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Landslide-geomorphosite assessment in the Dolomites (Italy): Application of a newly implemented method☆

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ABSTRACT

This paper aims at the definition of new geoheritage criteria to identify and assess landslides as geomorphosites. As first application of a newly implemented methodological approach, we propose a comparative evaluation of landslide geomorphosites in the Dolomites, north-eastern Italy. We quantitatively assess each site by using standard criteria well-established in geoheritage studies and newly defined ones related to risk perception, anthropic signature, and climate change. These new criteria aid in defining the most useful geomorphosites for educating visitors regarding themes such as landslide hazard and risk, the consequences of human activities on landslide triggering and development, and landslide activity in response to warming climatic conditions. In previous studies, geomorphosite assessment was not performed for landforms of one kind as opposed to any kinds of landforms within a specific geographic area. For the first time, we analyse a landform of a kind – namely landslides, as geomorphosites in a defined region, using old and newly defined criteria that can be applied to a variety of other landforms. Our methodology highlights the scientific importance of the definition of landslides as geomorphosites, emphasises how their consequences on human activities and the environment can be disseminated to the public, and can be applied for geomorphosite assessment of any other geomorphological landform.

1. Introduction

Geosite assessment typically involves the comparative quantitative evaluation of geosites within a specific area, using multiple values and criteria and corresponding indicators to assign scores (Reynard and Coratza, 2013; Brilha, 2018; Mucivuna et al., 2019). Despite two decades of evolving research, the Geoheritage scientific community is still actively debating the establishment of commonly acknowledged values and criteria, with no widely accepted method yet in place (Reynard, 2009; Bruschi et al., 2011; Brilha, 2016). Landforms and associated geomorphological processes can have characteristics that from a geoheritage viewpoint need to be highlighted by using specifically crafted values to be fully comprehensive of their importance as geosites. Landslides are one of the most fascinating landforms on Earth and beyond, and – as many other geological and geomorphological features – they present properties and attributes that can significantly raise their geoheritage importance (Morino et al., 2022).

In general, the values/attributes mostly used in literature (e.g., Kubalíková, 2014; Cappadonia et al., 2018; Coratza et al., 2019) for geosite and geomorphosite assessment can be classified into five categories: i) Scientific/intrinsic (scientific merit) values; ii) Additional values; iii) Exemplarity and educational potential of the site; iv) Existing threats and risks; v) Use values. In this study, we consider these standard values adopted for geomorphosite assessment, and try to adapt and expand them in order to cover the broad geoheritage significance of landslides, an approach that has not been used so far, since landslides have been scantly considered as geosites and have specific characteristics that require additional values/criteria when evaluated.

The evaluation of geomorphosites, and more in general of geosites, has been long debated in literature and many methods, both qualitative and quantitative, have been developing since the 1990s (Mucivuna et al., 2019), but at present there is still no consensus on a single universal assessment method. In the recent past, there has been a significant effort in developing quantitative assessment approaches, since they help

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in reducing subjectivity in the evaluation process. However, certain values may not be unequivocally measurable, and their quantification will depend on the subjectivity of the assessors, and/or the characteristics of the analysed site. All the quantitative evaluation methods assess the scientific value of sites, while additional, use and protection values are assessed according to the objectives of the evaluation. Generally, the assessment is based on the numerical evaluation of geosites' values, considering several criteria and relative indicators, which mainly refer to: (i) intrinsic characteristic of a geosite, (ii) potential for use, (iii) need for protection (Pralong, 2005; Serrano and González-Trueba, 2005; Kubalíková and Kirchner, 2016a). Some methodologies combine scores (numerical indices) attributed to geosites' values, sometimes with different weighting, through sum or arithmetic mean, to obtain a final score, commonly referred to as the 'global value'. Other qualitative assessment methods define independent criteria specific to the case study, without the need for defining a final total score, but by considering each set of criteria (Pereira et al., 2007; Bouzekraoui et al., 2018). This method allows to evaluate the criteria independently and enables the individual analysis of each geosite. Importantly, a major aspect in any geomorphosite assessment is the selection of the sites, which invariably begins with a comprehensive review of the scientific literature, a fundamental and robust foundation for any geological and geomorphological research. Therefore, unknown or scarcely studied landforms – landslides, in this case – will inevitably be discarded from selection, as their Scientific value cannot be assessed.

In the present study, landslides as geomorphosites are quantitatively assessed considering values and criteria standardly adopted in the literature (Kubalíková, 2014; Kubalíková and Kirchner, 2016b) and adding three new criteria adopted by Morino et al. (2022) specifically for landslides. We propose these new criteria because those used so far in other contexts are not fully suitable for comprehensively describing the complexity of conditions and settings preceding landslide occurrence and its consequences, which need to be considered when evaluating the overall framework of a landslide as geomorphosite. Here, we firstly describe our approach by defining the old and new values and criteria adopted for landslide-geomorphosite assessment. We then apply this approach to five selected landslide sites in the Dolomites, north-eastern Italy (Fig. 1), which present a variety of geomorphological, geological,

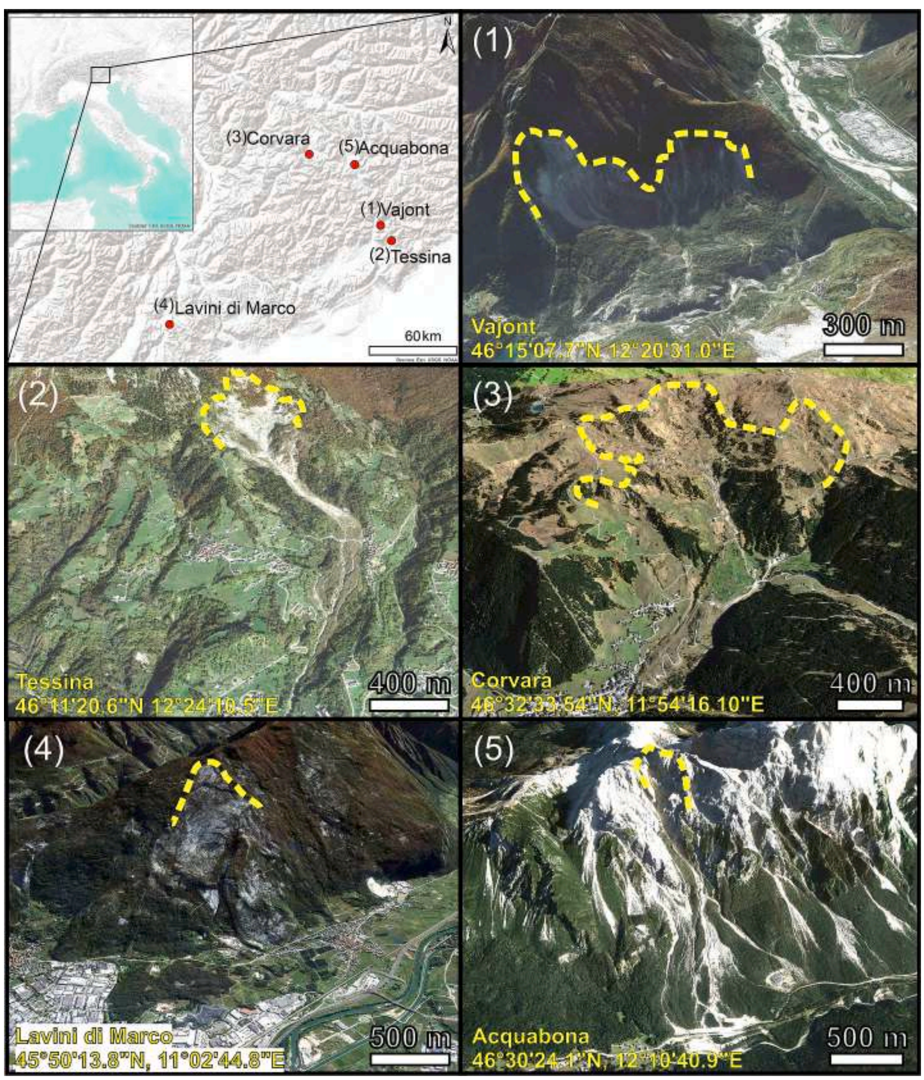

Fig. 1. Location of the study sites, with insets with oblique views of the selected landslides. Dashed yellow line in the insets indicates the upper detachment limit for each landslide. At the top left corner, shaded relief imagery used as basemap, source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community; in the insets, imagery sources: (1,2) Google Earth Pro v. 7.3 (October 18, 2022) Imagery 2024 CNES/Airbus, European Space Imaging, Landsat/Copernicus, Maxar Technologies (Accessed January 26, 2024); (3,5) Google Earth Pro v. 7.3 (October 16, 2017) Imagery 2024 CNES/Airbus, European Space Imaging, Landsat/Copernicus, Maxar Technologies (Accessed January 26, 2024); (4) Google Earth Pro v. 7.3 (October 24, 2017) Imagery 2024 CNES/Airbus, European Space Imaging, Landsat/Copernicus, Maxar Technologies (Accessed January 26, 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environmental, paleoenvironmental, natural-hazard, and climate-change related aspects that can be assessed by using this approach. While individual landslides have been defined as geomorphosites, or an entire region has been analysed with all its different landforms to assess its significance as geomorphosite, this is the first study that performs a comparative evaluation of landslides in a discrete region. We describe the geological, geographical and geoheritage settings of the selected landslides, and the main reasons for which we have chosen them to perform the first application of this method. We then report the results of the application of the method to the Dolomite region, and we finally discuss and highlight our conclusions on the importance of our approach and results in relation to previous geomorphosite-assessment studies.

