NOVEL AIRBORNE LIDAR-DERIVED DIGITAL TERRAIN MODELS
IN THE EMILIA-ROMAGNA REGION (ITALY): POTENTIAL
FOR ARCHAEOLOGICAL PROSPECTION OF MEDIEVAL CASTLES
IN THE VENA DEL GESSO ROMAGNOLA AND VALMARECCHIA

1. Introduction

Over the last two decades, archaeological prospection has been significantly transformed by studies employing LiDAR (Light Detection and Ranging), a tool particularly useful in densely forested regions where conventional remote sensing techniques face challenges and also field activities may be hindered by dense vegetation or the ruggedness of the terrain (Schindling, Gibbes 2014; Chase *et al*. 2017; Štular, Lozić 2022). Not surprisingly, exceptional results have been achieved when using airborne laser scanning to see through the canopy of tropical forest environments, like in Mesoamerica and SE Asia, to respectively map ruins of pre-Hispanic cultures (Chase *et al*. 2011; Canuto *et al*. 2018; Rostain *et al*. 2024) or an urban landscape around Angkor Wat temples in NW Cambodia (Evans *et al*. 2013). However, significant results have also been achieved in more accessible contexts, especially when detailed micro-relief mapping could highlight archaeological remains, whether or not beneath forest canopies, like for tumuli around Stonehenge (Bewley *et al*. 2005) and in NW Iberia (Berganzo-Besga *et al*. 2021), Dacian Fortresses in modern Romania (Pețan, Hegyi 2023), Roman military camps in Northern Spain (Menéndez Blanco *et al*. 2020), Viking ring fortresses in Denmark (Stott *et al*. 2019), and World War I military heritage in Flanders, Belgium (Gheyle *et al*. 2018) and Northern Italy (Magnini *et al*. 2022).

Thus, while LiDAR has become an integral part of the archaeological prospection toolkit, archaeologists are still dependent on data availability, usually collected through regional or state campaigns for purposes more related to landscape and environmental mapping than site prospection. The substantial differences in data availability and spatial resolution directly impact the potential application of this tool, which is not equally widespread everywhere, being typically more utilised in areas with regular high-resolution coverage (less than one square metre) than places where exists ample potential for under canopy mapping, like for example in Africa, where such coverage is lacking (Davis, Douglass 2022). Where both good spatial coverage and high-resolution LiDAR data exist, large-scale landscape mapping tests have also been conducted via automated recognition methods (e.g., Stott *et al*. 2019; Berganzo-Besga *et al*. 2021; Verschoof-van der Vaart, Lambers 2022; Arnoldussen *et al*. 2023). More recently, LiDAR sensors have started to be

mounted on drones (or UAV), ensuring even higher resolution (e.g., Casana *et al.* 2021; Masini *et al.* 2022), but a scale issue persists since instrumental and legal limitations allow for the study of single individual sites and, at most, their surrounding area. Therefore, if we want to conduct large-scale studies on entire territorial contexts, we are often limited by the existence or absence of datasets collected by public entities, with all their limitations in terms of spatial coverage, resolution, and any pre-processing of remote sensing data.

These limitations also apply to the Italian territory, where LiDAR data were collected at a national level between 2008 and 2015 through three campaigns, often managed at the regional level. However, since these data were primarily collected to support investigations of hydrogeological risk, with a focus on riverbeds and the coastline, they do not systematically cover the entire national territory (Sánchez 2018). Nevertheless, several studies have successfully used national LiDAR data to investigate many protohistoric hillforts (Bernardini *et al.* 2013; Vinci, Bernardini 2017; Sánchez 2018; Fontana 2022), unique Roman sites in Italian Karst (Bernardini *et al.* 2013, 2015; Bernardini 2023), and even medieval castles in the Alps (Forlin 2013; Brogiolo 2014; Gentilini *et al.* 2019). National LiDAR has also been tested on medieval castles in the Po Valley (Burigana, Magnini 2017), but its effectiveness is severely limited by the absence of forests and the widespread levelling for agricultural exploitation that has altered the micro-relief of these types of sites, which are still identifiable through other remote sensing methods (Abballe 2023).

Nevertheless, where targeted data acquisition campaigns have been carried out, like in Southern Italy, LiDAR has proven highly effective in facilitating the mapping of abandoned medieval castles and fortified settlements (Lasaponara, Masini 2009; Masini *et al.* 2010, 2018; Masini, Lasaponara 2020; Bortolotto *et al.* 2021; Abate *et al.* 2023). However, as mentioned earlier, these targeted acquisitions are limited to a handful of sites, while tailored territorial surveys for archaeological purposes are infrequent: an exception is the one promoted by the Lok-Med project to investigate the Colline Metallifere mining landscapes in Tuscany (Poggi *et al.* 2023). However, given the high cost of these targeted campaigns, a potential opportunity lies in new acquisition campaigns that could be conducted at both regional and national levels, with higher spatial resolution and coverage than a decade ago. A clear example in this regard is the new LiDAR acquisition ongoing in Switzerland since 2017 and up to 2024 (Caspari 2023), but the Emilia-Romagna region (RER) has also undertaken a new mapping campaign since 2022, starting with six test areas: 1) a portion of the Enza river basin; 2) the Apennine ridge in the provinces of Bologna and Modena; 3) the Vena del Gesso Romagnola parc, which recently entered the UNESCO World Heritage list; 4) Imola and Faenza urban centres; 5) nine municipalities of the Valmarecchia valley that became part of the Emilia-Romagna
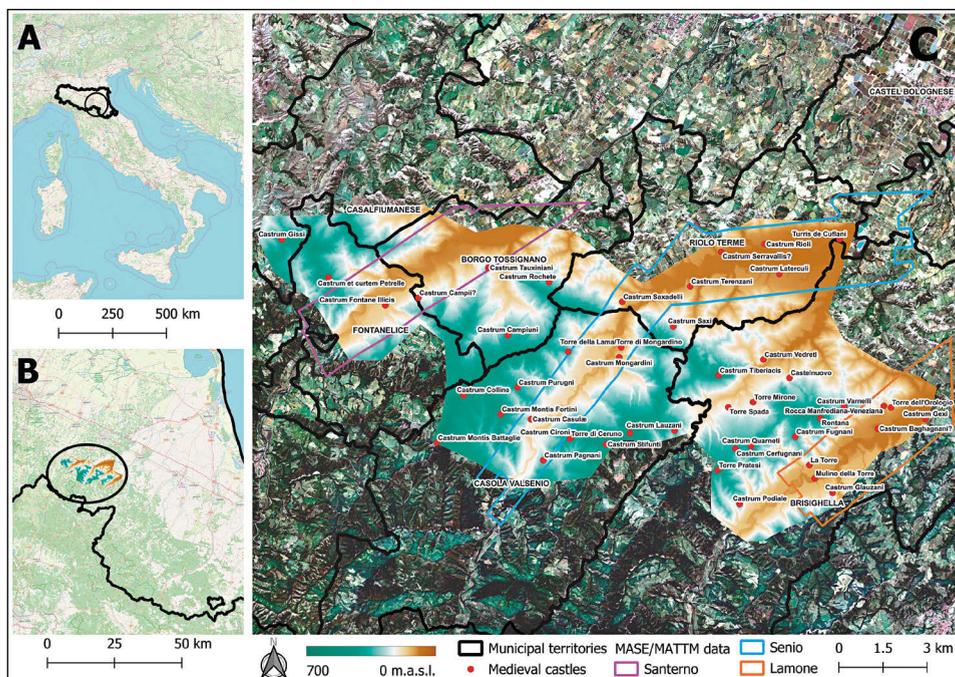
Fig. 1 – Location of the Vena del Gesso Romagnola area (C) within the Emilia-Romagna region (B) and the Italian Peninsula (A). The displayed Digital Terrain Model is the novel DTM RER 2022. Coloured polygons indicate areas covered by the MASE/MATTM 1 m LiDAR DTM, while red points indicate medieval castles documented in written sources; a question mark denotes uncertainty in the precise location of a specific site (background maps: A–B © OpenStreetMap contributors; C © ESA WorldCover 2021 / Contains modified Copernicus Sentinel data, 2021, processed by ESA WorldCover consortium).

