Archaeological Prospection

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SPECIAL ISSUE Under-canopy Airborne LiDAR for Archaeological Prospections in the Wooded Mediterranean Environment: Challenges, Best Practices and Future Prospects

RESEARCH ARTICLE

LiDAR Applications in Archaeology: A Systematic Review

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Received: 26 July 2023 | **Revised:** 27 January 2024 | **Accepted:** 13 February 2024

Funding: G.V. was supported by the University of Siena, project 'LiNXS - LIviNg by the Sea' (Grant 'MSCA SoE@UNISI 2021'), and by the European Commission (fundings PNRR Young Researchers - SOE).

Keywords: America | archaeology | Europe | LiDAR | remote sensing | vegetation cover

ABSTRACT

In the last two decades, the analysis of data derived from LiDAR (light detection and ranging) technology has dramatically changed the investigation and documentation of past cultural landscapes, sometimes revealing monumental architectures and settlement systems totally unknown before. Despite the exponential uptick of case studies, an extensive review of LiDAR applications in archaeology is so far missing. Here, we present a systematic survey of works published in international journals in 2001–2022, with the aim of providing an annotated bibliography on the theme and collect quantitative information about each case study. Data collected allowed to analyse the geographic distribution of LiDAR-based studies, the specifics of acquisitions, the topography and vegetation cover of each study area, the characteristics of the material culture detected, major goals and integrated techniques. The survey considers 291 studies, of which 167 located in Europe, 104 in the Americas and only 20 between Asia, Middle East, Oceania and Africa. Our analysis shows that the impact of LiDAR in archaeological studies was greater in some areas of Europe and North America, where scholars could rely on the availability of open data provided by the institutions. This is testified by the higher number of both case studies and large-scale projects investigating these regions. It also emerges that LiDAR potential largely depends on the characteristics of the material culture, the vegetation cover and data resolution. These factors underlie the outstanding results achieved through LiDAR in tropical rainforests compared to those obtained in temperate areas, such as the Mediterranean, where the outcropping archaeological evidence, albeit vast and widespread, is generally less preserved and obscured by the dense vegetation of the Mediterranean maquis. We conclude that the increasing availability of LiDAR data over vast areas could lead to enormous advances in the investigation, monitoring and protection of the cultural heritage.

1 | Introduction

In the last two decades, the analysis of topographic surfaces derived from LiDAR (light detection and ranging) technology has dramatically changed the investigation of the cultural landscapes and their documentation. Firstly used for meteorological aims (Goyer and Watson 1963), the pioneering applications in archaeology date back to the early 2000s, with few case studies from Germany and Scotland (Holden 2001; Motkin 2001; Sittler 2004). Among these, work carried in Baden-Württemberg revealed the high potential of combining the analysis of large sets of LiDAR data acquired by the local authorities in 2000–2005 with ground truthing (Bofinger and Hesse 2011; Bofinger, Kurz, and Schmidt 2006).

Since its introduction, LiDAR has proven to be highly effective in densely forested environments, allowing the detection of archaeological features that are outcropping at surface but are difficult to observe due to their limited elevation or not detectable on the field because of the dense vegetation cover. In these contexts, which constitute a significant portion of the Earth's surface yet remaining largely unexplored archaeologically (e.g., tropical rainforests), the application of LiDAR has yielded some of the most spectacular results leading to the discovery of monumental features (Figure 1). These include the standing ruins of large templar complexes and urban settlements spread across Mesoamerica and South-East Asia (e.g., Canuto et al. 2018; Chase et al. 2011; Chase et al. 2012; Evans 2016; Evans et al. 2013).

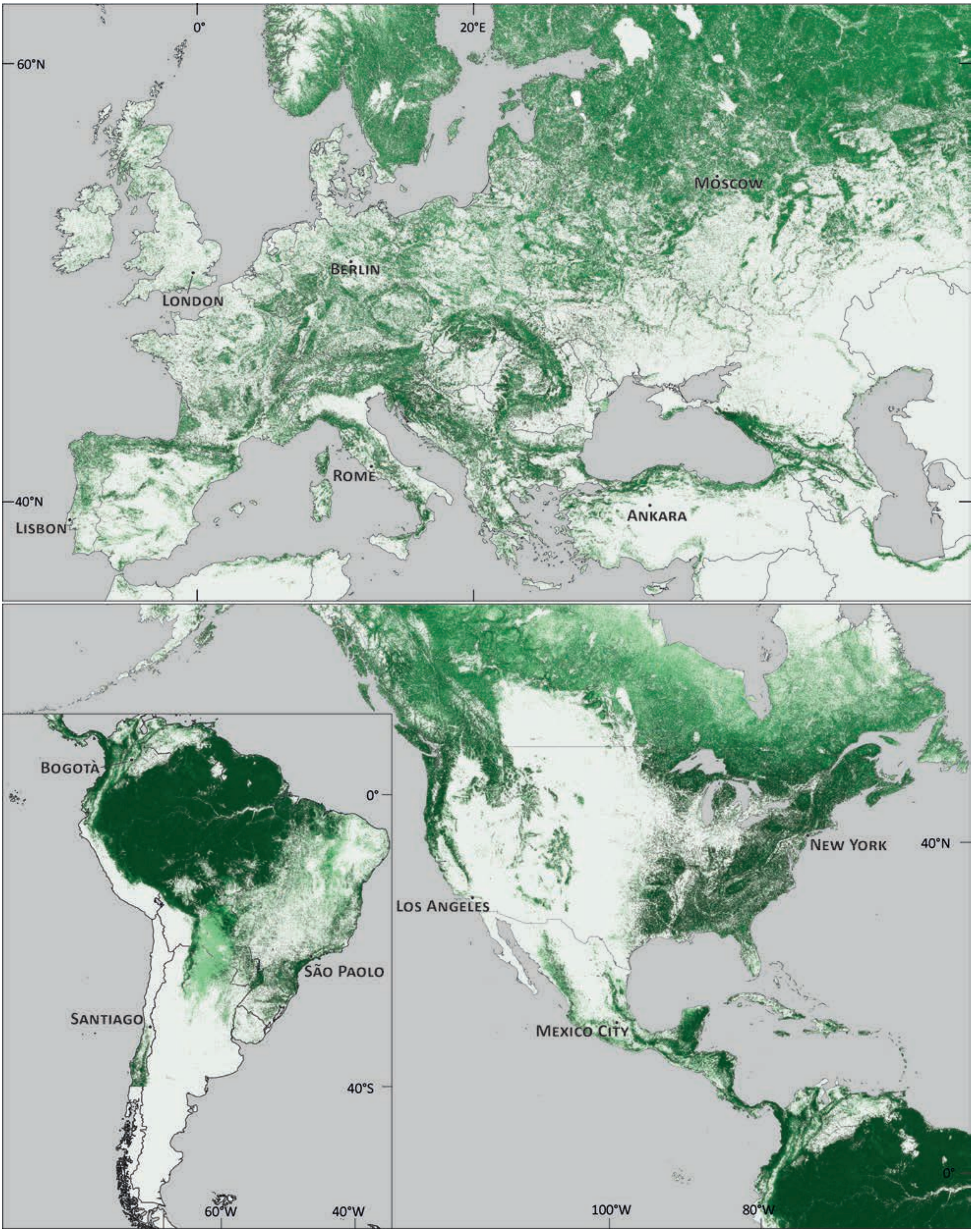

FIGURE 1 | Forest extent in the European and American continents obtained from Landsat time-series imagery (elaboration of data from Hansen et al. 2013).