2. Methodological principles

Our work introduces a methodological approach for landslide-geomorphosite quantitative assessment, considering values and criteria standardly used in geoheritage studies and adding three new criteria conceptualised in Morino et al. (2022) specifically for landslides. Our quantitative assessment of geomorphosite is based on the *Scientific*, *Additional*, and *Potential for use* sets of values. We divide the *Scientific* value into eight criteria (Table 1a): *Integrity* (INT), *Representativeness* (REP), *Rareness* (RAR), *Paleogeographic significance* (PAL), *Past climate-change implications* (PACI), *Present climate-change implications* (PRCI), *Anthropic influence* (ANIF), *Scientific knowledge* (SK). We divided the *Additional* value into five criteria (Table 1b): *Ecological* (ECOL), *Aesthetical* (AEST), *Cultural* (CULT), *Risk perception* (RP), *Anthropic signature* (ANSI). We divide the *Potential for use* value in four criteria (Table 1c): *Accessibility* (ACC), *Services and infrastructures* (SER), *Visibility* (VIS), and *Outreach and educational potential* (OEP).

A score between 0 and 3 can be attributed to each criterion. For each landslide geomorphosite, the total *Scientific/Additional/Potential for use* value (*Tot val*) is estimated by adding up the score of each criterion (a_i) and dividing it by the number of criteria (n_a) for each set of values (cf. Eq. (1):

$$Tot\ val = \frac{\sum a_i}{n_a} \tag{1}$$

The values, criteria and indicators used for this work are described in Table 1a-c, and their description largely coincides with those commonly used for standard geomorphosite assessment (e.g., Kubalíková, 2013; Mucivuna et al., 2019; Pereira and Pereira, 2010; Reynard et al., 2007). Nevertheless, this work is one of the first to conceive a method to perform geomorphosite assessment specifically on the landslide landform. Therefore, we adapt some definitions and categorisation of the criteria and indicators for landslides, and adopt new ones.

Among the set of *Scientific value*, we have introduced – according to Morino et al. (2022) – *Past climate change implications*, for assessing the role of past varying climate conditions in the occurrence and development of landslides. Past climate changes have caused various responses in the landscape over decades and longer timescales, including the onset and evolution of landslides (e.g., Pánek, 2019; Thomas, 2008; Wobus et al., 2010), and they can still impact the landscape today via reactivation (e.g., Kuhn et al., 2021). Furthermore, scientific knowledge on landslides occurred in the past as indirect consequences of varying climatic conditions can improve our understanding on the impact of future changing climatic scenarios. Following the new aspects defined by Morino et al. (2022), we have also added the criterion of *Present climate change implications*, in order to assess the influence of current climate change on landslide triggering and activity. Landslides can be among the exacerbating cascading consequences of current climatic trend. Total precipitation rates, precipitation intensity, mountain permafrost thaw

Table 1a
Scientific value, criteria, and scores for landslide-geomorphosite assessment.

Value	Criteria	Scores 0	1	2	3
Scientific value	Integrity (INT): state of conservation of the landslide	Completely modified by natural degradation processes and/or human intervention	Strongly affected by natural degradation processes and/or human intervention but some original landslide features are still preserved	Moderately affected by natural degradation processes and/or human intervention but most of the original landslide features are preserved	No traces of natural degradation processes and/or human intervention
	Representativeness (REP): exemplarity with respect to landslide processes and landforms	No specific features	Poor example of process or landform	Good example of process or landform	Reference landslide (in scientific literature) for the description of process or landform
	Rareness (RAR): uniqueness of the landslide with respect to a reference space	Very common	Rare at a regional scale	Rare at a national scale	Rare at an international scale
	Paleogeographic significance (PAL): importance of a landslide in defining processes or environments characterising the Earth history	No paleogeographic significance	Scarce paleogeographic significance	Good paleogeographic significance	Exceptional paleogeographic significance
	Past climate change implications (PACI): role of climate changes in landslide occurrence and development	No evidence of the role of past climate changes	Scarce and uncertain evidence of the role of past climate changes	Well-demonstrated evidence of the role of past climate changes	Abundant and well-demonstrated evidence of the role of past climate changes
	Present climate change implications (PRCI): influence of current climate change on landslide triggering and activity	No evidence of influence of current climate change	Scarce and uncertain evidence of influence of current climate change	Well-demonstrated evidence of influence of current climate change	Abundant and well-demonstrated evidence of influence of current climate change
	Anthropic influence (ANIF): influence of human activities on landslide occurrence	Landslide onset or activity not caused by human activities	Landslide onset or activity minorly caused by human activities	Landslide onset or activity partially caused by human activities	Landslide onset or activity mainly caused directly by human activities
	Scientific knowledge (SK): research significance based on number, clarity, and non-obsolescence of scientific publications	No scientific publications	Only local scientific publications	Mainly national scientific publications	Several national and international scientific publications

Table 1b
Additional value, criteria, indicators and scores for landslide-geomorphosite assessment.

Value	Criteria	Indicators	Scores 0	1	2	3
Additional value	Ecological value (ECOL): presence and protection of ecological features		No ecological elements and no landslide protection	Presence of rare ecological elements and protection at a local level	Presence of rare ecological elements and protection at a regional level	Presence of rare ecological elements and protection at a national level
	Aesthetic value (AEST)	Panoramic quality (PQ)	Landslide hardly visible from any viewpoint	Landslide partially visible from one viewpoint	Landslide entirely visible from one viewpoint	Landslide entirely visible from many viewpoints
		Vertical and/or horizontal displacement (VH)	Small vertical and/or horizontal displacement	Moderate vertical and/or horizontal displacement	Significant vertical and/or horizontal displacement	Exceptional vertical and/or horizontal displacement
	Cultural value (CULT)	Historical importance (HI)	No historical importance	Local historical importance	National historical importance	International historical importance
		Artistic importance (AI)	No artistic importance	Local artistic importance	National direct* artistic importance	International artistic importance
		Spiritual importance (SI)	No spiritual importance	Local spiritual importance	National spiritual importance	International spiritual importance
		Technical significance of preventive and mitigation measures (TS)	Absence of preventive and mitigation measures	Scarce presence of preventive and mitigation measures	Presence of preventive and mitigation measures of average technical significance	Presence of preventive and mitigation measures of exceptional technical significance
	Risk perception (RP)	Dissemination to residents and visitors (D)	No dissemination initiatives	Small and infrequent forms of dissemination initiatives	Permanent and/or recurrent forms of dissemination initiatives at local and regional level	Permanent and/or recurrent forms of dissemination initiatives at local, regional and national/international level
		Risk awareness by general public (RA)	No perceived awareness of the risk	Small awareness of risk	Good awareness of risk	Excellent awareness of risk
	Anthropic signature (ANSI): impact of landslide occurrence on human life and socio-economic activities	Negative impacts on human life and activities (NI)	No negative impact on human life and activity	Minor damage and disruption to human activities	Serious damage and disruption to human activities	Serious damage and disruption to human activities and injuries/fatalities
		Positive impacts on human life and activities (PI)	No positive impact on human life and activity	Minor and sporadic positive impact on human life and activity	Substantial and recurrent positive impact on human life and activity	Substantial and permanent positive impact on human life and activity

Table 1c
Potential for use value, criteria, and scores for landslide-geomorphosite assessment.

Value	Criteria	Scores 0	1	2	3
Potential for use	Accessibility (ACC): level of accessibility	No access	Accessible only to experts with specific technical skills (e.g. climbers, speleologists)	Accessible to people without mobility impairment/no specific technical skills are required	Accessible to people with mobility impairment
	Services and infrastructures (SER)	No services	Support services within a walkable distance but subject to seasonal availability	Equipment and services in the near proximity of the landslide subject to seasonal availability	Equipment and support services in the near proximity of the landslide, available all year round
	Visibility (VIS): perceivability of the landslide (e.g orography, vegetation, buildings, etc.)	Not visible	Hardly visible	Visible only under certain conditions	Well visible in all conditions
	Outreach and educational potential (OEP)	No outreach initiative	Infrequent forms of outreach initiatives at local level	Permanent and/or recurrent forms of outreach initiatives at local and/or regional level	Permanent and/or recurrent forms of outreach initiatives at local, regional and national/international level

rates, glacier retreat and warming air temperature are all factors that have been seen to determine an increase in frequency, magnitude, and seasonal unpredictability of landslide processes (Borgatti and Soldati, 2010a; Crozier, 2010; Uhlmann et al., 2013; Gariano and Guzzetti, 2016; Masson-Delmotte et al., 2021; Sæmundsson et al., 2021; Chiarle et al., 2023; Svennevig et al., 2023).

