Howey et al., 2020) and generate time-series of medium-to-high spatial and temporal resolution snow cover maps to continuously monitor its evolution in mountainous remote areas (Gascoin et al., 2019, 2020; Dietz et al., 2012).

To determine such snow cover evolution, and due to the difficulties of monitoring high-altitude environments with in-situ station networks, satellite EO data can be valuable option to complement scattered in-situ measurements (Thornton et al., 2021). Indeed, significant amount of satellite data are openly and freely available from EO programmes such as Landsat for more than 40 years (Zhu et al., 2019). With their global coverage and regular acquisitions it is therefore possible to monitor snow cover spatial and temporal variability through dense time-series observations (Gascoin et al., 2019; Crawford et al., 2013; Hüsler et al., 2014; Berman et al., 2018). Various applications of satellite EO data have demonstrated the benefits of remotely-sensed snow cover products (Li et al., 2019). They usually take advantage of the spectral properties of snow with high reflectance in the visible part of the spectrum and the very low reflectance in the shortwave infrared (SWIR) (Härer et al., 2018). It is now even possible to provide near real-time information on snow cover (and other geophysical variables) using the European Coperncius Sentinel's that provide images every 5 days at 10m resolution (Karbou et al., 2021; Gascoin et al., 2019; Berger et al., 2012).

Based on these considerations, we propose a methodology using time-series of satellite imagery for the identification of perennial snow and ice areas with a potential of conservation of archaeological remains. This work aims at providing a tool for yearly monitoring of ice/snow minimum cover enabling identification of perennial snowfields or icefields with an archaeological potential and thus preventing the loss of threatened ancient organic remains. The method was applied on a test area located near the Annibal Pass in the Valais Alps which is an important location for archaeological discoveries under current investigation (supplementary material 1).

This paper describes the methodology and implementation (section 2) to compute the probability to find snow and identify potential areas of interest; presents the main results and discuss benefits, limitations, and perspectives (section 3) of the proposed approach; before concluding with some lessons learnt and way forward towards an operational service (section 4).

2. Methodology & implementation

We present hereafter the four different steps of the proposed methodology used to determine area with high potential of archaeological conservation (Fig. 1). The overall objective is to identify permanent snow and/or ice fields using satellite images and therefore potentially conserve archaeological artifacts, as well as to assess the areas where the perennial cryosphere shows recent surface reduction trends and thus where glacial archaeological heritage may soon disappear. First is to access and analyze satellite imagery over the study area to produce annual snow cover maps for the summer season. Then second, apply thresholds and masks to extract the yearly minimum snow cover extension. Third, compute the probability to find snow and finally the last step intersect the probabilities maps with topographic and archaeological data to identify areas of interest. For this last step, the following three criteria have been applied to identify potential areas of conservation of archaeological remains to compute the Archaeological Potential:

- criteria 1(C1): Snow probability (2003–2018) - Snow probability (1984–2002) < 0
- criteria 2 (C2): Slope $< 35^{\circ}$
- criteria 3 (C3): TPI < 0

$$\text{Archaeological Potential (AP)} = C1 * C2 * C3 \tag{1}$$

Further details on the different processing steps presented in Fig. 1 are provided in the following sub-sections.

2.1. Accessing and processing Landsat 5-7-8 and Sentinel-2 satellite imagery

Since 2016, Switzerland has a unique satellite EO data archive covering the entire country (Chatenoux et al., 2021). The Swiss Data Cube (SDC) is an analytical cloud-based platform enabling users to discover, access and analyze 38 years (1984–2022) of optical (e.g. Landsat 5-7-8; Sentinel-2 A/B) and radar (e.g. Sentinel-1 A/B) satellite EO Analysis Ready Data (ARD) over Switzerland (Giuliani