After the multiplication of LiDAR-based projects in both Europe and America, the relatively short history of LiDAR in archaeology is marked, about midway, by the volume *Interpreting Archaeological Topography: 3D Data, Visualisation and Observation* edited by Cowley and Opitz (2013), which summarizes the advancements in landscape archaeology through the use of LiDAR and other technologies. In the following years, due to the growing availability of datasets acquired for environmental monitoring scopes by public agencies or ad hoc surveys commissioned by archaeologists, the number of archaeological projects using LiDAR has dramatically increased.

A few recent review papers and chapters outlined major results obtained, technological advancements and ethical issues arisen (Campana 2018; Chase, Chase, and Chase 2017, 2020; Cohen, Klassen, and Evans 2020; Johnson and Ouimet 2018; Risbøl et al. 2020; Schindling and Gibbes 2014). Also, an extensive and updated bibliography by year has been published online by Damien Evans (https://angkorlidar.org/bibliography/). Notwithstanding this, over 20 years after its debut, an extensive review of published works on the application of LiDAR in archaeology is so far missing. In which regions and countries have this technology yielded the most significant results for the study of the past and why? How did peculiarity of LiDAR technology, questions and objectives and, overall, archaeological approaches to the study of past landscapes change over time since its first applications? Moreover, why is LiDAR so poorly applied in the Mediterranean region which represents one of the richest areas of archaeology and research projects?

This contribution addresses these questions by presenting the results of a survey of published works which applied LiDAR in the archaeological field between 2001 and 2022. The aims of the survey are the following: (i) providing an annotated bibliography on the theme; (ii) providing quantitative information about the main characteristics of each case study, including the specifics of LiDAR acquisitions, the topography and vegetation cover, the characteristics of the material culture detected, major goals and integrated techniques; and (iii) tracing a state-of-the-art of this theme and suggesting possible future directions of landscape archaeology, based on the collected information.

2 | Material and Methods

This review is based on the systematic examination of papers published in major international journals and chapters including books relevant to this issue (Tables S1 and S2). Significant references were collected by querying selected journals' databases through the expressions ‘LiDAR AND archaeology’ and ‘airborne laser scanning AND archaeology’ occurring in titles, keywords or abstracts. Afterwards, all citations were collected and managed through Zotero (https://www.zotero.org/). The same queries were also explored in two of the main web platforms for literature investigation: Scopus (www.scopus.com) and Web of Science (www.webofscience.com). Information collected from each case study was stored into a geo-database, which included (a) ID data entering authors/year; DOI; approximate location in latitude/longitude coordinates; project name; (b) the characteristics of the associated material culture; (c) vegetation cover and topography; (d) specifics of the LiDAR acquisition; (e) targeted chronological period; (f) aims and objectives; and (g) methods and techniques adopted along with LiDAR.

In the ID section, the project name groups together multiple case studies referring to a single area and a research, which often use LiDAR data obtained from a single acquisition. This field was useful to calculate the overall extension in square kilometre of each acquisition without duplicating data.

The characteristics of the features detected through LiDAR were recorded according to a simplified version of the classification proposed by Štular, Eichert, and Lozić (2021, Figure 5). As for each case study, it was reported whether most of the detected features were (i) ‘embedded’ in the landscape, that is, completely covered by soil and detectable as ridges or depression of limited height and (ii) mostly ‘standing objects’ only covered by the vegetation. In addition, the minimum scale unit of the detected features was recorded (e.g., case studies targeting burial mounds of a few metres in diameter or large temples with sides of hundreds of metres) and a synthetic description of the main features detected.

The vegetation cover in each case study was described in these different typologies: (i) mostly temperate forest (mostly coniferous or mostly deciduous); (ii) mostly mixed vegetation consisting of open land interspersed with woodlands; (iii) mostly open land (grassland, cropland or other fields with no or low vegetation); and (iv) mostly Mediterranean maquis, that is, a peculiar type of temperate forest mostly featured by evergreen shrubs and bushes and mixed oak forest (Blondel 2008; Grove and Rackham 2001).

In each case study, we assessed the overall topography of the entire surveyed area by creating multiple topographic profiles using the Google Earth. These profiles were mapped with respect to the two main bearing axes and also in accordance with the orientation of the detected structures. They were generated based on the digital elevation model obtained from data collected during the Shuttle Radar Topography Mission (SRTM) in 2001. The resolution of the SRTM is 1 arcsecond, which corresponds to 30 m in most of the areas between 60° north and 56° south (https://srtm.csi.cgiar.org/). We roughly attribute the type of terrain according to slope gradient classes. The resulting terrain classes are as follows: (i) 0%–10% slope as plain; (ii) 10%–25% as hill; and (iii) >25% as mountain.

Regarding the specifics of the acquisitions used by single case studies, selected information included the following: (i) the sensor used in the acquisition; (ii) the density of points of each acquisition (pts/m^2); (iii) the ground point density (where specified by authors); (iv) the final pixel resolution (expressed in square metre) of the digital terrain model (DTM); (v) the overall area of acquisition in square kilometre through LiDAR; (vi) the LiDAR data availability; and (vii) the season of the acquisition along the year.

Unfortunately, many contributions, especially the earlier ones, lack detailed information about the specifics of acquisition. For example, many publications do not specify the density of points per square kilometre or whether the ‘density of points’ derives from the whole amount of points emitted by the aircraft or result from the only points reaching the bare ground. Thus, where the final DTM resolution was not specified, but the point density was declared, we used the following criteria: 0.5 pts/m^2 yields a 5-m resolution DTM; 1 pt/m^2 yields a 2-m resolution DTM; 4–5 pts/m^2 for 1 m; and more than 10 pts/m^2 yields 0.5 m.

We are aware that this is a conservative estimation compared to those presented in a few other studies (e.g., Mohtashami et al. 2022; Štular, Eichert, and Lozić 2021). Nonetheless, this is motivated by the fact that in many case studies, the value of the ground point density is not reported, and therefore, it is impossible to clearly evaluate how many points actually reached the ground surface. Moreover, this estimation is also supported by the experience on LiDAR data processing gathered by the authors (Bernardini et al., 2015, 2018, 2020, 2021; Bernardini and Vinci 2020; Fontana et al., 2017, 2018, 2023; Mazzacca et al. 2022; Ninfo et al. 2011; Vinci and Bernardini 2017; Vinci, Bernardini, and Furlani 2019).