In Morino et al. (2022), the importance of the *Anthropic signature* aspect is also discussed, which could be considered in a twofold way that we have expanded via two new criteria, specifically designed for landslide geomorphosites. Firstly, human activities such as slope-reprofiling, hydrogeological perturbation, surface or deep water-flow modifications, land-use change and degradation, inappropriate artificial structures, vibrations and explosive, ageing and degradation of infrastructures (e.g., Jaboyedoff et al., 2018) can bring to an increased landslide hazard and vulnerability levels (Lazzari et al., 2006; Nicolet et al., 2013). Therefore, in the *Scientific*-value set, we have added the criterion *Anthropic influence*, to assess how much landslide onset and development was caused by any human activity. Secondly, the anthropic signature can be interpreted as the impacts of a landslide event on human actions and activities. This can be exemplified by the act of ensuring the safe access and use of a territory affected by a landslide. Therefore, among the *Additional*-value set, we have introduced the criterion of *Anthropic signature*, to assess the impact of landslide occurrence on human life and socio-economic activities. This is measured via two indicators, namely i)

Negative impacts on human life and activities, and ii) *Positive impacts on human life and activities*, as the occurrence of a landslide can either bring disruption and degradation to a territory, but also create opportunities, especially in terms of tourism revenue and economic incomes, as a landslide itself, the modifications that can cause to the landscape, and the surrounding environment can attract tourists and increase local profit. Paradoxically, even after disastrous consequences caused by a landslide, the landforms and indirect consequences produced by a disastrous event can be leveraged to a socio-economical level to bring benefits to the local communities. Therefore, a high score for the *Negative impacts on human life and activities* indicator may coincide with a high score for the *Positive impacts on human life and activities* indicator for the same landslide.

In the *Additional*-value set, we have assigned to the aesthetic value two indicators, namely i) *Panoramic quality*, and ii) *Vertical and/or horizontal displacement*. While *Panoramic quality* standardly describes how much a landslide site is visible from one up to numerous viewpoints, the V*ertical and/or horizontal displacement* is an indicator that we have specifically designed for landslide geomorphosites. The mobility of landslides is commonly expressed with an index defining the angle of the line connecting the head of the landslide source to the toe of the displaced mass. This is widely used in the landslide community, is an efficient and prompt method to measure the relative mobility of a landslide, and has been designated as the *fahrböschung* angle or angle of reach (Heim, 1932a; Scheidegger, 1973; Corominas, 1996). This index can be used to directly derive the *Vertical and/or horizontal displacement* indicator, which therefore fairly approximates the scenic view of a landslide, its size and distribution in the landscape, and gives information on the mobility of the landslide.

The cultural value is assessed using four indicators, namely i) *Historical importance*, ii) *Artistic importance*, iii) *Spiritual importance*, and iv) *Technical significance of preventive and mitigation measures*. We have newly introduced the latter to assess the presence of structural mitigation measures and their technical significance. Landslide remedial measures can constitute modification of slope geometry, drainage, retaining structures and internal slope reinforcement. Landslide-early warning systems are a preventive measure whose design, implementation, management, and verification are gaining increasing attention in the scientific community and among government officials, decision makers, and the public. The technological improvement on these measures has vastly increased in the last decades, thus it is an aspect that needs to be included when considering a landslide geomorphosite.

Finally, we have introduced in the *Additional* value the criterion of *Risk perception*, according to the new aspects identified by Morino et al. (2022). Landslide risk perception has been seen to be influenced by factors such as experience of previous landslide events, psychological, social, and cultural values (Fischhoff et al., 1983; Morgan et al., 2001; Garrick and Gekler, 2013). Since it is important that those who might be affected are provided with knowledge, made aware of the risk, and are involved in decisions about risk management, we have proposed the indicator *Dissemination to residents and visitors*, to assess the forms of dissemination initiatives at local, regional, and national/international level that can aid in increasing the resilience of a community. The second indicator that we have introduced is the *Risk awareness by general public*, to assess how much a particular landslide geomorphosite is aiding in increasing landslide risk perception not just to a local level, but to a broader audience.

3. Application of the method

3.1. Study area and rationale

The Dolomites are universally renowned for their scenic beauty and scientific interest (Bainbridge, 2016; Panizza, 2018). They have been proclaimed in 2009 a UNESCO World Heritage property. This region of the European Alps is characterised by spectacular landforms with enormous vertical and light-coloured cliffs, pinnacles and towers emerging from vegetated slopes composed of darker rocks (Soldati, 2010). The Dolomitic Alps are mainly composed of dolomite rocks, with marls or limestones alternating with shales (Soldati et al., 2004). Landslides are widespread and comprise a great variety of processes (Borgatti and Soldati, 2010a, 2010b). Several studies have focussed on the general geoheritage importance and significance and their high geodiversity (Panizza, 2009a, 2009b; Testa et al., 2013, 2019; Aldighieri et al., 2016; Reynard and Coratza, 2016). Landslides are a geomorphological element that vastly enriches the broad geodiversity of the Dolomites. In general, landslides have been previously analysed as possible geomorphosites (*sensu* Panizza (2001)) at numerous specific sites around the world (Kubalíková and Kirchner, 2016a; Niculiţă and Mărgărint, 2018; Tognaccini, 2019; Forno et al., 2022; Tronti et al., 2023), and their importance as a landform in the global geological heritage has been defined in Morino et al. (2022).

3.2. Landslide sites

3.2.1. Vajont landslide

3.2.1.1. Geological and geomorphological description. The 1963 Vajont Slide (Fig. 2) is one of the best known and most tragic examples of a natural disaster induced by human activity. The global impact of the event stimulated a large body of research on the stability of natural rock slopes. On 9 October 1963 at 22.39 local time, the north slope of Mount Toc collapsed into the reservoir in less than 45 seconds, generating a 50 million m^3 displacement wave that overtopped the dam and swept into the Piave Valley below (Ghirotti, 2012). The flood destroyed many villages and caused the loss of about 2000 lives. Remarkably, the dam remained relatively intact. A residual lake is present upstream of the landslide. The landslide occurred in a region characterised by complex structural geological and geomorphological settings. The landslide is approximately 1.8 km wide and 1.5 km long, and mobilised a volume of 250 million m^3. The slide moved about 300 to 400 m horizontally a 250-m thick mass of rock after a long-term phase of accelerating creep lasting 2–3 years, before running up and stopping against the opposite side of the Vajont Valley (Petley and Petley, 2006). Most of the slide moved as a whole, without any change in shape apart from a general rotation. The movement occurred mainly along a chair-shaped failure surface, in part corresponding to a pre-existing slip surface, as indicated by the geological evidence recognised before 1963 (Semenza and Ghirotti, 2000). This failure surface was largely confined within 0.5–18 cm thick clay-rich layers, which were observed to be continuous over large areas of the failure surface (Hendron and Patton, 1985). Three years prior to the catastrophic failure, the presence of an M-shaped, 1 meter-wide, and 2.5 kilometres-long tension crack on Mount Toc delineated the failure. However, even if Mount Toc provided clear important evidence to infer its instability, technicians and experts of the time incorrectly hypothesised a very large and slow-moving landslide that could be controlled by reservoir operations (Müller, 1964, 1968).

3.2.1.2. Rationale of choice for landslide-geomorphosite assessment. The 1963 Vajont Slide is probably one of the most renown landslides in the world. It has been studied for over 60 years (Semenza, 1965; Chowdhury, 1978; Hendron and Patton, 1985; Belloni and Stefani, 1987; Semenza and Melidoro, 1992; Kilburn and Petley, 2003; Petley and Petley, 2006; Barla and Paronuzzi, 2013; Massironi et al., 2013; Zaniboni et al., 2013; Salvati et al., 2014; Wolter et al., 2014; Franci et al., 2020), and it is still receiving great scientific interest, as proved by the recent publications on its initiation, evolution, and dynamics (Paronuzzi et al., 2016; Wolter et al., 2016). During the International Union of Geological Sciences 60th anniversary celebration in 2022, the Vajont landslide was announced among the “First 100 IUGS Geological Heritage Sites”, formalising its scientific recognition as key geological site for

Fig. 2. Detailed oblique view of the Vajont landslide.

the Earth sciences research (Hilario et al., 2022). The Vajont site is also characterised by several additional values that makes the landslide stand out for its relevance as geomorphosite. Among many of these values, we underline its exceptional *Aesthetic* value, and its historical importance, given that the disaster was a breakthrough event in the geological, engineering, and civil protection history of Italy and the world. Furthermore, among the *Potential-for-use* values, human intervention with roads and paths construction enables a good accessibility to the site.