Region in 2009 and 2021; 6) the coast and part of the hinterland of Ferrara. These data, whose specifics will be discussed in more detail later, provide higher resolution DTMs at 0.5m and comprehensively cover each of the six study areas, thus including sites not covered by the previous national survey.

To assess the potential of these new data for archaeological prospection, the Vena del Gesso Romagnola (Fig. 1) and Valmarecchia (Fig. 2) were selected as case studies for the presence of numerous abandoned castles located on the tops of hills, typically covered by woods today. The first study area discussed is the Vena del Gesso Romagnola, which is located in the Romagna hinterland between Imola and Faenza (Fig. 1), straddling the provinces of Bologna (BO) and Ravenna (RA). The second study area analysed is Valmarecchia, a geologically diverse valley in the central Apennines of Italy, spanning the regions of Emilia-Romagna, Marche, and Tuscany (Fig. 2).

Fig. 2 – Location of the Valmarecchia area (C) within the Emilia-Romagna region (B) and the Italian Peninsula (A). The displayed Digital Terrain Model is the novel DTM RER 2022. The coloured polygon indicates the area covered by the MASE/MATTM 1 m LiDAR DTM, while red points indicate medieval castles documented in written sources; a question mark denotes uncertainty in the precise location of a specific site (background maps: A–B © OpenStreetMap contributors; C © ESA WorldCover 2021 / Contains modified Copernicus Sentinel data, 2021 processed by ESA WorldCover consortium).

A long history of research on fortified sites has enabled scholars to hypo-thesise their locations through the study of written sources and modern place names. Notably, during the publication of the first gazetteers between the 1950s and 1970s, these sites were systematically surveyed in search of ruins (Mancini, Vichi 1959; Montevecchi 1970, 1971, 1972). In the past two decades, the study of castles has gained renewed momentum in both areas, with updates to existing catalogues, new surveys, targeted excavations, and detailed analyses of fortified architecture. These new researches were primarily promoted by the University of Bologna in the Vena del Gesso Romagnola (Augenti *et al.* 2012; Ravaioli 2015; Fiorini 2019) and the University of Urbino in Valmarecchia (Sassi 2005; Ermeti, Sacco 2006, 2007; Sacco 2017, 2020, 2023). The abundance of previous studies on the castles in both areas, the limited knowledge of their planimetry, and the uncertainty about

the preservation of any ruins identified almost 50 years ago represent a unique opportunity to assess the potential of these novel LiDAR data, with the general aim to enhance our understanding of the 'incastellamento' and 'decastellamento' phenomena in two extensive regions of the Northern Apennines.

Motivated by the aim of evaluating these recently released and freely available elevation data, this paper examines seven selected fortified sites to highlight the advantages of the full coverage and significant resolution improvement provided by the novel RER data compared to the existing national LiDAR DTMs for mapping both standing remains and surface indicators of buried structures of medieval castles in two extensive regions (Figs. 1 and 2). Additionally, new evidence emerging from the systematic analysis of all known fortifications will be presented, emphasising the potential of these data to greatly enhance our understanding of hilltop castles.

2. Materials and methods

The novel airborne LiDAR-derived elevation DTMs tested for this research were created by RER from flights carried out between February and May 2022 and in January 2023, when reduced foliation was occurring. The survey was performed at a relative flight altitude of 3000 m, with a scanning angle of ± 36°, with at least four returns recorded per pulse with an elevation accuracy of ± 8 cm and a planimetric accuracy of ± 30 cm. The generated DTMs have a nominal resolution of 0.5m. Only the DTMs concerning the area of the Parco Vena del Gesso Romagnola (Fig. 1) and Valmarecchia (Fig. 2) were downloaded via WCS (DTM RER 2022[1]). At the moment, neither point clouds nor other derived products (e.g., first return DSM) are available, while 20-cm resolution orthophotos produced at the same time as the LiDAR survey can be accessed via Web Map Service (WMS), in both optical (RGB) and near-infrared visualisation (NIR) to verify possible issues in the DTM (Ortofoto RER 2022[2]).

This novel elevation dataset has been compared with the previously available 1m resolution DTMs derived from airborne LiDAR flights carried out in 2008 by the Italian Ministry of the Ecological Transition (MASE). The survey recorded between two and four returns per pulse with an elevation accuracy of ± 8 cm and a planimetric accuracy of ± 30 cm. MASE/MATTM LiDAR DTMs were accessed for both areas through WMS from

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[1] Id: r_emiro:2023-08-01T110615, website: https://geoportale.regione.emilia-romagna.it/approfondimenti/prodotti-lidar-e-ortofoto, WCS: https://servizigis.regione.emilia-romagna.it/wcs/dtmrer2022?request=getcapabilities&service=wcs.

[2] https://servizigis.regione.emilia-romagna.it/wms/rer2022_rgb?request=GetCapabilities%26service=WMS; https://servizigis.regione.emilia-romagna.it/wms/rer2022_nir?request=GetCapabilities%26service=WMS.

Study area	Total area in km² covered by MASE/ MATTM LiDAR	Medieval fortifications covered by MASE/ MATTM LiDAR	Total area in km² covered by RER LiDAR	Medieval fortifications covered by RER LiDAR
Vena del Gesso Romagnola	20.48 (Santerno) 37.16 (Senio) 15.79 (Lamone) Total 73.43	20	145.79	47
Valmarecchia	223.35	22	372.88	69

Tab. 1 – Total area in square kilometres covered by MASE/MATTM and RER LiDAR, along with the number of castles identified in each dataset for the Vena del Gesso Romagnola and Valmarecchia areas.

the Geoportale Nazionale for the Emilia-Romagna and Marche regions[3]. The 1m DTM tiles for the Vena del Gesso were obtained from MATTM via a procedure recently discontinued (explained in detail by Sánchez 2018), while tiles for Valmarecchia were directly downloaded from the newly released 'Download Banca Dati PST' created by MASE. After both downloads, tiles were merged into three files for the Vena del Gesso study area, covering the Santerno, Senio, and Lamone riverbeds (Fig. 1), and a single raster file for Valmarecchia, covering the Marecchia and Mazzocco riverbeds (Fig. 2).

Enhancement of the models before comparison was carried out using the Relief Visualization Toolbox (RVT), usable as a standalone software or QGIS plugin (Zakšek *et al.* 2011; Kokalj, Somrak 2019). A first comparison of all DTMs was conducted using Sky-View Factor outputs (Zakšek *et al.* 2011), while LiDAR data evaluation and comparison were carried out on image blends of multiple visualisation techniques. These blended images were computed using the Visualization for Archaeological Topography (VAT) method with standard settings for steep terrain by combining hillshade from multiple directions, slope, positive openness, and sky-view factor (Kokalj, Somrak 2019).

A first analysis of the LiDAR data was then conducted, aiming to identify hilltop sites and/or potential structural remains based on the VAT outputs. Subsequently, a dataset was created with all the medieval fortified sites (Tab. 1), mainly castles but also isolated towers, in the two study areas, by digitising the main available site catalogues. In the second phase, potential sites were compared with known fortifications, while further verification was conducted in a desktop-based approach by systematically examining

[3] MASE LiDAR DTM (formely MATTM LiDAR DTM) = National LiDAR data available on Banca Dati PST at https://sim.mase.gov.it/portalediaccesso/mappe/#/viewer/new; WMS Copertura Nazionale: http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/Vettoriali/QU_Lidar.map&service=wms&request=getCapabilities&version=1.3.0; WMS Regione Emilia-Romagna: http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/servizi-LiDAR/LIDAR_EMILIA_ROMAGNA.map; WMS Regione Marche: http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/servizi-LiDAR/LIDAR_MARCHE.map&service=wms&request=getCapabilities&version=1.3.0.