The availability of LiDAR datasets was another important recorded parameter. In this, we reported whether datasets used for archaeological research in each case study were 'restricted', that is, archaeology-oriented data commissioned within the project or 'open', that is, acquired by the institutions for different scopes. The same is true for the season when LiDAR acquisition was carried out. Recent studies have demonstrated that the potential identification of archaeological features through LiDAR is greatly affected by variability in the tree growth season (leaf-on and leaf-off conditions; cf. Doneus, Banaszek, and Verhoeven 2022). Consequently, acquisition date is an important parameter to be considered. Unfortunately, as for studies using open data, this information is generally not available as LiDAR acquisitions have been acquired by the institutions at different times during the year or even along several years. In contrast, as for case studies using archaeology-oriented LiDAR acquisitions, the season of flight is often reported by the authors, but not always. After careful consideration, we opted to present this information in a simplified manner, categorizing it as either (i) cold or (ii) warm seasons. This significant simplification was primarily necessitated by the limited availability of such data in each publication. Regrettably, this classification omits regions on Earth where the climate lacks distinct seasons. Furthermore, it does not account for precipitation data, a significant factor influencing the leaf-on/leaf-off condition. Consequently, in European case studies, we exclusively employed seasonality as a variable for multiple correspondence analysis (MCA) due to these constraints.

We also considered whether case studies addressed a specific target period or not. Information was classified as follows, according to the archaeological periodization of southern Europe: (i) before 200 BCE, roughly corresponding to prehistoric period; (ii) 200 BCE–500 CE, corresponding to classical period; (iv) after 500 CE to the present, corresponding to medieval-contemporary time period; and (v) diachronic, where no specific chronological span was addressed by each publication.

Among the aim and objectives pursued by single case studies, we summarized them as follows: (i) detection of archaeological features; (ii) monitoring of archaeological and cultural heritage known sites with the aim of recording destruction, looting, erosion or other damages; (iii) landforms characterization in order to map and document anthropogenic and natural landforms or paleo-environmental features; (iv) methodological (e.g., the development of techniques for data processing and analysis); and (v) geological or concerning the study of the natural environment.

Finally, we summarized methods and techniques integrated with LiDAR including (i) visual elaborations (e.g., slope, sky-view factor, local dominance, simple relief model, aspect, openness and others); (ii) the use of machine learning for the automatic and semi-automatic classification of features; (iii) field work through surface survey; (iv) field work through ground-based integrated techniques (e.g., geophysical methods such as ground-penetrating radar [GPR] and magnetometry, coring, soundings and laboratory analyses on artefacts); and (v) integration with other passive airborne remote sensing methods (satellite and aerial imagery) and historical cartography.

In order to better visualize the spatial distribution of data collected and test some correlations among the variables, some basic spatial and/or statistical analyses on the dataset were performed. These included kernel density, regression and MCA.

Kernel density estimation was employed to obtain a density map of the distribution of case studies in both Europe and America. Bandwidth of the kernel (represented by the letter sigma σ) can be explained as the search radius to calculate the density, and it is expressed with the same units of the point dataset (Baddeley, Rubak, and Turner 2015). In order to choose the best value of sigma, we decided to use the Kernel Density Tool in ArcGIS Pro software (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview), which calculate the bandwidth through the Silverman's Rule of Thumb (Silverman 1986). This method was chosen among others because of its resistance to spatial outliers as well as capability of handling sparse datasets.

Regression is a basic statistical method used to model and analyse the relationship between a dependent variable and one or more independent variables by fitting an equation to the observed data. We performed this analysis to explore the relationship between the mean point density in all case studies (dependent variable) and the year of publications (independent one).

MCA is a multivariate statistical method, which can be considered akin to principal component analysis (PCA), but for categorical variables (Abdi and Williams 2010). PCA is often employed with the aim of reducing the correlation between quantitative variables, by performing a rotation of the original space and detecting new uncorrelated variables, called principal components, explaining most variations in the datasets. Often two/three PCs are analysed to detect groups in the data, as well as how original variables contribute in explaining variations. MCA workflow is equivalent, with the difference that categorical variables are coded in binary columns or ranges of integer values (Abdi 2007). In this review, we employed MCA to test the correlation between season, vegetation and LiDAR availability in European case studies. We used FactoMineR package in RStudio software (https://cran.r-project.org/web/packages/FactoMineR/index.html), and we produce a final biplot depicting both individuals and variables along PC1 and PC2 (Figure S1 and Table S3).

The final product is an open geo-database including relevant information by each case study. All data collected are accessible through the open repository Zenodo (https://zenodo.org/records/8174095). Geographic information can also be queried by importing a table with coordinates into a Geographic Information System (GIS) software. The final table collects all the information regarding each case study/publication. Moreover, summing up the information of each publication related to a single project allowed to quantify the overall area of acquisition by projects and countries and the ratio between open and restricted data, as reported in the main text (Tables 1 and 2).

TABLE 1 | Largest scale LiDAR acquisitions by archaeological projects ($n = 30$).

km^2	Reference	Project location	Geographic area	Archaeological object	Size unit (m)	Embed. Y//N	Point density (m)	Final DTM	Availability
71 820	Stoner 2017	Veracruz	North America	Fields, monumental features	100	Y	NA	5	Open
42 036	Stott, Kristiansen, and Sindbæk 2019	Denmark	Europe	Ring fortress	120	Y	4.5	1.6	Open
40 000	Cerrillo-Cuenca and Bueno-Ramírez 2019	Alentejo, Extremadura	Europe	Burial mounds, enclosures	10	Y	0.5	5	Open
37 000	Carter, Blackadar, and Conner 2021	Pennsylvania	North America	Charcoal hearths	10	Y	NA	1	Open
29 733	Howey et al. 2016	Upper Great Lakes	North America	Cache pits	1	Y	1.98	0.31	Open
29 574	Berganzo-Besga et al. 2021	NW Iberia	Europe	Burial mounds	15	Y	NA	1	Open
24 000	Lieskovský et al. 2022	West Slovakia	Europe	Burial mounds, enclosures, ditches, warfare	10	Y/N	25	0.5	Open
15 296	Fontana 2022	Samnium	Europe	Enclosures	200	Y/N	1	1	Open
15 000	Pierik, Stouthamer, and Cohen 2017	Rhine-Meuse delta	Europe	—	—	—	NA	0.5	Open
12 542	Verschoof-van der Vaart et al. 2022	Connecticut	North America	Charcoal hearths	10	Y	2.85	0.6	Open
10 600	Menéndez Blanco et al. 2020	Cantabrian mountains	Europe	Roman camps	200	Y	0.5	1	Open
8160	Golden et al. 2016	Chiapas, Campeche, Yucatan	Mesoamerica and South America	Mounds, households	20	Y/N	6	0.5	Restricted
7870.8	Rodríguez González, Paniego Díaz, and Celestino Pérez 2021	Guadiana basin	Europe	Cemetery, burial mounds, settlements	100	Y	0.5	5	Open
4600	Henry, Shields, and Kidder 2019	Middle Ohio River Valley	North America	Enclosures	100	Y	1.35	1.5	Open
4500	van der Meulen et al. 2020	Lower Rhine Valley	Europe	—	—	—	NA	0.75	Open
4000	Sánchez Díaz, García Sanjuán, and Rivera Jiménez 2022	Sierra Morena	Europe	Settlements	200	Y	1	1	Open
3990	Cody and Anderson 2021	Willamette Valley	North America	Mounds	100	Y	8.14	1	Open
3680	Krasinski et al. 2016	Southcentral Alaska	North America	Cache pits	1	Y	2.8	1	Open
3660	Cerrillo-Cuenca 2016	Extremadura	Europe	Burial mounds	10	Y	0.5	5	Open
3517	Davis et al. 2021	Charleston	North America	Shell rings	75	Y	0.6	1.5	Open
3516	Trier, Cowley, and Waldeland 2019	Arran Island	Europe	Households, cairns, burial mounds, enclosures, kilns	20	?	2.75	0.25	Open