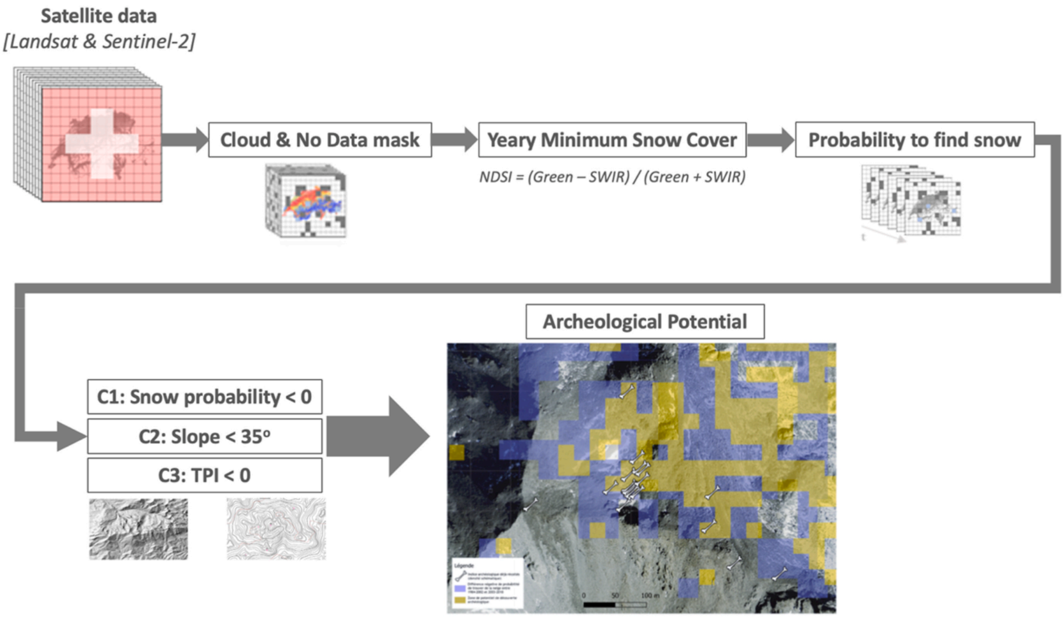

Fig. 1. General overview of the proposed methodology to compute the Archaeological Potential.

et al. 2017, 2018; Truckenbrodt et al., 2019). This platform aims at lowering the barriers (e.g., time and scientific knowledge) to run national-scale analyses of large volumes of consistently calibrated and spatially aligned remotely-sensed observations. For a detailed description of Landsat and Sentinel-2 data, please refer to Chatenoux et al. (2021)In order to automate the generation of consistent and comparable ARD products (e.g. surface reflectance and normalized terrain-flattened backscatter composites), the Swiss Data Cube uses the Live Monitoring of Earth Surface (LiMES) framework, which helps to search, download, (pre)process, index and ingest satellite data using interoperable processing chains (Giuliani et al. 2017a; Giuliani et al. 2017b). This ensures that the latest images acquired by satellites are available in the shortest time possible (i.e., typically one day). Currently, the archive is updated daily and accounts approximately 13,500 scenes corresponding to a total volume of 6 TB and more than 1000 billion observations/pixels. The WGS 84 coordinate system and the corresponding equi-rectangular projection EPSG:4326 are used. To process these large volumes of data and developed tailored applications, the SDC provides a Python application programming interface (API) that enables users to write their own processing algorithms. This API is accessible through Jupyter Notebooks, an interactive web-based programming interface that can be used for combining software code, algorithm output and explanatory text. Consequently, using these capabilities, dedicated analysis workflows have been implemented as Python scripts to produce yearly minimum snow cover maps and probabilities to find snow in the studied area.

2.2. *Yearly minimum snow cover maps production*

In order to detect permanent snow/ice fields, we chose to use with the Normalized-Difference Snow Index (NDSI), which is a commonly used method for snow/ice detection (Dietz et al., 2012; Frau et al., 2018; Crane and Anderson 1984). This index is based on the potential for distinguishing snow from other land cover and clouds through differences in the spectral signatures of these elements in the visible and infrared wavelengths. Specifically, this index is a measure of the relative magnitude of the difference in reflectance between the visible (usually green) and the shortwave infrared (usually SWIR) and is calculated as follows (Hall and Riggs, 2011):

$$\text{NDSI} = (\text{Green} - \text{SWIR}) / (\text{Green} + \text{SWIR}) \tag{2}$$