3.2.2. Tessina landslide

3.2.2.1. Geological and geomorphological description. The Tessina landslide (Fig. 3) is characterised by a complex movement, which threats an inhabited area since 1960 in the Alpago basin. It is classified as a rotational/translational slide (Hungr et al., 2014), with deposits with a thickness of about 30 to 50 m in the upper slope, evolving downhill into a 2.5 km-long earth/mud flow, which channelised the landslide material along the Tessina Valley and almost completely filled it (Silvano and Pasuto, 1995; Petley et al., 2002; Van Westen and Getahun, 2003; Cola et al., 2016). In April 1992, a huge reactivation took place, involving almost 1 million m^3 of material forming a thick mudflow. The flow travelled 2.5 km, skimming the village of Funes, and stretched downhill as far as the village of Lamosano (Cola et al., 2016). The serious possibility of a slope failure and a consequent mud overflow involving the two villages induced the public authorities to take urgent actions to protect houses and residents. After this event, the Italian National Department of Civil Protection assigned funds for designing and implementing a monitoring and alarm system. This system was also integrated into the Municipal Civil Protection Plan, which was successfully set up and tested in the very early stage of its establishment (Angeli et al., 2007; Pasuto and Schenato, 2022). At that time, the structure of the monitoring system and the selected instrumentations made the Tessina landslide one of the most up-to-date landslide monitoring sites in Italy.

The predisposing factor for the landslide activation is the geological and tectonic setting of the area, which is characterised by the presence of a thick (1000–1200 m) Middle Eocene geological formation, namely flysch, mainly constituted by folded and faulted layers of sandstone, marls and clays (Cola et al., 2016). The presence of sub-vertical fractures in the carbonate massif in the upper part of the slope of Mount Teverone favours rainfall and snow-melting water infiltration, which also feed several perennial springs in the flysch formation that are considered a triggering element for further potential reactivations (Mantovani et al., 2000). The landslide has been monitored since the reactivation of 1992. At present, the monitoring system is still active and provides warning and alarm signals and, if necessary, activates the emergency plan (Avolio et al., 2000; Casagli et al., 2002; Hervás et al., 2003; Tarchi et al., 2003; Angeli et al., 2007; Gabrieli et al., 2016; Pasuto and Schenato, 2021).

3.2.2.2. Rationale of choice for landslide-geomorphosite assessment. The Tessina landslide is one of the best-known and investigated landslides in the Italian Alps. The rich and copious scientific production reported above on this case study testifies its scientific importance. From a morphological point of view, it is an active landslide with distinctive geomorphological features that makes it a textbook case for scientific

Fig. 3. Detailed oblique view of the Tessina landslide.

and educational purposes. Among the additional values, the landslide stands out for the more than 30 years of monitoring data with innovative instrumentation and a well-developed emergency plan. This site became a landmark for landslide-monitoring specialists, allowing several European research groups to benefit from the research on the landslide and the available on-site geotechnical instrumentation for further experimental endeavours.

3.2.3. Corvara landslide

3.2.3.1. Geological and geomorphological description. The Corvara landslide (Fig. 4) is located immediately uphill of the village of Corvara, in the Badia Valley. It has been classified as a deep-seated rotational earth slide – earthflow (Hungr et al., 2014), covering an area of more than 2.5 km^2, and having a volume of more than 30 million m^3 (Corsini et al., 1999; Panizza et al., 2011). The landslide has a monitoring system and is classified as active, with movements ranging from 0.01 to more than 20 m/year (Corsini et al., 2005; Thiebes et al., 2016), causing continuous damage to power lines, cable cars and roads. Future movements of the landslide could impact buildings at the landslide toe. The landslide has been dated back to 10,000 cal B.P., and a second major phase of morphological development is registered from about 5000 to 2500 cal B.P. (Corsini et al., 2001; Soldati et al., 2004; Borgatti et al., 2007; Borgatti and Soldati, 2018). The bedrock is composed of sub-metre strata of rheologically hard rocks (marls, arenites and/or marly limestone) and sub-metre to metre strata of weak rocks (claystone or clayshales). Pervasive structural jointing and faulting affect these rock masses with spacing ranging from a few centimetres to decametres.

3.2.3.2. Rationale of choice for landslide-geomorphosite assessment. The Corvara landslide has a high geomorphological importance, it is highly relevant from a monitoring point of view (Corsini et al., 2012; Iasio et al., 2012; Mulas et al., 2015; Darvishi et al., 2020) and is a key example of a landslide developing during variations in past climatic conditions. Therefore, this landslide showcases a variety of values that lead to assess its importance as landslide geomorphosite among many cases in the Dolomites. The Corvara landslide has also a peculiar morphology that has been exploited to build ski slopes and a golf course, positively favouring the tourist and economic development of the area.

3.2.4. Lavini di Marco rock avalanche

3.2.4.1. Geological and geomorphological description. The Lavini di Marco rock avalanche (Fig. 5) is located on the western side of Mount Zugna Torta (1257 m a.s.l.), near the city of Rovereto in the Adige Valley. It is among the largest rock avalanches of the Dolomites, with a volume of about 2×10^8 m^3 over an area of 6.8 km^2 (Fuganti, 1969; Eisbacher and Clague, 1984; Orombelli and Sauro, 1988a; Martin et al., 2014). A thorough geological description of the landslide deposit is reported in (Martin et al., 2014). The rock avalanche complex comprises the main Lavini di Marco and the smaller Costa Stenda deposits, which are composed of Jurassic carbonate rocks of the Calcari Grigi Group, extensively present across the Eastern Southern Alps and consisting of layered limestones with marly clayey interbeds (Masetti and Romano, 2008). The sliding occurred along shear planes oblique to the bedding (Orombelli and Sauro, 1988b; Martin et al., 2014), and the landslide has a *fahrböschung* angle of 12°(Abele, 1974). The complex structural setting of the area, characterised by multiple tectonic features, and the presence of clay interbeds in one of the limestones of Calcari Grigi Formation are thought to control the past instability of the slope, which does not seem to have reached the equilibrium (Tommasi et al., 2009).

The Lavini di Marco rock avalanche age was highly debated, and generally attributed – like many other large landslides in the area – to stress release following downwasting of glaciers at the end of the Last Glacial Maximum, between 18,000 and 12,000 years ago (Noriller, 1871; Taramelli, 1881; Penk and Brückner, 1909; Heim, 1932b; Eisbacher and Clague, 1984; Matsuoka and Murton, 2008). The ages obtained by cosmogenic ^{36}Cl dating are however much younger, namely 3.0 ± 0.4 ka for both the Lavini di Marco and Costa Stenda rock avalanches, with some small-scale reactivation along the sliding plane and release headwall. An early Medieval age was defined for the sliding plane, probably corresponding to a catastrophic flood event of the Adige River in Verona in 883 CE (Martin et al., 2014), and a single age of 800 ± 210 years from the headscarp suggests some activity coinciding with the Verona earthquake at 1117 CE (Orombelli and Sauro, 1988a; Galadini et al., 2001; Stucchi et al., 2008).

The Lavini di Marco rock avalanche also hosts a unique palaeontological site. A wide fossil tidal flat of Early Jurassic age with an extensive set of dinosaur prints are exposed along bedding planes, and are subject to ichnological and paleobiological studies (Avanzini and Zampieri, 2000; Avanzini et al., 2001, 2003).

The Lavini di Marco rock avalanche is even mentioned by Dante Alighieri in the “Inferno” of the “Divina Commedia, Canto XII”. The poet describes the deposits reaching the river Adige that detached from the top of the mountain because of an earthquake or missing support («o per tremoto o per sostegno manco»; Ilieş et al. (2011)).

Fig. 4. Detailed oblique view of the Corvara landslide.

Fig. 5. Detailed oblique view of the Lavini di Marco rock avalanche (courtesy of M. Zumiani).

3.2.4.2. Rationale of choice for landslide-geomorphosite assessment. The case of Lavini di Marco rock avalanche has been thoroughly covered by tens of scientific studies that reveal a complex evolution, with multiple stages of reactivation (Martin et al., 2014). The landslide also stands out for having exposed a dinosaur tracksite that has been vastly studied for its paleontological, stratigraphic and sedimentological importance, and that is now a major tourist attraction in the area. The Lavini di Marco rock avalanche is one of the few landslides in the Dolomites for its size and geographical position to be visible from kilometres of distance at different locations. Finally, the deposits of the rock avalanche are described by Dante Alighieri in the Divina Commedia, a unique case of a landslide portrayed in one of the most important poems in human history.