TABLE 1 (Continued)

km^2	Reference	Project location	Geographic area	Archaeological object	Size unit (m)	Embed. Y//N	Point density (m)	Final DTM	Availability
3140	Johnson and Ouimet 2018	Rhode Island	North America	Building foundations	10	Y	2	1	Open
2851	Johnson and Ouimet 2018	Connecticut	North America	Building foundations	10	Y	2	1	Open
2448	Suh et al. 2021	Litchfield County	North America	Charcoal hearths	10	Y	1.25	1	Open
2390	Davis, Sanger, and Lipo 2019; Davis et al. 2020, 2021	Beaufort County	North America	Mounds	10	Y	0.6	1.2	Open
2350	Verschoof-van der Vaart and Lambers 2019	Veluwe/Utrechtse Heuvelrug	Europe	Burial mounds, Celtic fields	10	Y	8	0.5	Open
2289	Pluckhahn and Thompson 2012; Rochelo, Davenport, and Selch 2015	Fort Center	North America	Mounds, ditches, settlement	20	Y	0.46	5	Open
2260	Fonte et al. 2021	Viana do Castelo	Europe	Mining landscape	20	Y	2	1	Open
2144	Canuto et al. 2018	Petén	Mesoamerica and South America	Monumental features	50	N	3.2	1	Restricted
2144	Garrison, Houston, and Firpi 2019	El Zotz	Mesoamerica and South America	Rural landscape	—	—	3.2	1	Restricted

Abbreviation: Embed., embedded features.

TABLE 2 | Total area of LiDAR acquisitions, average DTM resolution and availability of LiDAR datasets by archaeological projects in each country.

Country	No. of projects	Total area (km^2)	DTM (mean)	Open data percentage (0–1)
USA	34	112 506	1.10	0.68
Spain	21	96 424	3.07	0.95
Mexico	25	84 109	0.94	0.12
Denmark	1	42 036	1.60	1
Slovakia	2	24 017	0.75	1
The Netherlands	11	23 188	0.52	1
Italy	29	15 994	0.89	0.36
UK	23	4060	1.17	0.43
Cambodia	5	3337	1.00	0
Guatemala	2	2614	0.75	0
Poland	9	2339	0.63	0.56
Portugal	1	2260	1.00	1
Belize	6	1729	0.83	0
Norway	4	1307	0.49	0.5
Finland	2	1010	0.15	0.5
Honduras	4	859	0.67	0
France	6	717	0.66	0
China	2	650	1.25	0
Sweden	4	572	0.75	0.75
Canada	2	320	1.00	0
Lebanon	1	290	1.00	0
Tonga	1	259	1.00	0
Slovenia	7	242	0.60	0.43
Bolivia	2	210	0.50	0
American Samoa	2	141	1.00	1
Ireland	5	136	0.73	0.8
Austria	6	106	0.51	0
Brazil	3	102	0.75	0
Croatia	6	94	0.40	0
Czech Republic	2	90	1.50	0
Bulgaria	1	41	0.50	0
South Africa	2	27	0.63	0
Turkey	1	21	0.50	0
Germany	2	20	0.50	0
Japan	2	20	0.50	0
Peru	2	20	0.30	0
Romania	2	18		0
Estonia	1	12	5.00	1
Greece	1	10	2.00	0
Israel	1	10	1.00	0
Jordan	1	10		0

3 | Data and Results

Worldwide, the application of LiDAR in archaeology has seen exponential growth in the last two decades. This is well visible by comparing results from major online platforms (Scopus and Web of Science) with our survey (Figure 2). The higher number of matching results in Scopus is motivated by the occurrence of the selected keywords not only in scientific journals but also in conference proceedings, books and review papers.