We used the Snow Observations from Space (SOfS) algorithm to compute snow cover extension (Frau et al., 2018; Poussin et al., 2019) and produce frequencies of observations (Giuliani et al., 2020). SOfS is implemented as a Python script available in Jupyter Notebook, an interactive web-based programming interface, for extracting and processing satellite data from the SDC. First, the script specifies the area and periods of interest to build an initial dataset, using a bounding box covering the whole canton of Valais as well as its border zones (Longitude: 6.77–8.47 Longitude; Latitude 45.85–46.66). The dataset covers a times series ranging from 1984 to 2018 (for Landsat) and 2015–2018 (for Sentinel-2). For each year, we selected the August to September timeframe as it corresponds to the annual period of maximum snow retreat according to the observations of the archaeologists of the Office of the Canton of Valais. The August-September images of each year are summarized in mosaics using the NDSI median, to avoid effects caused by extreme values (e.g., important occasional snowfalls). Mosaics were created from at least 12 images (except 1984 with only 8 images). To avoid misclassification, the algorithm also includes a data cleaning step to identify cloud and no-data pixels using the Pixel Quality Assurance (pixel_qa) band that is provided in the SDC (https://www.usgs.gov/core-science-systems/nli/landsat/landsat-sr-derived-spectral-indices-pixel-quality-band). This band is produced during the surface reflectance (e.g., L2 products) of the pre-processing workflow (e.g., before ingestion in the SDC). It provides indication on pixels affected by instrument defects or subject to cloud contamination (USGS 2017; 2019). Whilst snow can be identified through NDSI values above a threshold of 0.2–0.5, we selected an intermediate value of 0.4 which is a reasonable choice to obtain good results (Crawford et al., 2013; Riggs et al. 2006; Selkowitz and Forster 2016). Thus, resulting images are classified in three values: Not-a-Number "NaN" for clouds and no data, 0 for NDSI median values < 0.4 ("no snow") and 1 for NDSI median values > 0.4 ("snow"). Finally, as NDSI cannot properly discriminate between snow and water, we filtered the data using a mask of water surfaces with a coarse resolution of 30 m. We then assigned the "NaN" value to the water pixels. The final output is a yearly raster file classified as snow/no-snow corresponding to the minimum snow cover extension (supplementary material 3 and 4).

2.3. Probability to find snow

Using the outputs of the previous step, we also computed a raster of probability of snow presence for the whole 1984–2018 period (supplementary material 5). This was obtained by dividing, for each pixel, the sum of years with the "snow" value by the sum of years unequal to cloud, water or no data values.

$$\text{Snow probability} = \Sigma(\text{years} = \text{snow}) / \Sigma(\text{years} \neq \text{cloud, water,NaN}) \tag{3}$$

The same calculation was also applied on two temporal subsets (1984–2002 and 2003–2018) to produce a difference map, which offers an insight on recent snow cover evolution, especially regarding zones with formerly known or suspected archaeological potential. We chose 2003 as a splitting point for the two subsets, as this year was characterized by an exceptional ice loss of alpine glaciers (Zemp and PaulHoelzle, 2008).

The quality of the snow probability per pixel/year can be evaluated through the number of images used to create the annual mosaic and the number of pixels in "NaN" (cloud/water/no data). Given that the use of the median excludes extreme values, the bias of a mapping based on a small number of images taken during unrepresentative and punctual snow events may have been reduced in most of cases. Since the number of available images is increasing (notably because only one satellite was in operation between 1984 and 1999) and the number of cloud/no data pixels is decreasing along the series, the reliability of mapping is improving over time (Poussin et al., 2019).