Source	Year	Type	Sensor
Volo Istituto Geografico Militare Italiano (IGMI)	1931-1937	Aerial	B/W
Foto Royal Air Force (RAF)	1943-1944	Aerial	B/W
Istituto Geografico Militare Italiano (IGMI), Volo GAI (Gruppo Aeronautico Italiano)	1954-1955	Aerial	B/W
Regione Emilia-Romagna (RER)	1976-1978	Aerial	RGB
Ministero dell'Ambiente e della Tutela del Territorio e del Mare (MATTM)	1988-1989 1994-1996 2000 2006-2007 2012	Aerial	B/W (first 2 series) RGB (last 3 series)
Google Earth Pro	2002-2024	Satellite	RGB
Agenzia per le Erogazioni in Agricoltura (AGEA)	2008, 2011, 2019, 2020	Aerial	RGB NIR
Esri World Imagery	2011-2023	Satellite	RGB
Consorzio telerilevamento agricoltura (TeA)	2014, 2017	Aerial	RGB
Compagnia Generale Ripreseaeree (CGR)	2018	Aerial	RGB NIR
Yandex	2021	Satellite	RGB
Regione Emilia-Romagna (RER)	2022-2023	Aerial	RGB NIR
Microsoft Bing	2024	Satellite	RGB

Tab. 2 – List of aerial and satellite images used in this research, including temporal coverage, type of capturing support, and sensor employed.

all aerial and satellite images available online (Tab. 2), looking for standing/buried features or disruptive activities such as construction, excavation, or levelling. The twin peaks of Montemaggio, located in the municipality of San Leo (RN), were selected to compare and validate potential anthropogenic features identified in the LiDAR data, with two field verifications conducted on 22 June and 21 December 2024.

3. Medieval castles seen through LiDAR

To evaluate the effectiveness of the new RER data in identifying evidence of medieval fortifications and comparing it with the earlier MASE/MATTM DTMs, seven fortified sites were selected for discussion in this paper, with precedence given to locations where standing structures are present. In only two cases a comparison with MASE/MATTM data is not possible due to lack of coverage, but these sites were included because of their particular significance in the evaluation of the RER DTMs data. Additionally, to better highlight the general contribution of LiDAR data in the comparisons with other remote sensing tools, a satellite image (where the site is best visible, e.g., with minimal canopy) has always been included. In two cases, an archaeological site plan is presented because particularly relevant for the discussion of the results.
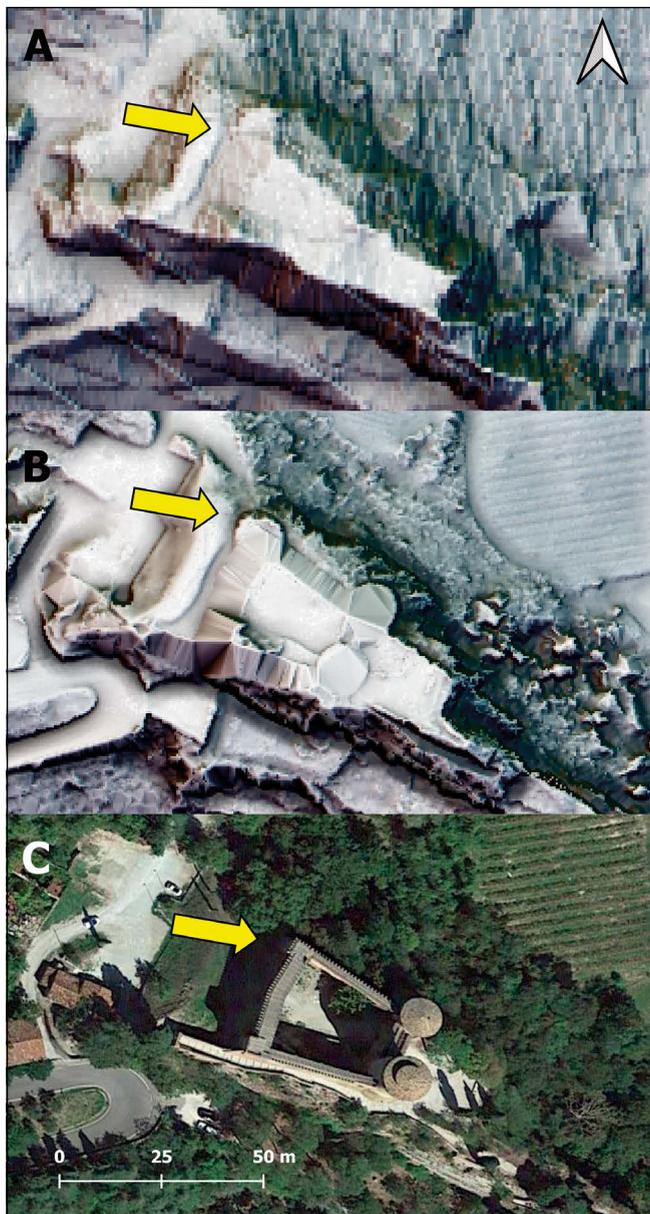
Fig. 3 – Site of Rocca Manfrediana-Veneziana di Brisighella (RA), with yellow arrows pointing to the potentially newly discovered round tower: A) VAT visualisation of MASE/MATTM 1m LiDAR DTM; B) VAT visualisation of 0.5m DTM RER 2022; C) Google Earth satellite basemap (13 September 2022).

3.1 *Vena del Gesso Romagnola*

The first area discussed is the Vena del Gesso Romagnola (Fig. 1), where the new RER data cover a total of 47 known fortified sites across 145 km², compared to the 20 sites covered by the MASE/MATTM dataset across 73 km² (Tab. 1). The first selected site for comparison between the previous MASE/MATTM data and the newly collected RER DTMs is the Rocca Manfrediana-Veneziana (Fig. 3), overlooking Brisighella (RA) town centre. This fortification was built by the Republic of Venice between 1503 and 1509 CE on a pre-existing one, with a castle documented in the written sources at least since 1290 CE (AUGENTI *et al.* 2012, 83-85, id. 12). While the MASE/MATTM data elaboration completely filtered out the fortification (Fig. 3A), leaving only the different altimetric levels faintly visible, the new RER DTM reveals the general layout of the Rocca (Fig. 3B). In particular, the outlines of the two circular bastions on the eastern side are clearly recognisable, namely the Manfrediana Tower and the larger keep to the S, known as the Venetian Tower. However, these new data seem to highlight the possible foundation of an additional circular tower on the NW side, encircling the standing quadrangular tower visible in the satellite image (Fig. 3C).

The second site analysed is the *Castrum Tauxiniani* (Fig. 4) in Borgo Tossignano (BO), one of the oldest known in the region, documented as early as the 9th century and used for military purposes until the 16th century CE (MONTEVECCHI 1970, 358-361, id. 310). Over this long period, the site undoubtedly underwent numerous renovations, including the construction of a massive circular tower, the footprint of which is only faintly visible in the MASE/MATTM DTM (Fig. 4A). This large structure, however, is clearly recognisable in the new RER data (Fig. 4B), along with many other structures currently present in a state of ruin (Fig. 4C).

The third and final site in the Vena del Gesso Romagnola is *Castrum Tiberiacis* (Fig. 5) in Brisighella (RA), one of the oldest known, documented as early as the mid-8th century and in use until the 16th century CE (AUGENTI *et al.* 2012, 109-111, id. 49). The site underwent targeted excavations between 2010 and 2012 by the local Soprintendenza, which remapped the wall surrounding the central tower (Fig. 5C), for which plans already exist from the early 19th century CE (GUARNIERI 2019). The RER DTM with VAT visualisation undoubtedly reveals the layout of the fortification wall (Fig. 5A), which would otherwise be unreadable amidst the dense tree cover (Fig. 5B). It also highlights the elevated morphology of the site where the central tower is located, the depression linked to the water cistern to the NW, and the remains of the modern ruined building known as Casetto Coppari, located in the western corner of the walled area (Fig. 5A).