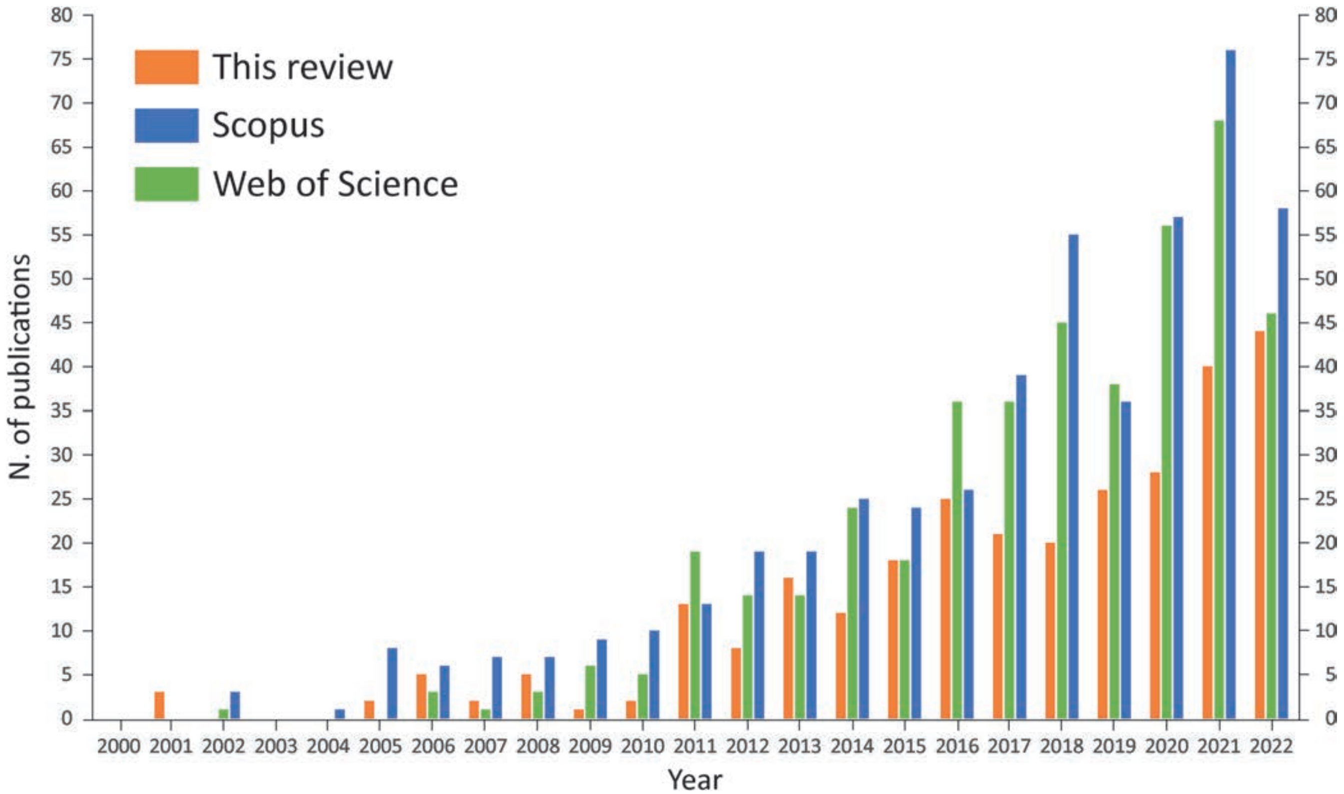

FIGURE 2 | Number of publications regarding the application of LiDAR to archaeological studies in the presented review, Scopus and Web of Science (2000–2022).

It is also important to note that some archaeological work on LiDAR is not published in international journals, and therefore, they are not reported in this survey. However, limiting the search to the only publications on international journals, the overall amount of publications from our survey and Scopus are comparable. On one hand, this supports the reliability of our survey, while, on the other, it tells that most of the publications concerning LiDAR in archaeology were published on high impact international journals, in both multidisciplinary and more specific ones.

Geographically, most of the surveyed case studies are located in Europe (167 case studies) and the American continent, including North, Central and South America (104) whereas only few studies are spread in the other regions of the world, such as Asia (11, of which 7 are in Cambodia), Middle East (4), Oceania (3) and Africa (2; Table 2).

As the number of European and American publications are similar, they will be compared and discussed in detail in the following paragraphs. It is worth noting that for other regions, most studies carried out in Asia are related to the Angkor Wat project in Cambodia (Chevance et al. 2019; Evans 2016; Evans et al. 2013; Evans and Fletcher 2015; Stark et al. 2015). Within this area, investigations carried out from 2011 based on remote sensing and fieldwork have produced an accurate archaeological mapping of more than 2500 km^2. In this vast region, thanks to the good conservation of the archaeological evidence, that are mostly lying at shallow depths under the tropical forest, LiDAR acquisitions (generally at 4–5 pts/m^2) revealed extended agro-urban landscapes consisting of residential areas, agricultural systems, infrastructural networks, ritual spaces and temples mostly dated to the Angkor period (9th to 15th centuries CE; Chase, Chase, and Chase 2017).

The application of LiDAR in other regions has so far been very limited, and a few case studies from the Middle East, Africa and Oceania came out rather recently. Among these, it is worth mentioning four case studies located in Turkey, Israel, Lebanon and Jordan (Grammer et al. 2017; Price, Adams, and Tepper 2023; Rom et al. 2020; Stott, Kristiansen, and Sindbæk 2019), two recent projects from South Africa (Lombard et al. 2021; Sadr 2016) and three from Tonga and American Samoan islands (Freeland et al. 2016; Quintus et al. 2015; Quintus, Day, and Smith 2017).

The magnitude of LiDAR application in archaeology can be measured by calculating the overall extension of datasets analysed by each project. At global scale, only 3 projects analyse datasets larger than 40 000 km^2, 5 projects between 10 000 and 40 000 and 10 projects between 1000 and 10 000 km^2, and the remaining are smaller scale projects ($n = 163$). The three largest scale studies (>40 000 km^2) are spread across Mexico, Denmark and the Iberian Peninsula (Cerrillo-Cuenca and Bueno-Ramírez 2019; Stoner 2017; Stott, Kristiansen, and Sindbæk 2019). They are all very recent studies aiming at the detection and documentation of anthropogenic features, which are generally embedded in the actual landscape and covered by soil (terraces and field divisions, large settlement complexes or ring fortresses). The minimum scale of the recognized features is always larger than 10 m and generally more than 100 m. The detected features derive either from visual inspection, automatic detection through machine learning or DTM segmentation. These two latter techniques allowed to detect features over large areas, as demonstrated by largest-size projects carried out in Denmark and the Iberian Peninsula (Table 1).

Overall, it emerges that large- and medium-scale LiDAR projects target both forested and non-forested environments (croplands and grasslands) and generally use public data gathered by institutions at low resolutions (0.5–5 pts/m^2). Consequently, the pixel resolution of the DTMs generally varies from 1 to 5 m, as clearly documented by considering the 30 largest scale projects (Table 1).

3.1 | Case Studies From Europe

As for Europe, archaeological LiDAR-based publications passed from 3 in 2001 to 33 in 2022, reaching a total number of 167 recorded case studies. The distribution of publications by country gives especially an idea of the archaeological application of LiDAR in Europe. Italy with 33 case studies, the United Kingdom with 28 and Spain with 23 are the European countries in which LiDAR has been more extensively applied (Figure 3a). In these three countries, most case studies analysed limited areas of less than 10 km^2 (18 out of 33 in Italy; 24 out of 28 in the United Kingdom; 13 out of 23 in Spain; Figure 3b). Significantly, in these countries, the coverage of open LiDAR data has been progressively increasing from the last two decades. As for Spain and the United Kingdom, public agencies have recently completed the LiDAR survey of the entire territory, providing rough point clouds (.las format) and DTMs at 1-m resolution resulting from 0.5–4 pts/m^2 (the United Kingdom: https://environment.data.gov.uk/DefraDataDownload/?mapService=EA/SurveyIndexFiles&Mode=spatial; Spain: https://centrodedescargas.cnig.es/CentroDescargas/locale?request_locale=en). In Italy, the coverage is patchy, and data provided by the state are generally at low resolution (less than 1 pt/m^2; see Fontana 2022). Some datasets at better resolution are provided by regional authorities and are currently available only for a few administrative regions (Fontana 2022; Kakoulaki et al. 2021).

The largest LiDAR-based archaeological project in EU is a recent study that analysed the LiDAR data of the entire Denmark (more than 40 000 km^2), to detect Viking Age ring fortresses with automatic processing (Stott, Kristiansen, and Sindbæk 2019). This is followed by few other large-scale studies, mostly based on machine learning and automatic detection of features, covering more than 7000 km^2 and spread across the Iberian Peninsula (Berganzo-Besga et al. 2021; Cerrillo-Cuenca and Bueno-Ramírez 2019; Menéndez Blanco et al. 2020; Rodríguez González, Paniego Díaz, and Celestino Pérez 2021), Central-Southern Italy (Fontana 2022), Netherlands (Pierik, Stouthamer, and Cohen 2017) and Slovakia (Lieskovský et al. 2022). However, these large-scale studies stand out as exceptions as most of the projects encompass limited areas of less than 50 km^2 (119 out of 167).