3.2.5. Acquabona debris flows

3.2.5.1. Geological and geomorphological description. The Acquabona catchment is located about 5 km south-southeast to Cortina d'Ampezzo in the in the Boite River Valley and is affected by at least one debris-flow event every year (Tecca and Genevois, 2009). From a geomorphological point of view, it is characterised by an upper rock basin, with a drainage area of 0.3 km^2 with the highest elevation of 2667 m a.s.l., and an average slope of 43 %. Here, the bedrock is composed of upper Triassic to Lower Jurassic massive dolomites, limestones and marls (Berti et al., 1999). At the base of rock cliff, a thick mantle (40 m at least) of talus deposits (including heterogeneous scree, alluvium and debris-flow deposits containing boulders up to 3–4 m in diameter), covers the bedrock up to the valley bottom. Deep channels (somewhere reaching 30 m depth; Fig. 6) are mostly carved into the talus and the marls bedrock in places (Berti et al., 1999, 2000; Genevois et al., 2001). This setting is extremely prone to the occurrence of recurrent debris flows, which have been observed to originate with initial failures involving the loose material in the upper sections of the channels, causing substantial (up to 30,000 m^3) volume increase in the flowing mass (Tecca and Genevois, 2009). A detailed geomorphological description of the site is available in (Berti et al., 1999; Genevois et al., 2001). The Acquabona catchment and the debris-flow events have been studied since 1997, based on a field-monitoring system that changed in the years. The monitoring system was installed with the aim of characterising the phase of initiation, propagation and deposition of debris flows typical of the Dolomites by numerical modelling (Berti et al., 2000; Tecca et al., 2003; Berti and Simoni, 2005; Armento et al., 2008), and to assess the risk posed by frequently occurring debris-flow events (Archetti and Lamberti, 2003). The data collected led to a significant number of scientific publications (Genevois et al., 2000; Armento et al., 2008; Gregoretti and Fontana, 2008; Scotton et al., 2011). Besides the monitoring system, several remediation measures have been put in place in the following years on this site. Recently, because of the coming Winter Olympic Games of 2026, a very large trap basin with a complex draining network has been realised by the Italian National Road Authority to protect the State Road n. 51 "Alemagna" that leads to Cortina d'Ampezzo.

3.2.5.2. Rationale of choice for landslide-geomorphosite assessment. The Acquabona site is the unique case among those chosen for this study that showcases debris flows. Tens of scientific publications have been produced about this site for its debris-flow monitoring system and relevant

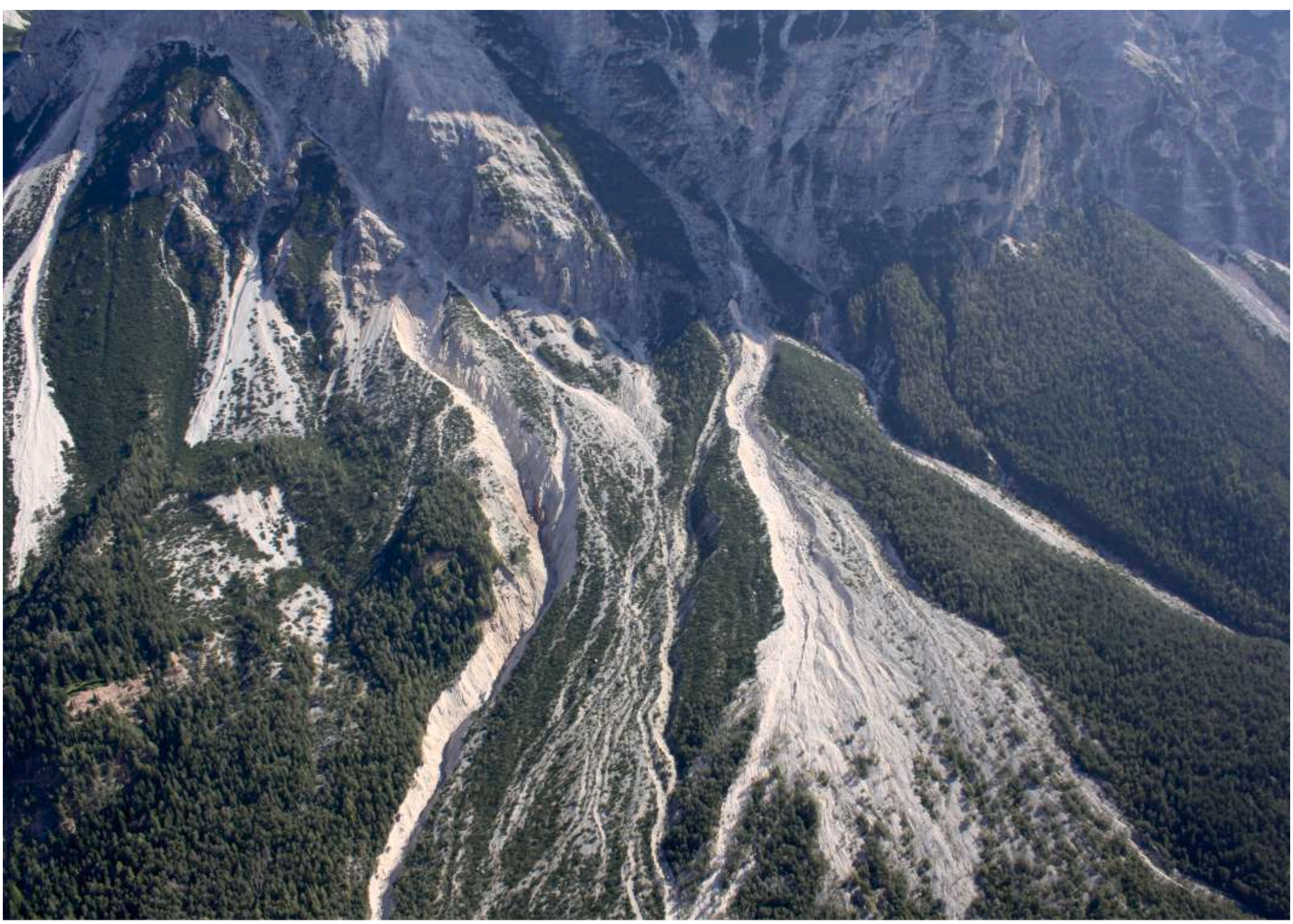

Fig. 6. Detailed oblique view of two channels of the Acquabona debris flows.

protection measures have been designed and realised. The site has also been chosen because the debris flows in the area have been caused by sudden and intense precipitation (Floris et al., 2010), a phenomenon related to local changing climatic conditions in the Dolomites (Borgatti and Soldati, 2010b) and generally in mountain environments (Kellerer-Pirklbauer et al., 2012; Stoffel et al., 2014a, 2014b; Brönnimann et al., 2018; Morino et al., 2019).

3.3. Application of landslide-geomorphosite assessment to the selected case studies in the Dolomites

In the following, we apply our approach to perform a comparative analysis of five landslides in the Dolomites (Fig. 1), which showcases different old and new values in geomorphosite assessment. The evaluation process builds on bibliographical data and on the detailed and well consolidated knowledge of the geological and geomorphological features of the study area acquired by the authors. Our approach and knowledge on the sites chosen for this study have allowed us to quantitatively assess the different values and criteria of the Vajont, Tessina, and Corvara landslides, the Lavini di Marco rock avalanche and the Acquabona debris flows (Table 2). Multivariate representation allows one to compare geosites with one another, with the data length of spokes proportional to the magnitude of each criterion and indicator (Fig. 7).

3.3.1. Geomorphosite assessment of the Vajont landslide

The Vajont landslide is the geomorphosite with the highest scores for the values and criteria adopted, with a total of 49 (Table 2). In terms of *Representativeness*, it is one of the most known landslides in the world, even outside the landslide scientific community. It is a key example of landslide, as an unprecedented amount of data were collected before and after its occurrence (Giudici and Semenza, 1960; Müller, 1964, 1968; Selli et al., 1964; Semenza, 1965; Semenza and Ghirotti, 2000; Genevois and Prestininzi, 2013). There is a vast and detailed knowledge about the geology, geomorphology, geomechanics and modelling of the landslide, resulting in more than one hundred publications on these topics (Superchi et al., 2010). This is also the reason why the Vajont landslide scores 3 in the *Scientific knowledge* criterion. The Vajont landslide is a rare example of catastrophic landslide, as in the human history there have been few landslides of such magnitude in densely populated areas caused by anthropic action. Consequently, the *Anthropic influence* criterion scores the maximum, as the Vajont disaster was caused by the inadequate assessment from experts of the possible consequences of damming the valley. For this reason, the site has been listed in the UNESCO Memory of the World Programme (Musolino, 2016). A drop in elevation of about 560 m and a length of the deposits of 1530 m from the source area to the bottom of the valley rise the *Aesthetic value* of the landslide when considering the *Vertical and/or horizontal displacement* indicator. The landslide serves to many dissemination activities that have been undertaken to increase the risk awareness of the landslide to residents, visitors, and the general public, with the *Risk perception* value reaching the maximum scores. The Vajont disaster killed 1917 people, destroyed the villages of Frasègn, Le Spesse, Il Cristo, Pineda, Ceva, Prada, Marzana, San Martino, Erto, Longarone, Pirago, Faè, Villanova, Rivalta, Codissago, Castellavazzo, Fortogna, Dogna, Provagna, damaged the villages of Soverzene, Ponte nelle Alpi, Borgo Piave, Quero Vas, Caorera, and the costs associated to the event are quantified to 900 million of euros (2023). Therefore, the *Negative impacts on human life and activities* indicator scores 3. In terms of *Accessibility*, although the way to Mount Toc and the landslide deposits are difficult to reach, the point views to observe the dam and the landslide are accessible to people with mobility impairment. On the topic of the Vajont landslide, several books, movies, documentaries, tv shows and theatre performances have been produced, and two local museums on the Vajont disaster are present in the valley, raising the *Outreach and educational potential* value. In terms of *Historical importance*, the Vajont landslide is the only site to score 2, as it is the only landslide whose catastrophic consequences profoundly influenced the civil and socioeconomic history of Italy, and represents a watershed in the landslide disaster history.