Fig. 4 – Site of *Castrum Tauxiniani* in Borgo Tossignano (BO), with yellow arrows pointing to main surviving round bastion: A) VAT visualisation of MASE/MATTM 1m LiDAR DTM; B) VAT visualisation of 0.5m DTM RER 2022; C) Google Earth satellite basemap (15 April 2023).
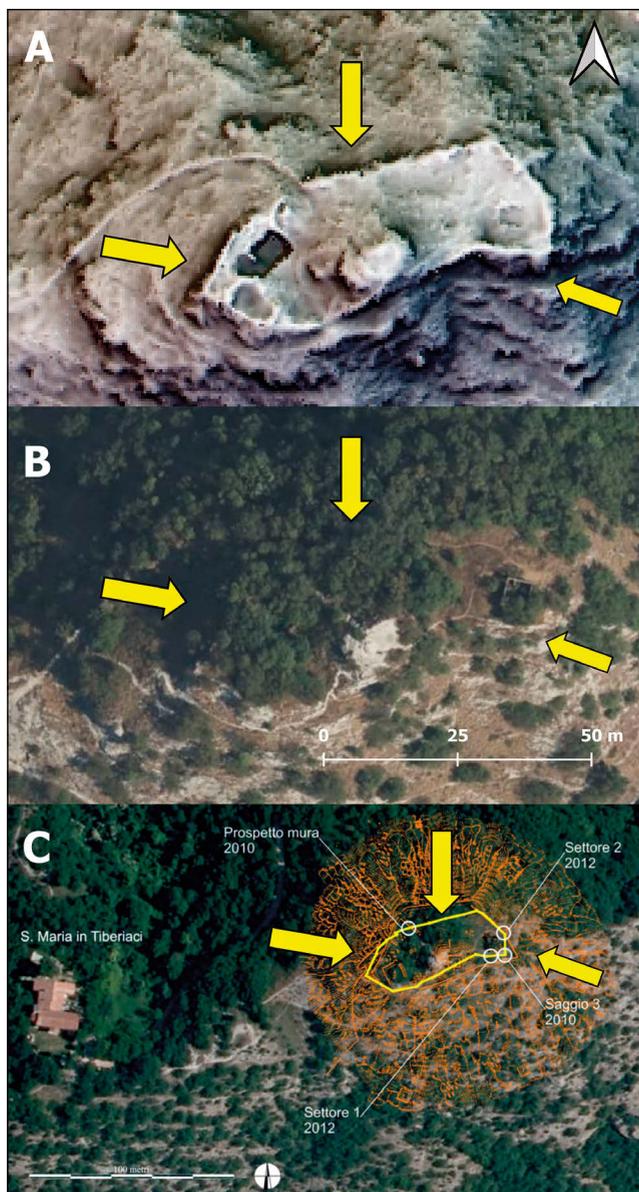
Fig. 5 – Site of *Castrum Tiberiacis* on Monte Mauro in Brisighella (RA), with yellow arrows pointing to the fortification wall: A) VAT visualisation of 0.5m DTM RER 2022; B) Bing Virtual Earth basemap; C) plan of the castle of Monte Mauro with archaeological trenches conducted in 2010 and 2012 by R. Gabusi (after GUARNIERI 2019).

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3.2 *Valmarecchia*

The second area discussed is Valmarecchia (Fig. 2), where the new RER data cover a total of 69 fortified sites across 372 km², representing a significant increase compared to the 22 sites covered by the MASE/MATTM dataset across 223 km² (Tab. 1). The first site in Valmarecchia selected for comparison between the previous MASE/MATTM data and the newly collected RER DTMs is the *Castrum Montis Copioli* (Fig. 6) in Montecopiolo (RN). Historically, the site is particularly significant as the original seat of the Counts of Montefeltro, later Dukes of Urbino, one of the most important families of Renaissance Italy. Two decades of archaeological research at the site have demonstrated that the castle was established in the 10th century CE, predating its first attestation in written sources from 1155 CE. Excavations conducted between 2002 and 2018 have documented the construction of six successive defensive walls over the centuries, along with numerous other structures, including a church, a noble residence, various residential and
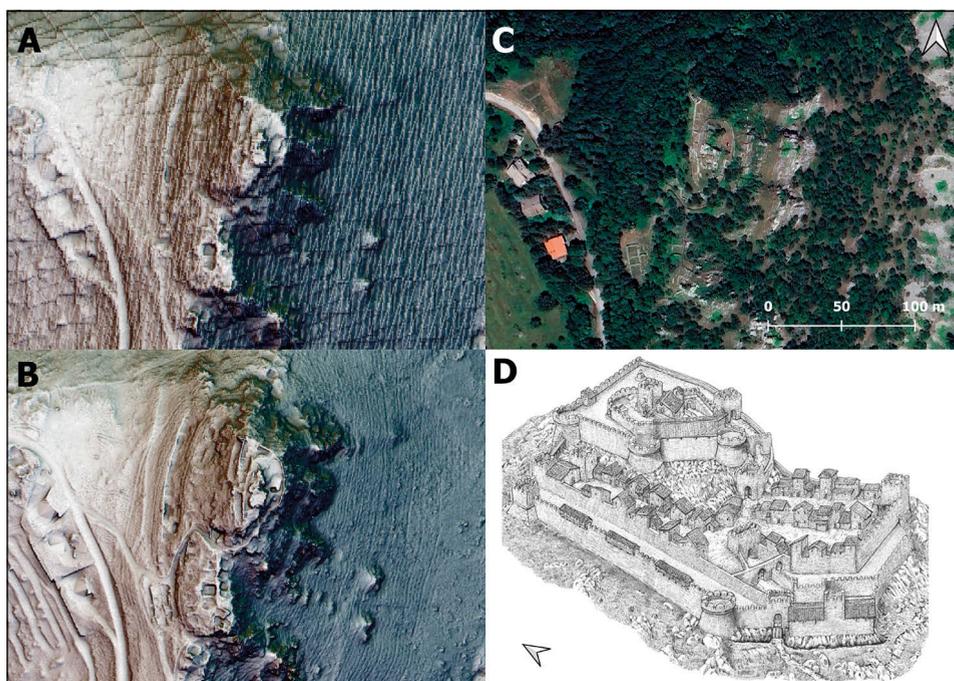

Fig. 6 – Site of *Castrum Montis Copioli* in Montecopiolo (RN): A) VAT visualisation of MASE/MATTM 1m LiDAR DTM; B) VAT visualisation of 0.5m DTM RER 2022; C) Google Earth satellite basemap (17 July 2023); D) graphic reconstruction of the castle of Monte Copiolo in the 15th century CE by E. Zonzini (after Sacco 2023).
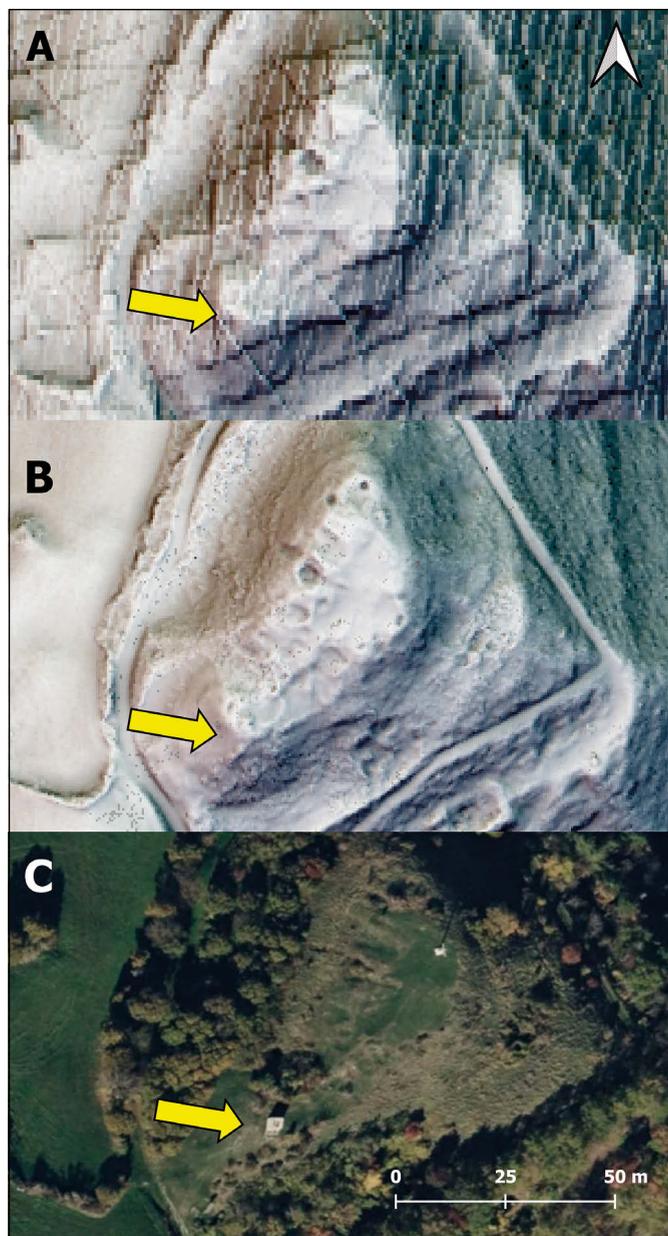
Fig. 7 – Site of *Castrum Montis Bovaginis* in Montecopiolo (RN), with yellow arrows pointing to standing tower: A) VAT visualisation of MASE/MATTM 1m LiDAR DTM; B) VAT visualisation of 0.5m DTM RER 2022; C) Bing Virtual Earth basemap.