Regarding the characteristics of the features detected through LiDAR, the great majority of European case studies recognized mainly features of limited height that are completely embedded in the landscape (122 out of 167). In contrast, case studies that targeted mainly standing features are very rare (12). In the few documented cases, these include hillforts, terraces, war storage sites, mining sites and cairns (Doneus and Kühteiber 2013; Kiarszys 2019; Küçükdemirci et al. 2023; Matías and Llamas 2018). Moreover, out of 167 publications, the minimum unit scale of the feature detected by each study is less or equal to 10 m in 81 cases, between 11 and 100 in 53 cases and equal or more than 100 m in 33 cases. In other words, most case studies used LiDAR to recognize medium-large archaeological features from some metres up to hundred metres (Figure 4a,b).

In considering the vegetation, about one fourth of the LiDAR acquisitions was carried out in forested areas (both deciduous and coniferous temperate forest). This is quite reasonable, as the accurate detection of relatively minor altimetry variations even over dense tree canopy is among the main benefits of LiDAR technology. Mixed areas (forested and open lands) and areas with poor or absent vegetation are also represented (respectively, 49 and 36 publications). Acquisitions targeting the Mediterranean forests (maquis) are less attested (9 case studies). This can be related to the difficulty encountered by laser pulses to penetrate this particular type of vegetation, which can grow extremely thick (Figures 3d–f and 4c).

The analysis of terrain morphology indicates that the large majority of case studies are located in easy-to-reach plain areas or undulated areas with low slope gradient (107 out of 167 cases). Point density is a crucial parameter in LiDAR acquisitions, which can vary greatly from one area to the other with respect to the morphology of the area and the vegetation cover. Out of 128 publications that reported information about it, 59 have 0–4.5 m mean points/m^2, 23 between 5.1–10 pts/m^2; 29 between 10.1 and 20; 10 between 20.1 and 40; 8 more than 40 pts/m^2. As a consequence, the final DTM resolution is generally between 1 and 5 m and only in a small number of case studies is lower (0–1 m).

Among the high-resolution acquisitions with more than 40 pts/m^2 reaching the ground (sometimes up to hundreds of points), it is worth mentioning the pioneering work carried out in both Austria and Italy through the use of unmanned aerial vehicle (UAV) and high-resolution sensors in the last few years, which allowed for accurate vegetation filtering and assessment of the impact on the visibility of archaeological features (Doneus, Banaszek, and Verhoeven 2022; Doneus, Mandlburger, and Doneus 2020; Mazzacca et al. 2022).

However, there is generally poor correlation between the number of case studies per country and both the point density of acquisition and the final DTM resolution. For example, in the United Kingdom and Spain where the number of LiDAR-based archaeological projects is high, most studies used data gathered from public institutions, with generally a low point density (5 pts/m^2 or lower) and DTM resolution of 1 m^2 or higher. In other words, this means that significant results on site detection and morphological mapping can be achieved from the analysis of LiDAR data at low-medium resolution. As for the projects that use restricted and archaeology-oriented data (83 out of 167), we expected acquisition dates to mostly occur during the dry and cold seasons, in order to take advantage of the leaf-off period. However, we found that out of 58 case studies reporting season parameters, only 33 LiDAR surveys were taken in the cold season, and 25 during the warm season. The reason may lie in difference of purposes among the projects (for example, the investigation of vegetation biomass or methodological comparisons between different seasons), as much as in regional climatic and topographic