3.3.2. Geomorphosite assessment of the Tessina landslide

The Tessina landslide shows high scores for many of the values and criteria adopted. The high frequency of reactivation of the landslide movements from 1960 up to recent years has contributed to create a very distinguishable landslide landform, so that the landslide *Integrity* is high. The landslide has also a high *Representativeness*, as it is a well-known landslide in Italy, it is a key example of long-term monitored

Table 2
Quantitative assessment of the selected landslide geomorphosites.

Value	Criteria	Indicators	Vajont	Tessina	Corvara	Lavini	Acquabona
Scientific value	Integrity (INT)	–	2	2	1	1	1
	Representativeness (REP)	–	3	2	2	3	3
	Rareness (RAR)	–	3	2	2	3	1
	Paleogeographic significance (PAL)	–	0	0	2	3	0
	Past climate change implications (PACI)	–	1	0	3	3	0
	Present climate change implications (PRCI)	–	1	2	2	0	3
	Anthropic influence (ANIF)	–	3	3	0	0	0
	Scientific knowledge (SK)	–	3	3	3	3	3
Additional value	Ecological value (ECOL)	–	1	1	1	3	0
	Aesthetic value (AEST)	Panoramic quality (PQ)	2	3	3	3	3
		Vertical and/or horizontal displacement (VH)	3	3	3	3	3
	Cultural value (CULT)	Historical importance (HI)	2	0	0	0	0
		Artistic importance (AI)	2	0	0	3	0
		Spiritual importance (SI)	0	0	0	0	0
		Technical significance of preventive and mitigation measures (TS)	2	3	2	0	3
	Risk perception (RP)	Dissemination to residents and visitors (D)	3	1	1	2	0
		Risk awareness by general public (RA)	3	3	2	0	2
	Anthropic signature (ANSI)	Negative impacts on human life and activities (NI)	3	1	2	0	1
		Positive impacts on human life and activities (PI)	2	3	3	3	0
Potential for use	Accessibility (ACC)	–	3	3	3	2	1
	Services and infrastructures (SER)	–	2	0	3	3	3
	Visibility (VIS)	–	2	2	3	3	2
	Outreach and educational potential (OEP)	–	3	1	1	2	1
TOTAL			49	38	42	43	30

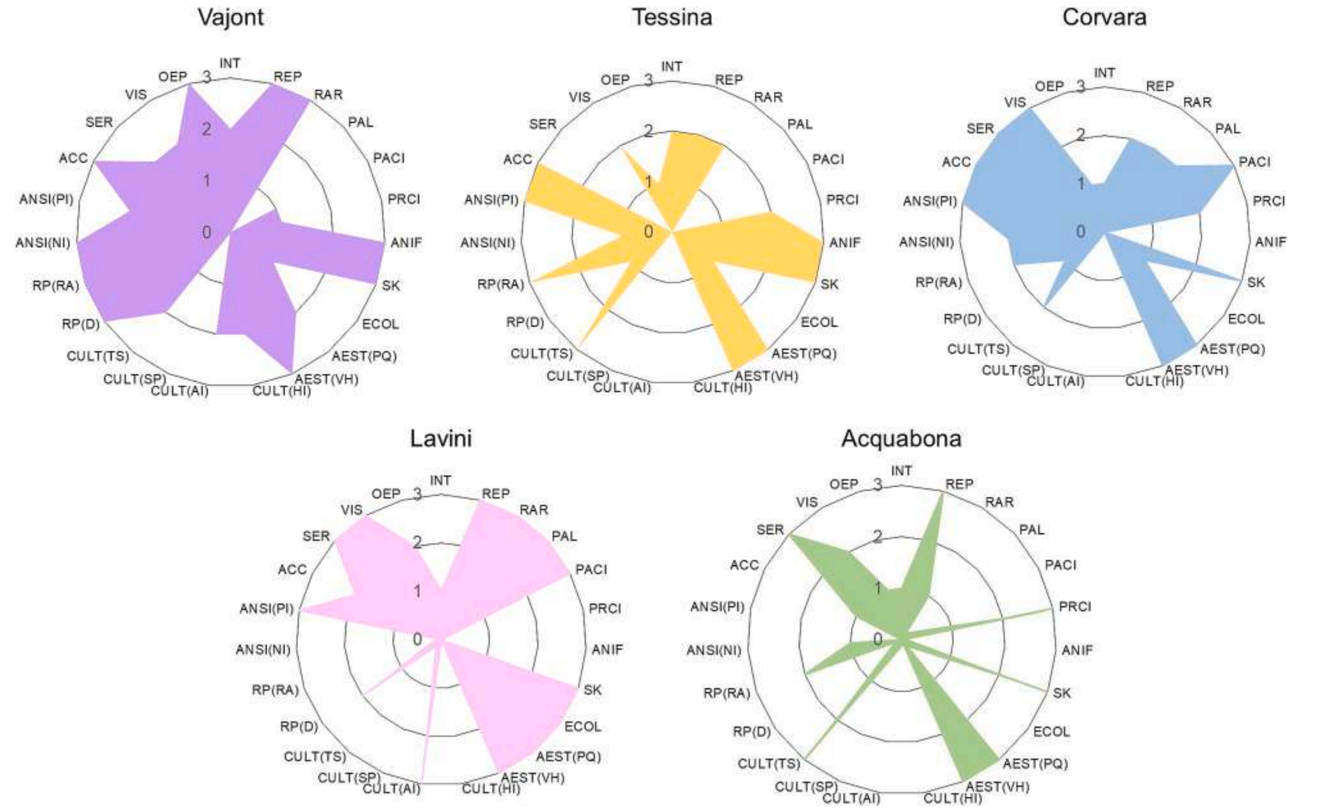

Fig. 7. Web chart representing the relative values for criteria and indicators for each geomorphosite.

landslide, and several works have been published on international scientific journals regarding the use of optical remotely-sensed imagery, innovative and conventional techniques for monitoring the evolution of the landslide and define hazard-scenario modelling (Avolio et al., 2000; Mantovani et al., 2000; Hervás et al., 2003; Tarchi et al., 2003; Van Westen and Getahun, 2003). For this reason, the landslide geomorphosite has a high *Scientific knowledge* criterion. In terms of *Anthropic influence*, the landslide scores a high value because a new road construction contributed to the 1960 activation. The landslide has also a high *Aesthetic value* since the site is entirely visible from many viewpoints (high *Panoramic quality*) and has an exceptional vertical displacement, with a drop in elevation from the source area to the bottom of the deposits of 550 m and a length of 2200 m. Over the past few decades, the site has been extensively monitored to analyse the evolution of the landslide dynamics and to identify the appropriate mitigation strategies to reduce the risk to the valley below. The site is equipped with the state-of-the-art displacement and photogrammetric-based monitoring systems that allow the real-time analysis of the landslide movements. For these reasons, the landslide has the highest score for *Technical significance of preventive and mitigation measures*. The site has not been valorised by any initiative to disseminate its importance and significance to residents and visitor, but the *Risk awareness* of local population is presumably very high – despite not having been quantitatively estimated in any scientific publication, because the reactivation movements are frequent and mobilising high volumes (up to 10 million m^3), significantly impacting the area. The landslide caused minor damage and disruption to human activities, but the *Positive impacts on human life and activities* have been significant, since the geotechnical challenges posed by the landslide forced to pursue a series of improvements in the stabilisation of the slope, roads and surrounding villages and towns. Moreover, the water discharge of the drainage tunnel to reduce the water infiltration in the source area is currently exploited to produce electricity by mean of a small power plant. The Tessina landslides is in an easily accessible area, with local roads that cross the deposits and reach the head scarp on both sides, so, if access to the site occurs by motorised means, the landslide is accessible to people with mobility impairment, allowing a score of 3 in terms of *Accessibility*.

3.3.3. *Geomorphosite assessment of the Corvara landslide*

The Corvara landslide is a typical case of deep-seated rotational earth slide – earthflow (Corsini et al., 2005; Schädler et al., 2015). The site is not a rare type of landslide, but it is highly representative of slow-moving landslides, which are particularly common in this area of the Italian Alps, because of the presence of weak clayey rocks on the slopes of valleys dominated by dolomite massifs (Angeli et al., 1998; Borgatti et al., 2007; Glastonbury and Fell, 2008; Lacroix et al., 2020). The Corvara landslide existed since at least about 10,000 cal BP, when rock mass release and adjustment occurred after the post-LGM glaciers withdrawal, and further developed from about 5000 to 2500 cal BP (Soldati et al., 2004). The first pulse of activity of the landslide corresponds to the general warming up of the beginning of the Holocene, while the second pulse is thought to be related to the increase of precipitation in the Subboreal–Subatlantic period (Goudie, 1999). Today, the landslide responds to long periods of high cumulative precipitation or effective infiltration. As many other large mass movements in the area (Soldati et al., 2004; Soldati and Borgatti, 2009), the landslide was therefore initially originated because of the environmental and climate changes occurring in the Holocene, and therefore this landslide is a key example in representing *Past climate change implications*. With more than 20 publications on international scientific journals focussing on the geological, geomorphological and hazard assessment of the landslide and on the remote-sensing applications to detect the landslide movements, the Corvara site scores 3 in terms of the *Scientific knowledge* criterion. The site is visible from many viewpoints also at a great distance, and therefore has a high *Panoramic quality*. It scores high in the *Vertical and/or horizontal displacement* indicator, as the elevation drop from the main scar to the bottom of the deposits is almost 550 m and its length is about 3400 m. The Corvara landslide is a great example of how a landslide landform favoured the economic development of an area (high *Positive impacts on human life and activities*), as the landslide deposits formed morphologies well-suited to host ski slopes and a golf course that contribute to the tourism development of the area. Given the proximity to the town of Corvara and the tourist facilities in the area, the landslide is accessible to people with mobility impairment (high *Accessibility*), and has equipment and support services in the near proximity of the site, available 7/24 all year round (high *Services and Infrastructures*). Finally, the landslide is visibly perceivable in all conditions, as there are no obstacles such as orography, vegetation, buildings (high *Visibility*).