2.4. Topographic and archaeological data

To identify ice/snow areas with high potential of conservation of archaeological remains, we crossed snow areas from the snow/no snow products with two topographic criteria. First, snow pixels were crossed with a raster of slopes over 35°, as they are difficult to access and more likely to be affected by avalanches and snowpack movements. We also crossed snow pixels with a Topographic Position Index (TPI) raster (De Reu et al., 2013), in order to identify depressions with stagnant snow accumulation, more likely to preserve artifacts (Hafner 2012). Both slopes and TPI rasters were computed using the Digital Elevation Model (DEM) at 25 m resolution from the Federal Office for Topography (https://shop.swisstopo.admin.ch/en/products/height_models/dhm25) using QGIS. Finally, to identify depressions covered by snow, selected pixels are those that satisfy the conditions of having slopes smaller than 35°, having a TPI <0, and having a probability to find snow <0.

The effectiveness of the resulting raster was then evaluated in the test area of the Annibal Pass, where numerous wood artifacts were recently collected (see section 3).

3. Results and discussion

The Landsat time series shows a clear decreasing trend of the snow/ice cover during the August-September period. This decreasing trend can be attributed as a consequence of climate change (C. Marty et al., 2017; Marty, Tilg, and Jonas 2017). Pixels classified as snow over the 34-year observation period show a decline of around 15%, equivalent to a 45 km^2 area (Fig. 2). Summer seasons known for particularly high temperatures (2003, 2015, 2018) are also clearly visible in the produced dataset. However, the decrease might be even more important, as the 2017 year shows a very high increase while the recorded average summer temperature for this year is high (over 15°). While this could be explained by a short and important snow episode, this anomaly may also correspond to calculation errors but for which the source could not be clearly identified.

The map of difference calculated between the 2003–2018 and 1984–2002 snow probability shows important reductions in snow cover in some areas (supplementary material 2), such as a length of 600 m at the Findelgletscher towards Zermatt or almost 1 km at the Aletsch glacier. However, the probability of snow is increasing in some regions, particularly in the Bernese Alps. Understanding this phenomenon requires further investigations, which are not addressed here. As the Sentinel-2 2015–2018 time series is too scarce to infer any temporal trend, its spatial resolution offers a better insight on regions of interest and might be more performant for specific archaeological applications that requires more detailed images.

To assess the suitability of the proposed methodology and obtained results for further use in glacial archaeology, we took a closer look at a site where archaeological investigation was recently conducted. It is a depression slightly west of the Annibal Pass, between Valais and Aosta valley (Italy) (supplementary material 1; Fig. 3). The TPI calculated from the 25 m DEM allows identifying this depression. Aerial images, historical maps and field observations allowed determining that the ice field has been declining since its first known archives. In recent years, only a small area of ice (50 × 20m) with a height of 5–6m has remained, with a clear declining trend. This is confirmed with the obtained results, as the area shows a decreasing probability of finding snow between the 2003–2018 and 1984–2002 periods.

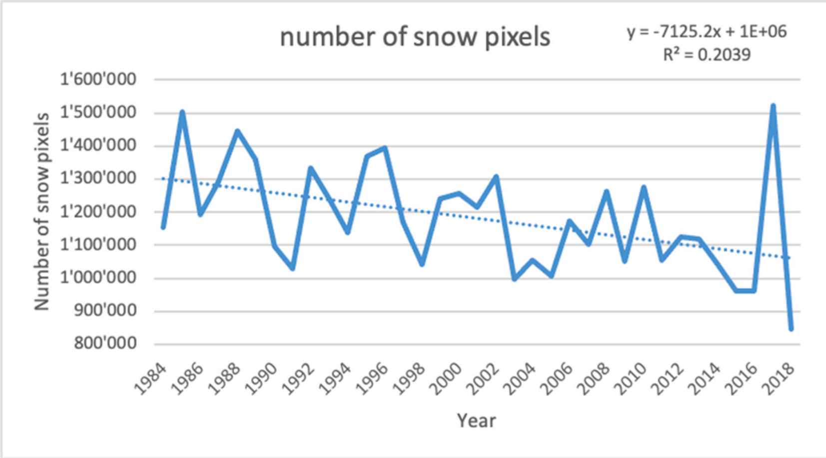

Fig. 2. Number of snow pixels at maximum melting.