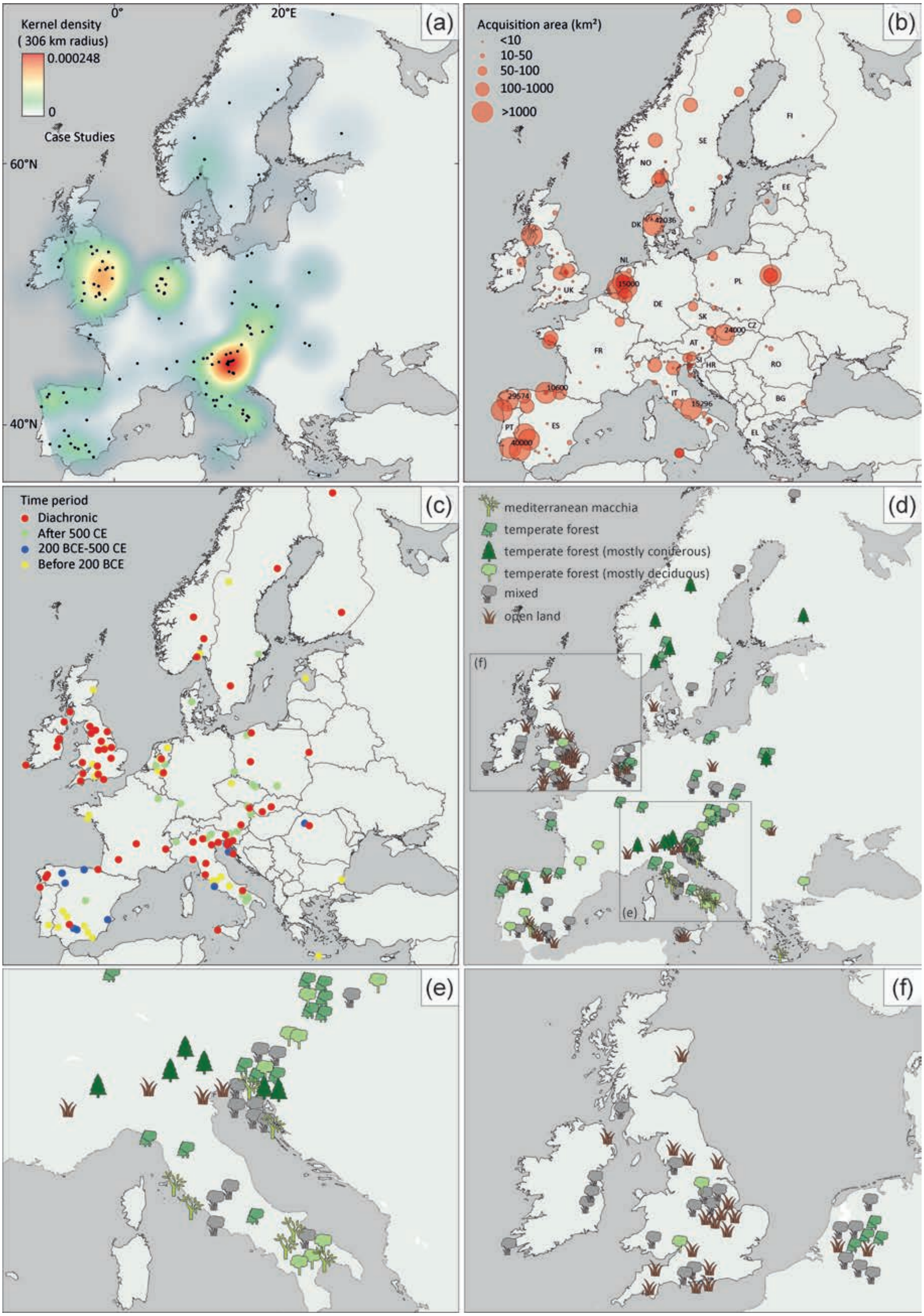

FIGURE 3 | Maps of the European case studies: (a) case studies distribution and kernel density (306 km sigma). Density is expressed in units/km^2; (b) size of LiDAR acquisition areas. AT = Austria; BG = Bulgaria; DE = Germany; DK = Denmark; EE = Estonia; EL = Greece; ES = Spain; FI = Finland; FR = France; HR = Croatia; IE = Ireland; IT = Italy; NL = the Netherlands; NO = Norway; PL = Poland; PT = Portugal; RO = Romania; SE = Sweden; SI = Slovenia; SK = Slovakia; UK = United Kingdom; (c) investigated archaeological period; (d) vegetation types in the study areas with a focus on (e) Italy, Slovenia and Austria and (f) the United Kingdom, Ireland and the Netherlands.

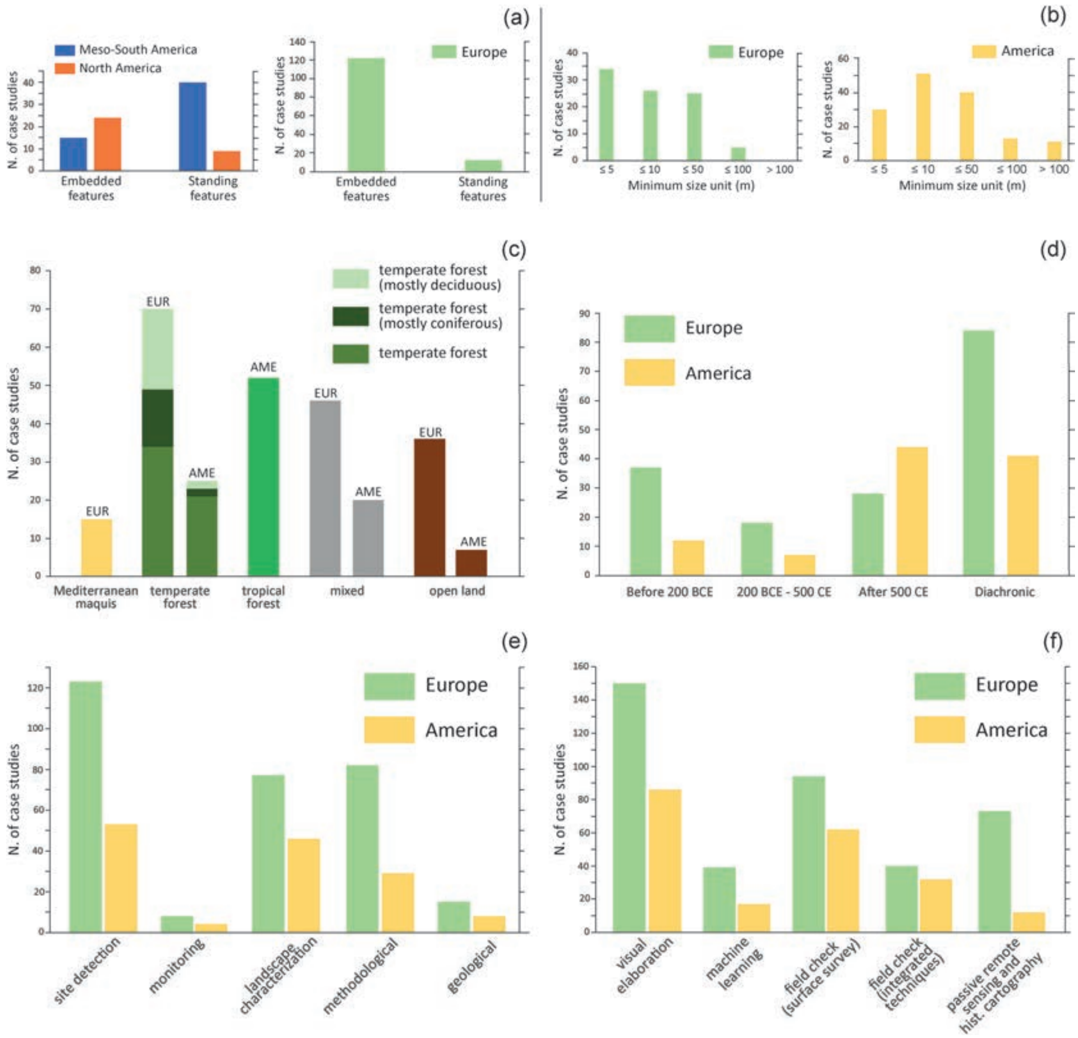

FIGURE 4 | Histograms showing the frequency distribution of (a) the main characteristics of the detected objects; (b) the minimum size unit of the recognized features; (c) the type of vegetation; (d) the targeted time period; (e) the targeted objectives; and (f) the adopted methods in both Europe (EUR) and America (AME).

variables which can restrict the suitable period for the survey (e.g., in the Alps and Scandinavia). We attempted to understand the correlation between dataset availability, seasonality and vegetation by performing a MCA on case studies located in Europe. The results clearly show that a vast majority of case studies use open access datasets, which in turn do not provide information about the seasonality of acquisition. The opposite is true for ad hoc acquisitions. The analysis also shows that, when the case study area is located in a forested environment, ad hoc acquisition is more common, while in non-forested environments, projects tend to settle for open access datasets, as seasonal influence on vegetation cover is not as important (see Figure S1 and Table S3).

Moving to the chronological periods targeted by case studies, out of 167 cases, 84 cases do not point to a specific time span but use LiDAR to decipher the landscape diachronically, whereas 83 are specific to a defined chronological period (prehistoric, classical and medieval-modern). Among them, those addressing the pre-classical periods are the most represented (37), followed by the medieval-modern periods (28) and classical period (18; Figures 3c and 4d).

In considering the European case studies' objectives, the majority of studies (123) used LiDAR for site detection and/or landscape characterization and mapping (77). This is concordant with the primary use of LiDAR technology that allows to both detect even subtle topographic variations, possibly connected to anthropogenic activity and obtain an overview of the topography over vast areas (Figure 4e). Interestingly, a high number of LiDAR-based case studies (82) presents the implementation of new methods and techniques. These include, for example, the development of new algorithms for point filtering, visualization techniques and so forth. Other scopes such as the reconstruction of geological aspects and monitoring are by far less attested (respectively, 15 and 8).