functional buildings, as well as evidence of local quarrying for construction purposes (ERMETI, SACCO 2006; SACCO 2020, 2023).

The numerous structures revealed by the excavations and progressively restored to ensure permanent public accessibility are only partially visible in the MASE/MATTM DTM (Fig. 6A). This limitation can only be partly attributed to the fact that some of these structures had not yet been uncovered at the time these LiDAR data were captured more than a decade ago. However, this does not fully account for the absence of other visible structures that were already standing or had been excavated at the time. By contrast, the new RER data (Fig. 6B) not only reveal the layout of multiple buildings but also highlight their structural elements and portions of the defensive walls unearthed during excavations (Fig. 6D), even in areas obscured by dense woodland vegetation as can be seen in recent satellite images (Fig. 6C).

The second site analysed is *Castrum Montis Bovaginis* (Fig. 7) in Montecopiolo (RN), which was certainly occupied between the 14th and 15th centuries CE (MONTEVECCHI 1972, 190, id. 964). Today, only a partially preserved tower remains on the hill, not far from a modern cross. A survey conducted in the early 1970s identified 'the foundational remains of the fortress, two subterranean rooms' (translated from MONTEVECCHI 1972, 190, id. 964) in addition to the tower. However, only one of these subterranean rooms appears to be recognisable in the MASE/MATTM DTM (Fig. 7A). In contrast, the VAT visualisation of the new RER LiDAR data reveals several additional sub-quadrangular features (Fig. 7B), potentially indicating buried structures that require ground-truthing. Notably, no clear traces of the fortress or possible fortification walls are discernible either on the hilltop or its surroundings (Fig. 7C).

The third site analysed is *Castrum Ancise* (Fig. 8) in Casteldelci (RN), mentioned only once in historical records, in 1329 CE. However, the reliability of this attestation has been questioned recently, as the original document has not survived (ERMETI, SACCO 2007, 95). A survey conducted in the early 1970s identified 'traces of wall bases and foundations' (MONTEVECCHI 1972, 117, id. 730). While these findings were insufficient to confirm the presence of a castle, the possibility of a settlement on the hill has not been ruled out (ERMETI, SACCO 2007, 95-98). In the absence of MASE/MATTM coverage, the only DTM available for analysis is the RER dataset, which reveals a semi-circular feature that could potentially represent an earthwork or an accumulation of debris beneath the few remaining trees on the present-day, extremely flat hilltop (Fig. 8A). Conversely, no corresponding relief evidence is discernible for the quadrangular feature observed in the satellite data (Fig. 8B). This feature may not represent an ancient structure but rather a recent construction resulting from the significant earthmoving activities that reshaped the summit around 2010-2011 (Fig. 8C).
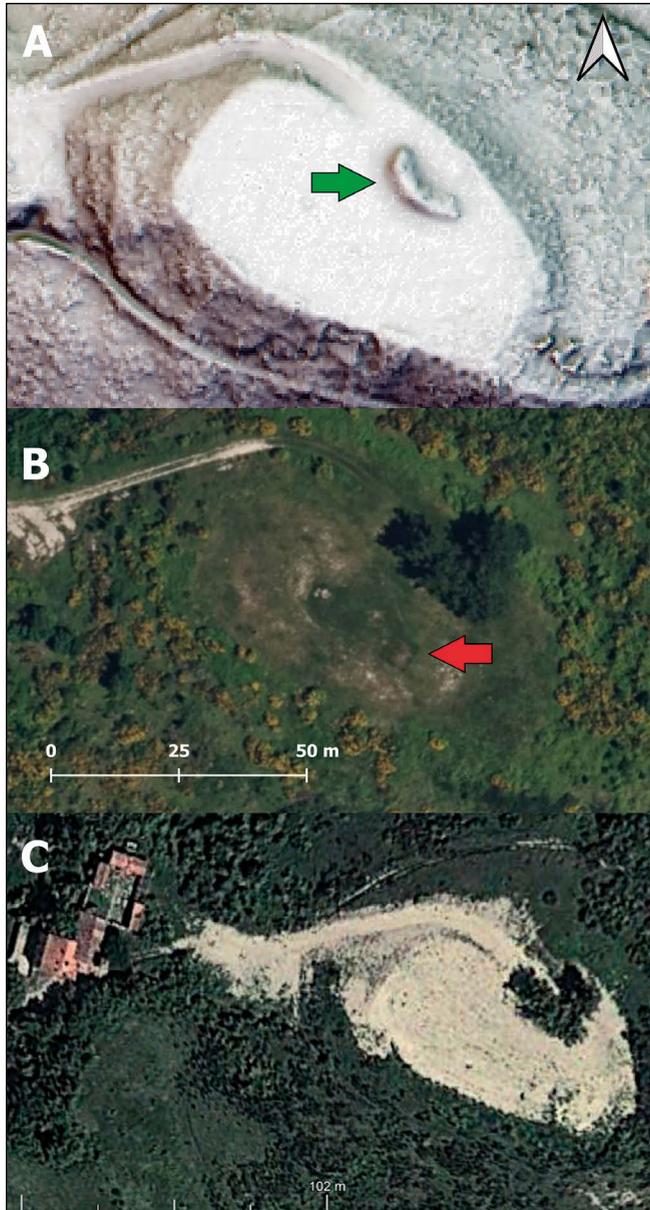
Fig. 8 – Site of *Castrum Ancise* in Casteldelci (RN): A) VAT visualisation of 0.5m DTM RER 2022, with the green arrow pointing to potential earthwork/debris accumulation; B) Microsoft Bing basemap, with the red arrow pointing to quadrangular evidence; C) Google Earth satellite basemap (22 May 2011).

Fig. 9 – Site of *Castrum Montis Madii* in San Leo (RN), with red arrows pointing to Castello di Montemaggio site while green arrows pointing to eastern twin peak: A) Google Earth satellite basemap (6 October 2017); B) VAT visualisation of MASE/MATTM 1m LiDAR DTM; C) VAT visualisation of 0.5m DTM RER 2022; D) main evidence identified in LiDAR data, later verified in the field: lowercase letters refer to corresponding photos of structure shown in Fig. 10.

Fig. 10 – Field verification of evidence identified in LiDAR data on the site of *Castrum Montis Madii* in San Leo (letters a-d) and the eastern twin peak (letters e-h).

The fourth site in Valmarecchia is *Castrum Montis Madii* (Fig. 9) in San Leo (RN) documented as early as the second half of the 10th century and continuing through to the mid-15th century (MONTEVECCHI 1972, 210, id. 483). A survey conducted in the early 1970s identified numerous remains of the castle and the associated settlement, including 'sections of foundations, three subterranean rooms, a still-functioning cistern, and wall remains incorporated into the buildings of the church and an abandoned ruined farmhouse' (translated from MONTEVECCHI 1972, 210, id. 483). Remains of the castle have also been recently reported as being in a state of abandonment in a study that conducted geomorphological mapping across several sites in Valmarecchia, aiming to update its geoheritage inventory and promote geotourism (GUERRA, LAZZARI 2021).