3.3.4. Geomorphosite assessment of the Lavini di Marco rock avalanche

The Lavini di Marco rock avalanche is a unique geomorphosite, not only because of the rock avalanche itself, but also for many other features that are present in the area. The Lavini di Marco comprises two landslide deposits that have been dated with cosmogenic ^{36}Cl, revealing a complex landslide history. The main Lavini di Marco and the closely related smaller Costa Stenda events occurred during the late middle Holocene in the Subboreal period, and smaller-scale reactivations are linked to earthquake activity in 1117 CE (Martin et al., 2014). In the scientific literature, it is a reference paleo-landslide with well-constrained dating that allowed the definition of two different paleo-episodes and more recent reactivation. For these reasons, the landslide scores high in *Representativeness*. It is also an incredible rare landslide for its natural, geographic and geological setting: the area hosts two wetlands – Laghet Grant and Laghet Picol, home to animals and plants of rare beauty. The wetlands are located in two dolines, which formed because limestone rocks in Lavini area are characterised by karstic phenomena (Tommasi et al., 2009). Moreover, several dinosaur tracks (Fig. 8) are present on a bedding plane of Grey Limestones of the Lower Jurassic exposed during seismic activity in Medieval ages. These fossil tracks are left by Carnosaurus Ornithischia and Theropods (Avanzini et al., 1997, 2001), and allowed the reconstruction of a semi-arid, coastal, life-sustaining environment for these species that lived in the western margin of tropical Pangaea at the Triassic-Jurassic transition. For similar reasons, the Lavini di Marco rock avalanche has also a high *Paleogeographic significance* because of its gravity-induced processes linked to environmental changes, with age estimates ranging from the Last Interglacial to historic times (Martin et al., 2014). The landslide also shows abundant and certain evidence of the role of past climate changes in the area (high *Past climate change implications*), as dating of the deposits allowed to link the failure of other gravity-induced events in the Eastern Alps and reconstruct an enhanced slope failure activity in the area, perhaps related to the climatic transition to cooler and wetter conditions at the beginning of the late Holocene (Martin et al., 2020). With more than 10 national and international scientific publications on the rock avalanche history, geomechanics and dynamics, the Lavini di Marco case scores 3 in the *Scientific knowledge* criterion. The Lavini di Marco deposits have a unique *Ecological value*, and the site is part of a biotope. The vegetation surrounding the two wetlands hosted in the landslide is represented by species typical of wet environments. The ponds are also of great importance in terms of faunal aspects. As many as

Fig. 8. Preserved dinosaur footprints at the Lavini di Marco paleontological site.

51 of the 200 invertebrate species present in Italy have been found in Marco's ponds. Amphibians, reptiles, and birds live in the area too (Poli, 1999). The Lavini di Marco rock avalanche also scores the maximum in regard to the *Aesthetic value*. The landslide is perfectly visible from the villages downslope and from the opposite slope, from the state road SS112, from the provincial roads SP3 and SP90, and even from the highway A22. The landslide has an outstanding *Horizontal displacement*, with more than 1000 m in elevation drop from the headscarp to the toe. The Lavini di Marco rock avalanche is of high *Artistic importance*. Dante Alighieri in the 12th canto of the Inferno refers to it as "la ruina che nel fianco di qua da Trento l'Adige percosse, o per tremoto o per sostegno manco" (i.e., the failure that on the same slope as of Trento hit the Adige River, because of earthquake or missing support), hinting that the landslide would have been caused by a seismic event. *Dissemination to residents and visitors* is an indicator with a score of 2, as the site is free to access, and explanatory panels have been installed in the area describing the geological history of the area and its peculiarities. The Fondazione Museo Civico di Rovereto offers regularly guided tours on the palaeontology, geology and landslide history of the Lavini di Marco site. While there is no record of any death nor disruption due to the most recent historical episodes of failure, and therefore the rock avalanche has the lowest score in terms of *Negative impacts on human lives and activities*, the richness of geological, geomorphological, ecological and artistic features listed above in the Lavini di Marco rock avalanche has a substantial and permanent positive impact on human life and activity in the area, which attracts a significant flow of tourists each year (high *Positive impacts on human lives and activities*). The site is equipped with several services and facilities available all year round for tourists and visitors (high *Services and infrastructures*). Finally, due to its size and its position in the Adige Valley, the Lavini di Marco rock avalanche is perceivable in all conditions (high *Visibility*).

3.3.5. Geomorphosite assessment of the Acquabona debris flows

The Acquabona debris flows occur in a small catchment, and show geomorphological and hydrological conditions that are typical of other debris flow-prone areas in the Dolomites and many other mountain areas in the world (Morino et al., 2019; Berti et al., 2020; Pastorello et al., 2020). Since 1997, it was chosen as an observation and experimental site for its near-yearly debris-flow frequency, and it has been taken as a gold-standard in terms of debris-flow monitoring system worldwide. For these reasons, the Acquabona geomorphosite scores 3 in terms of *Representativeness*. It has been showed that in this area of the Dolomites local climatic changes might have produced an increase in the frequency of extreme rainfall events, potentially triggering debris flows (Floris et al., 2010). Therefore, the Acquabona site showcases a high *Present climate change implications* on landslide triggering and activity. Tens of papers have been published on international journals, particularly focussing on the monitoring systems emplaced in Acquabona, which for this reason scores 3 in terms of *Scientific knowledge*. The *Panoramic quality* of Acquabona is also high, as the site is visible for many kilometres along the state road SS51, as well as for the *Vertical and horizontal displacement*, with an elevation drop of more than 1000 m and 3000 m of horizontal displacement. The Acquabona site showcases perfectly the indicator of *Technical significance of preventive and mitigation measures*, as since 1997 state-of-the-art monitoring systems have been put in place to analyse the debris-flow activity via instruments such as pluviometers, geophones, water pressure transducer, cameras, seismic and ultrasonic sensors. High standard structural measures have been built at the base of the slope, to protect the National Road n. 51 "Alemagna", which is very busy both in winter and summer seasons. Finally, since terminal lobes of the debris flows often reach the road, equipment and support services are in the near proximity of the site and available all year round (high *Services and infrastructures*).

4. Discussion

Our study proposes an approach for the assessment of a landslide geomorphosite including new criteria and indicators, and it is the first attempt to perform a comparative analysis of landslides as geomorphosites in a defined region. In former literature, geomorphosite assessment has been done for specific geographic areas, but landslides have hitherto been neglected for their geoheritage significance. For example, in Pérez-Umaña et al. (2019) three different volcanoes of Costa Rica, Mexico and Spain are compared, and geomorphosite assessment is performed with the goal of defining their suitability for tourism purposes. Karst geomorphosites in Kučaj and Beljanica mountains in Serbia are analysed and assessed in Petrovic et al. (2020) in order to establish a karst-based geopark, while in the Anina karst region in Romania karst landforms are assessed as geomorphosites with the aim of protecting the karst landscape (Artugyan, 2017). In Zgłobicki et al. (2019), gullies are chosen at different locations in nine European countries to establish their geotourism potential. Landslides are assessed as geoarcheosites in the Moldavian Plateau in north-eastern Romania for their role in providing favourable setting for fortified settlements (Niculiţă and Mărgărint, 2018). Different quantitative assessment approaches are used in Comănescu and Nedelea (2017) for glacial and periglacial geomorphosites in the Southern Carpathians, Romania. In the French Pyrenees, the results from geomorphosite assessment of glacial and periglacial landforms are classified based on the priority for management and tourism priorities (Feuillet and Sourp, 2011).