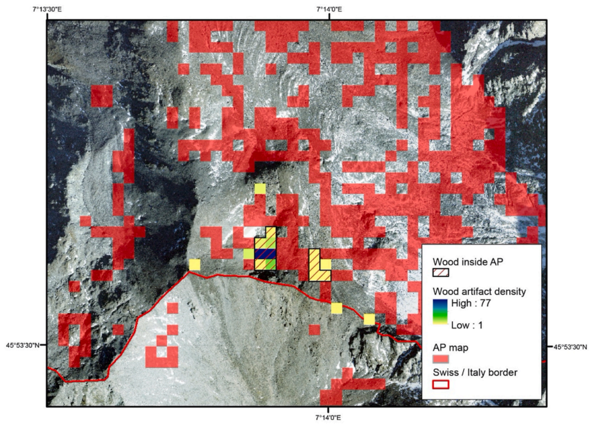

Fig. 3. Archaeological Potential (AP) map and archaeological wood artifact densities in the test area, located near the Annibal Pass (pixel resolution 25 m). Image: Federal Office for Topography.

On the highest edges of this depression, more than a hundred carved wood fragments, presumably dating from Roman times were discovered in 2016 (Andermatten and Pignolet 2016). They are currently being dated and their function remains unknown as they could correspond either to marking stakes for a path or to defensive structure remains.

According to their position, it is assumed that these artifacts have been released from ice for some time and regularly exposed to the open air, especially since more fragile organic matter such as skins or wool, which are often discovered in such contexts, were not found. This agrees with our classification based on Landsat imagery, as areas where wood remains were collected are regularly classified as snow/ice during the earliest years of the dataset (13 years between 1984 and 2002), in contrary of the latest period (4 years between 2003 and 2017). The Sentinel-2 2015–2018 data also shows that most of the zone was uncovered by snow during recent past summers.

Consequently, crossing negative values of snow probability difference with TPI < 0 and slopes under 35° allows identifying areas with important loss of former "perennial" and static snow/ice patches (Fig. 3). The resulting product provides an Archaeological Potential (AP) map which is effective for circumscribing zones with a higher potential of current or imminent release of archaeological remains. Combining the AP map with a density of wood artifacts at the same resolution (25 m) shows that only 12 artifacts out of 159 (7.5%) are outside the snow/ice retreat areas (Fig. 3). Therefore, this approach provides a basis for defining new archaeological protection areas and may enhance the efficiency of future field research campaigns at high altitudes. Accordingly, the product will be tested on different selected areas during survey campaigns in the next summers.

Currently, the proposed methodology entirely relies on optical imagery that may be affected by the presence of clouds and therefore can influence results either by hiding the observed area or by impending effective discrimination of snow and clouds. To overcome this issue, the use of Synthetic-Aperture Radar (SAR) imagery can be beneficial as it is not affected by clouds, can easily detect snow and offer a mean to identify snow melting areas (Small et al., 2013).

4. Conclusions

Using remotely-sensed satellite time-series data, the proposed methodology enables a yearly monitoring of ice/snow minimum cover and provides an innovative tool for identifying perennial snowfields or icefields with an archaeological potential and thus preventing the loss of threatened ancient organic remains, at relatively low costs. It provides a tool for systematic surveys planning as well as a valuable basis for the definition of archaeological protection areas. In addition, this approach method may contribute to broadening the scope of the SDC initiative to a field larger than environmental sciences and, more generally, will contribute to the current challenge of enhancing existing geospatial data.

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Ethical statement

The authors declare that all ethical practices have been followed in relation to the development, writing, and publication of our article « Identifying areas of archaeological potential in the Swiss Alps using remotely-sensed snow cover maps time-series ».

Author statement

Camille Cornut: Conceptualization, Methodology, Implementation, Investigation, Validation Writing- Original draft preparation **Sylvain Ozainne:** Methodology, Writing- Reviewing and Editing **Charlotte Poussin:** Methodology, Writing- Reviewing and Editing **Romain Andenmatten:** Methodology, Writing- Reviewing and Editing **Gregory Giuliani:** Supervision, Methodology, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rsase.2022.100838.

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