Of the structures mentioned at the Castello di Montemaggio site, which are currently covered by dense vegetation (Fig. 9A), very little is visible in the national LiDAR data, with perhaps only some rectangular buildings on the western side being recognisable (Fig. 9B). However, the higher-resolution elevation data captured by RER reveal a significant number of features (Fig. 9C), whose interpretation (Fig. 9D) was revised following field verifications conducted on two occasions in 2024 (Fig. 10). The structures revealed by the LiDAR data that can be easily linked to those described in Montevecchi's site report include the cistern at the centre of the site (ca. 7.2×6.6 m), likely realised into a tower (Fig. 9D-a), owing to its strategic location and the significance of the masonry (Fig. 10a). The new LiDAR data also allow for a clearer delineation of much of the defensive wall that still surrounds three sides of the site (Fig. 9D-b), which is preserved in some areas to a height of several metres (Fig. 10b). Still, accurately delineating the layout of the modern cemetery, which is detached from the still-standing church and was abandoned only after World War II, would have been challenging without the field verifications.

The LiDAR data reveal a linear feature (Fig. 9D-c) at its centre, resembling the evidence associated with the NE perimeter wall. Consequently, it would have been difficult to discern that this feature is actually a much more modest earthwork (Fig. 10c), standing only a few dozen centimetres high and perfectly aligned with the cemetery entrance on one side and the annexed chapel on the other. Finally, there are numerous rectilinear features interpretable as walls that define potential sub-rectangular structures, likely to be associated with the fortified settlement, in greater numbers than those reported by Montevecchi: a selected example is shown in Figs. 9D-d and 10d.

Moving east, beyond the more recent church built after the Second World War, the most significant evidence from this initial evaluation of the novel RER LiDAR data can be found on the twin eastern summit, which is

believed to have inspired the name *Montis Gemini* (= twins) reported in the historical sources (Montevecchi 1972, 210, id. 483). So far, no mention of archaeological structures has ever been reported on this second peak, but several features of interest can be clearly recognised besides a partially standing structure, only recently abandoned. The more significant is a long wall approximately 2 m thick (Fig. 9D-g) that encloses about a quarter of the summit, specifically the southeastern corner (Fig. 10g), defining a rectangular walled area that extends more in length than width. At least a room, although rather small, is attached to this wall circuit (Figs. 9D-e and 10e), while a second room, currently subterranean, does not seem to be directly connected to the wall itself (Figs. 9D-f and 10g).

Furthermore, this rectangular enclosure could potentially have been linked to a second wall, partially adjacent to the access road along the western side of the summit. If these two walls were indeed connected, together they would have enclosed the whole summit. On the highest point, located in the northern part, there seem to be no clear structural remains, except for a long pile of stones, oriented N-S, which could be concealing masonry remains. Stone accumulations are indeed present at several points within the site, particularly within the area enclosed by the rectangular circuit wall. At present, it is difficult to propose an interpretation for them, because their considerable size (Figs. 9D-e and 10h) would exclude the possibility of structural collapse, but a stone-clearing activity for agricultural use would have likely resulted in an accumulation of stones on the structures rather than in the centre of the field. In the absence of a clear interpretation, further field verification activities will likely be necessary, which could help assess the fortified nature of this apparently overlooked site together with its chronology.

4. Final remarks and future perspectives

The seven selected sites discussed in this paper offer a clear evaluation of the capabilities of each of the two available LiDAR-derived DTMs, demonstrating the transformative potential of the novel RER data compared to the earlier MASE/MATTM ones. The latter often failed to reveal standing fortification structures, likely due to filling and smoothing techniques used for the DTM creation not being optimised for preserving archaeological elements (Fontana 2022), and only partially illuminated surface indicators of buried structures. In contrast, the higher-resolution RER LiDAR-derived DTMs, equal to 0.5m, highlighted the overall layouts of those sites encircled by clear fortification walls, as well as numerous standing remains or partially subterranean structures. These features are often present in greater numbers or appear where none was previously identified during earlier,

non-systematic surveys conducted for the first gazetteers of fortified sites in Romagna, which were compiled more than 50 years ago. These achievements have been made possible not only thanks to the higher spatial resolution but also because these novel DTMs provided by RER offer full coverage of the two study areas for the first time. The complete coverage is indeed crucial for the study of hilltop sites, which were often overlooked by previous national surveys due to a focus on valley bottoms that are subject to higher hydrogeological risks.

More broadly, this initial evaluation, aimed at assessing the potential of two novel RER datasets, clearly demonstrates their remarkable ability to reveal numerous hidden structures, often concealed beneath dense tree cover that hinders other remote sensing techniques, as exemplified by the seven selected medieval fortifications. While this evaluation highlights the significant potential of the RER DTMs, it also suggests promising directions for future development, which could follow two primary approaches. The first approach involves expanding the study areas to neighbouring territories, as in 2023 and 2024, full coverage was achieved for the Ravenna and Rimini provinces, while only parts of the nearby Forlì-Cesena and Bologna provinces have been surveyed to date (RER 2023/24). Given the promising results of this initial evaluation, it is hoped that RER will fund additional survey campaigns to eventually achieve complete regional coverage at similar higher resolution. The second approach involves requesting raw point cloud data, which, as previously mentioned, have not yet been made available, for reprocessing with optimised filtering algorithms tailored to archaeological evidence detection. Although it is not possible to say this with certainty at present, such reprocessing could greatly enhance the utility of these data for archaeological prospection, much like the improvements made with the national MASE/MATTM datasets. Combining improved filtering and larger spatial coverage with targeted field verifications could lead to a more accurate and comprehensive mapping of medieval castles, a site type for which knowledge has seen limited advancement in recent decades. Most studies have focused on a few excavated sites or the study of standing structures, while little has been done to provide a more detailed planimetric mapping, despite significant technological advancements in archaeological research in recent years. The new DTMs provided by the RER dataset could thus represent a crucial step forward, opening new opportunities for the investigation of hilltop sites, particularly medieval fortifications, across much of the Emilia-Romagna region.

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REFERENCES

ABATE N., RONCHI D., VITALE V., MASINI N., ANGELINI A., GIURI F., MINERVINO AMODIO A., GENNARO A.M., FERDANI D. 2023, *Integrated close range remote sensing techniques for detecting, documenting, and interpreting lost medieval settlements under canopy: The case of Altanum (RC, Italy)*, «Land», 12, 2, 310 (https://doi.org/10.3390/land12020310).

ABBALLE M. 2023, *Legacy imagery, continuous satellite monitoring and targeted drone surveys for the study of deserted medieval fortified settlements in the hinterland of Ravenna, Italy*, «Archeologia e Calcolatori», 34.2, 225-246 (https://doi.org/10.19282/ac.34.2.2023.12).

ARNOLDUSSEN S., VERSCHOOF-VAN DER VAART W.B., KAPTIJN E., BOURGEOIS Q.P.J. 2023, *Field systems and later prehistoric land use: New insights into land use detectability and palaeodemography in the Netherlands through LiDAR, automatic detection and traditional field data*, «Archaeological Prospection», 30, 3, 283-300 (https://doi.org/10.1002/arp.1891).

AUGENTI A., FICARA M., RAVAIOLI E. 2012, *Atlante dei beni archeologici della provincia di Ravenna, 1. Il paesaggio monumentale nel Medioevo*, Bologna, Ante Quem.

BERGANZO-BESGA I., ORENGO H.A., LUMBRERAS F., CARRERO-PAZOS M., FONTE J., VILAS-ESTÉVEZ B. 2021, *Hybrid MSRM-based deep learning and multitemporal sentinel 2-based machine learning algorithm detects near 10k archaeological tumuli in North-Western Iberia*, «Remote Sensing», 13, 20, 4181 (https://doi.org/10.3390/rs13204181).