Among studies proposing a geomorphosite assessment of a certain region, the work from Bollati et al. (2013) stands out, as the area of Miage Glacier and Veny Valley is chosen to illustrate the scientific and educational importance of glacial features located along three main tourist trails. Glacial and additionally karstic landforms are assessed and mapped in the Cantabrian Range in northern Spain, and potential uses are suggested (Serrano and González-Trueba, 2005). Another well-established example is from Coratza et al. (2011), where two different quantitative approaches are adopted to perform geomorphosite assessment of the coastal landforms in the Il-Majjistral Nature and History Park in north-western Malta. Similarly, Comănescu and Nedelea (2010) propose a statistical analysis of geomorphosite assessment in the Bucegi Mountains for a variety of landforms, including the feedback received from tourists. Different studies have also dealt with hazard implications during geomorphosite assessment in order to define the most vulnerable areas of the identified geomorphosites (Kubalíková, 2013; Zgłobicki et al., 2015; Ovreiu et al., 2019). However, the important and specific characteristics of landforms and associated processes have never been translated into criteria and values for geomorphosite assessment, thus our approach is the first to have provided specific new criteria and values for a landform of a kind, namely landslides. Ours is a quantitative assessment method, which is the only current attempt to minimise subjectivity during evaluation, particularly when certain values are difficult to measure, their quantification is influenced by assessor bias, or they rely heavily on the specific attributes of the site being analysed. Importantly, this approach of defining new values and criteria for assessing more thoroughly the geoheritage importance of certain characteristics of landslides can be easily extended to many landforms of various environments. This is something that we encourage the geoheritage community to do, while acknowledging its potential for further refinement. We recognise that it inherits the limitations of quantitative approaches, including subjectivity, the challenges associated with nuanced quantification, or equal weighting. We have selected landslides in the Dolomites to apply our method for landslide-geomorphosite assessment, having different characteristics that exemplify the *Scientific, Additional and Potential of use* values from various points of view, and Fig. 9 graphically shows these differences. Firstly, these are all cases of landslides characterised by spectacular geomorphological features and valuable engineering/geological aspects, which is the reason why they have been all subject to several internationally relevant scientific studies

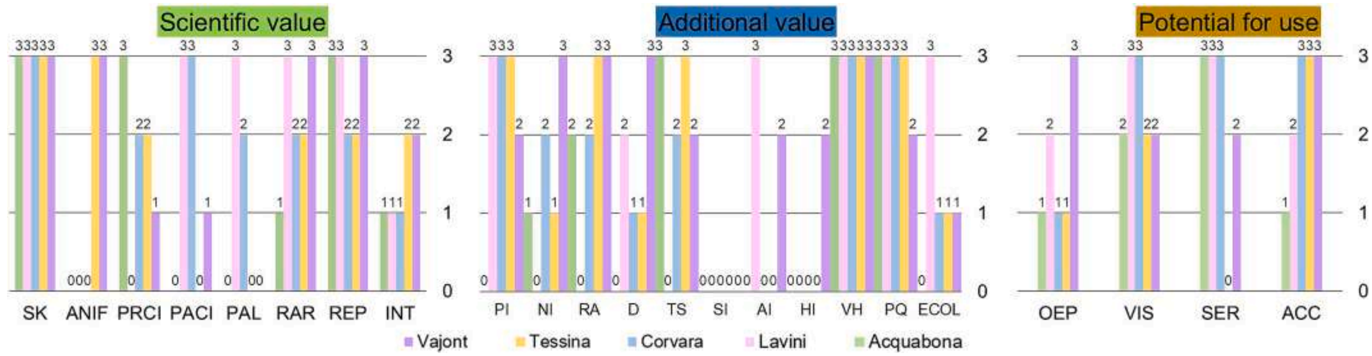

Fig. 9. Clustered column charts representing the difference in indicators' values for each landslide for the "Scientific", "Additional" and "Potential for use" values.

in the past years. They also have an outstanding *Aesthetic* value due to their high vertical and/or horizontal displacement that favours an optimal scenic view, as well as being in geographical settings that make them extremely well visible.

This study allows to demonstrate that the Vajont landslide is highly relevant as geomorphosite particularly regarding the new criteria and indicators defined after the study of Morino et al. (2022). The Vajont was a disaster directly caused by human action, thus the landslide is probably one of the most representative in terms of *Anthropic influence* criterion not only for the Dolomites, but worldwide. The same applies for the indicator of *Negative impacts on human life and activities*, as the destruction, damages and loss of lives caused by the Vajont event were unprecedented and the worst in Europe. Furthermore, the extent of this tragedy had profound cultural and historical effects, which brought to unique and advanced forms of dissemination to establish and develop *Risk awareness and perception* in residents and visitors.

Two of the new aspects identified by Morino et al. (2022) apply well also to the Tessina landslide. The landslide has been triggered by human activities, so it is fully representative for the criterion of *Anthropic influence*. The landslide posed significant geotechnical challenges to geologists and engineers, who were able to respond by improving the stability of the unstable slope and the quality of the infrastructures by means of a drainage tunnel, so the site well represents the criterion of *Anthropic Signature* regarding *Positive impact on human life and activities*. In terms of the criterion of *Risk perception*, the local population is very aware of landslide risk due to the long-term experience of living on a slope affected by this challenging landslide and the implementation of a very effective Civil Protection Plan with strong involvement of the population.

The Corvara landslide has characteristics that represent the aspects of *Past climate change* and *Anthropic signature* of Morino et al. (2022). The landslide was generated by the deglaciation history of the area, with the first activity dating back to 10,000 cal BP. The site also is a rare case of how landslides can sometimes improve human life and activities, as the landslide formed a morphology that allowed the establishment of ski slopes and a golf course that boosted the tourism industry in the area.

The Lavini di Marco rock avalanche showcases, like Corvara landslide, the aspects of *Past climate change* and *Anthropic signature*. Changing climatic conditions at the beginning of the late Holocene have been linked to the rock avalanche activity, which therefore exemplifies the criterion of *Past climate change implications* value. The rock avalanche has also positively improved the human life activities of the area, as tourism industry thrives here because of the unique geological, geomorphological, ecological, and artistic characteristics of the Lavini di Marco site.

Finally, the Acquabona debris flows are valuable examples of the criterion *Present climate change implications*. At this site, frequent and intense rainfall episodes trigger the reactivation of the debris flows, and in this area of the Dolomites local climatic variations might have produced an increase in the frequency of extreme precipitation events.

The five cases analysed here allow us to demonstrate how the three aspects of *Past and present climate changes, Anthropic signature* and *Risk perception* proposed by Morino et al. (2022) are critical in the identification and assessment of a landslide geomorphosite in addition to commonly recognised criteria and indicators. Normally, the purpose of geomorphosite evaluation and assessment is to develop solutions for their protection and even their promotion as tourist and educational destinations (Reynard, 2008; Kubalíková, 2013; Santos et al., 2020). Here we have shown that it is possible to go even further and improve the educational purposes of a landslide geomorphosite by incorporating criteria and indicators that can aid the public in understanding the impacts of anthropic activities and human-induced climate change, and to develop risk perception of such potentially hazardous events.

Valuing and promoting a landform of a kind, such as a landslide, in a certain region is a crucial step in the geoconservation and management process. Isolated examples of landslides at different sites around the world have been recognised as geomorphosites (Niculiță and Mărgărint, 2018; Cocean et al., 2019; Tognaccini, 2019; Forno et al., 2022; Tronti et al., 2023). Landslide geomorphosites can serve the public interest, and their valorisation and conservation are key instruments to communicate geoscience and Earth systems processes, and to make them accessible to society. In this study, we highlight that risk perception, anthropic signature and climate change can be introduced to add a reinforcing educational element in the geomorphosite assessment process. The Dolomites are an area where the process of knowledge transfer on the geological changes that affects the Earth at different time and spatial scales through landscapes, landforms, and outcrops is already well established. By identifying and assessing five cases of landslide geomorphosites with a focus on risk perception, anthropic signature, and climate change, we provide an example of how a landform of a kind can be assessed in a certain region with new values that target urgent themes from natural-hazard and climate-change perspectives. Among these five cases, only the Vajont landslide has been formally listed as a geosite in an inventory produced by a public institution, so adding our other four cases to more recognised and/or formal initiatives could aid in bringing landslide awareness among the public and enhancing their importance as geomorphosites in the Dolomites.

5. Conclusions

Our study presents a newly implemented approach to assess landslides as geomorphosites, using well-established values and criteria and adding newly defined ones, namely risk perception, anthropic signature, and climate change. These new criteria are crucial for the correct identification and definition of the best landslide geomorphosites for educating visitors on urgent topics such as landslide hazard and risk, human impact on landslide onset and development, and landslide response to increasing atmospheric temperatures. When applied, our method can aid in disseminating to the public the scientific importance of landslides and their consequences on human activities and the environment. We therefore applied this method to perform a comparative evaluation of landslide geomorphosites in the Dolomites, in northeastern Italy. Our study is the first that assesses a landform of a kind – landslides – as a geomorphosite by looking at selected cases in a defined region, and the results show the great variety of characteristics that can raise the geoheritage significance of landslides. Our approach has so far been limited to one landform, but the broad diversity of geomorphology should be an invite for the scientific community to the application of our method to many other landforms whose characteristics, evolution and related processes can be linked to risk perception, climate change and anthropic signature.

CRediT authorship contribution statement

Costanza Morino: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Paola Coratza:** Writing – review & editing, Data curation, Conceptualization. **Monica Ghirotti:** Writing – review & editing, Data curation. **Alessandro Pasuto:** Writing – review & editing, Data curation. **Mauro Soldati:** Writing – review & editing, Data curation, Conceptualization.

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.

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Data availability

Data will be made available on request.

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