BERNARDINI F. 2023, *Rediscovering the lost Roman landscape in the Southern Trieste karst (North-Eastern Italy): Road network, land divisions, rural buildings and new hints on the Avesica road station*, «Remote Sensing», 15, 6, 1506 (https://doi.org/10.3390/rs15061506).

BERNARDINI F., SGAMBATI A., MONTAGNARI KOKELJ M., ZACCARIA C., MICHELI R., FRAGIACOMO A., TIUSSI C., DREOSSI D., TUNIZ C., DE MIN A. 2013, *Airborne LiDAR application to karstic areas: The example of Trieste province (north-eastern Italy) from prehistoric sites to Roman forts*, «Journal of Archaeological Science», 40, 4, 2152-2160 (https://doi.org/10.1016/j.jas.2012.12.029).

BERNARDINI F., VINCI G., HORVAT J., DE MIN A., FORTE E., FURLANI S., LENAZ D., PIPAN M., ZHAO W., SGAMBATI A., POTLECA M., MICHELI R., FRAGIACOMO A., TUNIZ C. 2015, *Early Roman military fortifications and the origin of Trieste, Italy*, «Proceedings of the National Academy of Sciences», 112.13, E1520-E1529 (https://doi.org/10.1073/pnas.1419175112).

BEWLEY R.H., CRUTCHLEY S.P., SHELL C.A. 2005, *New light on an ancient landscape: LiDAR survey in the Stonehenge World Heritage Site*, «Antiquity», 79.305, 636-647 (https://doi.org/10.1017/S0003598X00114577).

BORTOLOTTO S., CATTANEO N., GARZULINO A., MASSA S., MASSEROLI S.M., ROMBOLÀ R.M. 2021, *Castelseprio archaeological site: LiDAR and GIS multiscale dataset supporting on-field investigation and enhancing landscape understanding*, «PCA. Post classical archaeologies», 11, 163-189.

Brogiolo G.P. 2014, *Costruire castelli nell'arco alpino tra V e VI secolo*, «Archeologia Medievale. Cultura materiale. Insediamenti. Territorio», 40, 143-156.

Burigana L., Magnini L. 2017, *Image processing and analysis of radar and lidar data: New discoveries in Verona southern lowland (Italy)*, «STAR: Science & Technology of Archaeological Research», 3, 2, 490-509 (https://doi.org/10.1080/20548923.2018.1426273).

Canuto M.A., Estrada-Belli F., Garrison T.G., Houston S.D., Acuña M.J., Kováč M., Marken D., Nondédéo P., Auld-Thomas L., Castanet C., Chatelain D., Chiriboga C.R., Drápela T., Lieskovský T., Tokovinine A., Velasquez A., Fernández-Díaz J.C., Shrestha R. 2018, *Ancient lowland Maya complexity as revealed by airborne laser scanning of northern Guatemala*, «Science», 361.6409, eaau0137 (https://doi.org/10.1126/science.aau0137).

Casana J., Laugier E.J., Hill A.C., Reese K.M., Ferwerda C., McCoy M.D., Ladefoged T. 2021, *Exploring archaeological landscapes using drone-acquired lidar: Case studies from Hawai'i, Colorado, and New Hampshire, USA*, «Journal of Archaeological Science: Reports», 39, 103133 (https://doi.org/10.1016/j.jasrep.2021.103133).

Caspari G. 2023, *The potential of new LiDAR datasets for archaeology in Switzerland*, «Remote Sensing», 15, 6, 1569 (https://doi.org/10.3390/rs15061569).

Chase A.F., Chase D.Z., Weishampel J.F., Drake J.B., Shrestha R.L., Slatton K.C., Awe J.J., Carter W.E. 2011, *Airborne LiDAR, archaeology, and the ancient Maya landscape at Caracol, Belize*, «Journal of Archaeological Science», 38, 2, 387-398 (https://doi.org/10.1016/j.jas.2010.09.018).

Chase A.S.Z., Chase D.Z., Chase A.F. 2017, *LiDAR for archaeological research and the study of historical landscapes*, in N. Masini, F. Soldovieri (eds.), *Sensing the Past: From Artifact to Historical Site*, Cham, Springer, 89-100 (https://doi.org/10.1007/978-3-319-50518-3_4).

Davis D.S., Douglass K. 2022, *Aerial and spaceborne remote sensing in African archaeology: A review of current research and potential future avenues*, in C. Gokee, C. Klehm (eds.), *Spatial Approaches in African Archaeology*, Singapore, Springer, 9-24 (https://doi.org/10.1007/978-981-19-7380-2_2).

Ermeti A.L., Sacco D. (eds.) 2006, *Il Castello di Monte Copiolo nel Montefeltro. Ricerche e scavi 2002-2005*, Firenze, All'Insegna del Giglio.

Ermeti A.L., Sacco D. (eds.) 2007, *Archeologia del paesaggio nel territorio di Casteldelci. Montefeltro. Atlante dei siti medievali della vallata del Senatello. Indagini 2005-2007*, Firenze, All'Insegna del Giglio.

Evans D.H., Fletcher R.J., Pottier C., Chevance J.-B., Soutif D., Tan B.S., Im S., Ea D., Tin T., Kim S., Cromarty C., De Greef S., Hanus K., Bâty P., Kuszinger R., Shimoda I., Boornazian G. 2013, *Uncovering archaeological landscapes at Angkor using LiDAR*, «Proceedings of the National Academy of Sciences», 110.31, 12595-12600 (https://doi.org/10.1073/pnas.1306539110).

Fiorini A. 2019, *I castelli della Romagna: indagini di archeologia dell'architettura*, Firenze, All'Insegna del Giglio.

Fontana G. 2022, *Italy's hidden hillforts: A large-scale Lidar-based mapping of Samnium*, «Journal of Field Archaeology», 47, 4, 245-261 (https://doi.org/10.1080/00934690.2022.2031465).

Forlin P. 2013, *Castelli e paesaggi del Trentino orientale: alcuni casi studio dalla Valsugana e dalla Val di Cembra*, in E. Possenti, G. Gentilini, M. Cunaccia, W. Landi (eds.), *Castra, castelli e domus murate. Corpus dei siti fortificati trentini tra tardo antico e basso medioevo*, Mantova, SAP, 299-309.

Gentilini G., Possenti E., Zamboni I. 2019, *The fortified landscape in Trentino, Italy. The experience of the APSAT project. Environment and landscapes of the high-ground sites in Trentino*, in M. Fumo, G. Ausiello (eds.), *Sustainable Mediterranean Construction. Land Culture, Research and Technology*, Napoli, Luciano Editore, 95-102.

Gheyle W., Stichelbaut B., Saey T., Note N., Van den Berghe H., Van Eetvelde V., Van Meirvenne M., Bourgeois J. 2018, *Scratching the surface of war. Airborne laser scans of the Great War conflict landscape in Flanders (Belgium)*, «Applied Geography», 90, 55-68 (https://doi.org/10.1016/j.apgeog.2017.11.011).

Guarnieri C. 2019, *Sondaggi archeologici nel castello di Monte Mauro: primi dati per una ricerca*, in M. Costa, P. Lucci, S. Piastra (eds.), *I gessi di Monte Mauro. Studio multidisciplinare di un'area carsica nella Vena del Gesso romagnola*, Bologna, Società Speleologica Italiana, 623-630.

Guerra V., Lazzari M. 2021, *Geomorphological mapping as a tool for geoheritage inventory and geotourism promotion: A case study from the middle valley of the Marecchia River (Northern Italy)*, «Géomorphologie: relief, processus, environnement», 27, 2, 127-145 (https://doi.org/10.4000/geomorphologie.15193).

Kokalj Ž., Somrak M. 2019, *Why not a single image? Combining visualizations to facilitate fieldwork and on-screen mapping*, «Remote Sensing», 11, 7, 747 (https://doi.org/10.3390/rs11070747).

Lasaponara R., Masini N. 2009, *Full-waveform Airborne Laser Scanning for the detection of medieval archaeological microtopographic relief*, «Journal of Cultural Heritage», 10, e78-e82 (https://doi.org/10.1016/j.culher.2009.10.004).

Magnini L., Rovera G., De Guio A., Azzalin G. 2022, *A digital and archaeological perspective of the World War One Veneto-Trentino front line trench systems in Northern Italy*, in A. Bondesan, J. Ehlen (eds.), *Military Geoscience: A Multifaceted Approach to the Study of Warfare*, Cham, Springer, 83-106 (https://doi.org/10.1007/978-3-030-79260-2_6).

Mancini W., Vichi F. 1959, *Castelli, rocche e torri di Romagna*, Bologna, Edizioni ALFA.

Masini N., Abate N., Gizzi F.T., Vitale V., Minervino Amodio A., Sileo M., Biscione M., Lasaponara R., Bentivenga M., Cavalcante F. 2022, *UAV LiDAR based approach for the detection and interpretation of archaeological micro topography under Canopy. The rediscovery of Perticara (Basilicata, Italy)*, «Remote Sensing», 14, 23, 6074 (https://doi.org/10.3390/rs14236074).

Masini N., Coluzzi R., Lasaponara R. 2010, *Investigating lost medieval villages using Satellite and Airborne Laser Scanning: The case of Yrsum in Basilicata (Southern Italy)*, «Archeologia e Calcolatori», 21, 127-144 (https://www.archcalc.cnr.it/journal/articles/568#close).

Masini N., Gizzi F.T., Biscione M., Fundone V., Sedile M., Sileo M., Pecci A., Lacovara B., Lasaponara R. 2018, *Medieval archaeology under the Canopy with LiDAR. The (re)discovery of a medieval fortified settlement in Southern Italy*, «Remote Sensing», 10,10, 1598 (https://doi.org/10.3390/rs10101598).

Masini N., Lasaponara R. 2020, *On the reuse of multiscale LiDAR data to investigate the resilience in the late medieval time: The case study of Basilicata in South of Italy*, «Journal of Archaeological Method and Theory» (https://doi.org/10.1007/s10816-020-09495-2).

Menéndez Blanco A., García Sánchez J., Costa-García J.M., Fonte J., González-Álvarez D., Vicente García V. 2020, *Following the Roman army between the Southern foothills of the Cantabrian mountains and the Northern plains of Castile and León (North of Spain): Archaeological applications of remote sensing and geospatial tools*, «Geosciences», 10, 12, 485 (https://doi.org/10.3390/geosciences10120485).

Montevecchi F. 1970, *Repertorio dei castelli, rocche e torri*, in P. Gazzola, G.F. Fontana, D. Berardi (eds.), *Rocche e castelli di Romagna. I, Imola, Faenza e il Ravennate*, Bologna, Alfa, 139-400.

Montevecchi F. 1971, *Repertorio dei castelli, rocche e torri*, in D. Berardi, P. Gazzola, G.F. Fontana (eds.), *Rocche e castelli di Romagna. II, Cesena e il Forlivese*, Bologna, Alfa, 107-432.

Montevecchi F. 1972, *Repertorio dei castelli, rocche e torri*, in D. Berardi, P. Gazzola, G.F. Fontana (eds.), *Rocche e castelli di Romagna, III. Rimini e il Montefeltro Romagnolo*, Bologna, Alfa, 114-438.

Peţan A., Hegyi A. 2023, *Freely available LiDAR-derived digital terrain model (DTM) uncovers the heartland of the Dacian Kingdom*, «Digital Applications in Archaeology and Cultural Heritage», 31, e00292 (https://doi.org/10.1016/j.daach.2023.e00292).

Poggi G., Dallai L., Volpi V. 2023, *Mining under the canopy: Unveiling the archaeo-mining record in the Colline Metallifere with LiDAR analysis and multidisciplinary studies*, «Quaternary International» (https://doi.org/10.1016/j.quaint.2023.08.006).

Ravaioli E. 2015, *L'insediamento fortificato in Romagna tra fonti scritte e dati archeologici (VIII-XVI sec.): le province di Forlì-Cesena e Ravenna*, Bologna, Bononia University Press.

Rostain S., Dorison A., de Saulieu G., Prümers H., Le Pennec J.-L., Mejía Mejía F., Freire A.M., Pagán-Jiménez J.R., Descola P. 2024, *Two thousand years of garden urbanism in the Upper Amazon*, «Science», 383.6679, 183-189 (https://doi.org/10.1126/science.adi6317).

Sacco D. 2017, *Il paesaggio degli arcivescovi. Processi di trasformazione del territorio tra alto e basso Medioevo nelle Marche settentrionali*, Firenze, All'Insegna del Giglio.

Sacco D. 2020, *Il Castello di Monte Copiolo. La casa dei duchi di Urbino*, Bologna, CLUEB.

Sacco D. 2023, *La nascita della regione storica del Montefeltro (IX secolo) e l'incastellamento della rupe di Monte Copiolo (X secolo) alla luce di venti anni di ricerche*, in D. Sacco (ed.), *Dinamiche dell'incastellamento in Adriatico. Secoli X-XIII*, Sesto Fiorentino (FI), All'Insegna del Giglio, 79-110.

Sánchez J.G. 2018, *Archaeological LiDAR in Italy: Enhancing research with publicly accessible data*, «Antiquity», 92.364, e4 (https://doi.org/10.15184/aqy.2018.147).

Sassi M. 2005, *Castelli in Romagna. L'incastellamento tra X e XII secolo nelle province romagnole e nel Montefeltro*, Cesena, Il Ponte vecchio.

Schindling J., Gibbes C. 2014, *LiDAR as a tool for archaeological research: A case study*, «Archaeological and Anthropological Sciences», 6, 4, 411-423 (https://doi.org/10.1007/s12520-014-0178-3).

Stott D., Kristiansen S.M., Sindbæk S.M. 2019, *Searching for Viking age fortresses with automatic landscape classification and feature detection*, «Remote Sensing», 11, 16, 1881 (https://doi.org/10.3390/rs11161881).

Štular B., Lozić E. 2022, *Airborne LiDAR data in landscape archaeology. An introduction for non-archaeologists*, «it - Information Technology», 64, 6, 247-260 (https://doi.org/10.1515/itit-2022-0001).

Verschoof-van der Vaart W.B., Lambers K. 2022, *Applying automated object detection in archaeological practice: A case study from the southern Netherlands*, «Archaeological Prospection», 29, 1, 15-31 (https://doi.org/10.1002/arp.1833).

Vinci G., Bernardini F. 2017, *Reconstructing the protohistoric landscape of Trieste Karst (north-eastern Italy) through airborne LiDAR remote sensing*, «Journal of Archaeological Science: Reports», 12, 591-600 (https://doi.org/10.1016/j.jasrep.2017.03.005).

Zakšek K., Oštir K., Kokalj Ž. 2011, *Sky-view factor as a relief visualization technique*, «Remote Sensing», 3, 2, 398-415 (https://doi.org/10.3390/rs3020398).

ABSTRACT

LiDAR technology has significantly advanced archaeological prospection, but its potential has been limited by the availability of data, as these are often collected through regional or state campaigns aimed at landscape and environmental mapping rather than archaeological research. Although LiDAR has been widely applied in Italy, partial coverage has left significant areas unexplored, including Emilia-Romagna (RER). Notably, RER launched a new LiDAR mapping campaign in 2022, starting with six test areas. Two of them, the Vena del Gesso Romagnola and Valmarecchia, were selected to assess the potential of the novel RER LiDAR-derived DTMs, which have 0.5m resolution and comprehensive coverage, compared

to earlier national MASE/MATTM DTMs with lower 1m resolution and incomplete coverage. The analysis of RER DTMs revealed site layouts, standing remains, and partially buried features across seven medieval castles, including many structures previously unknown in national data and not recorded by earlier field surveys. Higher resolution and full coverage of RER DTMs proved to be especially valuable for hilltop sites, so it is hoped that RER will fund additional mapping campaigns to achieve complete regional coverage. Meanwhile, newly acquired datasets from 2023 and 2024 offer valuable opportunities to further advance archaeological research in the region.