Finally, with respect to the methods and techniques adopted in each study, visual elaborations are by far the most commonly integrated with the analysis of LiDAR data (150). Investigations are also usually followed by ground truth checking, mainly consisting of surface surveys (94). In descending order, other remote analysis including aerial and satellite imagery, historical cartography and, increasingly, 3D photogrammetry, are quite extensively applied (73 cases), followed by other ground-based techniques (40) and the automatic or semi-automatic detection of features from LiDAR datasets (39). As for the latter techniques, despite the recent rise in machine learning applications for archaeology, this approach is still the least used in Europe (Figure 4f).

3.2 | Case Studies From the North and South America and Mesoamerica

Similarly to Europe, the number of American archaeological projects using LiDAR shows a sharp increase, passing from 1 to 104 in the interval 2006–2022, with a peak of 19 publications in 2021.

Most of the case studies considered in our survey are located in North and Central America, while only 7 are located in South America (Bolivia, Brazil and Peru). However, the largest numbers of LiDAR-based studies are in the United States (35), Mexico (29) and Belize (22), while largest scale projects are spread between the north-eastern states of the United States and Mexico (Figure 5a,b).

In contrast to Europe, the material culture targeted includes more standing than embedded features. Out of 49 case studies targeting standing features, 40 were located in Mesoamerica and South America, where the material culture mainly consists of monumental standing features from some metres up to tens of metres in size. This information is also congruent with the minimum scale unit, which ranges between some metres (less or equal to 5 m in 34 cases out of 104), or larger, between 5 and 50 m (51 cases), with few cases between 50 and 100 m (five cases). The higher resolution of LiDAR data in the American projects (especially in the Mesoamerican ones) is mainly related to the fact that most acquisitions are archaeology-oriented and commissioned by archaeologists (Figure 4a,b).

In considering the vegetation coverage, half of the reviewed case studies (52) examines areas covered by tropical forests. In these, LiDAR applications have obtained some of the most spectacular results, revealing largely unknown landscapes including complex and undocumented settlement distribution and imposing structures related to the Maya society (Chase, Chase, and Chase 2017 with references). This is

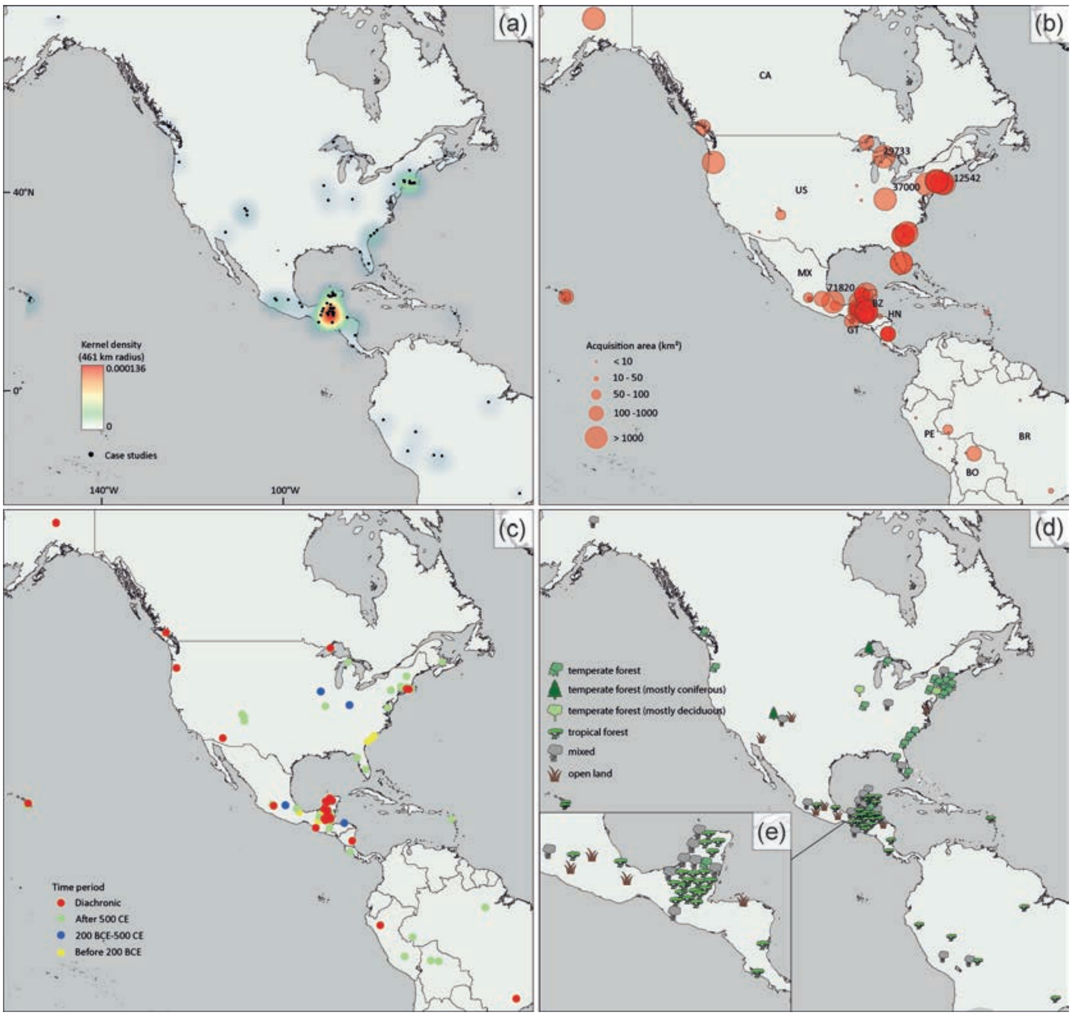

FIGURE 5 | Maps describing the characteristics of the case studies in the Americas: (a) case studies distribution and kernel density (461 km sigma). Density is expressed in units/km^2; (b) size of LiDAR acquisition areas. BO = Bolivia; BR = Brazil; BZ = Belize; CA = Canada; GT = Guatemala; HN = Honduras; MX = Mexico; PE = Peru; US = United States; (c) the time period target; (d) the type of vegetation in the study areas with a focus on (e) Central America case studies.

best represented by the case of Caracol, in Belize, where in 2009–2013, an overall LiDAR acquisition of about 1300 km^2 shed light on impressive anthropogenic landscapes consisting of urban settlements, roads and terraces (Chase et al. 2011, 2012, 2014a, 2014b; Chase and Weishampel 2016; Hightower, Butterfield, and Weishampel 2014; Krasinski et al. 2016; Wienhold 2013). Coupled with surveys and excavations, these investigations played a crucial role in deeper understanding regional spatial patterns and time depth among the Maya society (Chase, Chase, and Chase 2017). Other types of vegetation, such as temperate-forested and mixed environments featured by woodlands interspersed with open lands, are less represented (respectively, 25 and 20 out of 104), while open lands' case studies are very few (7; Figures 4c and 5d). Moreover, similarly to Europe, the majority of case studies are located in plain (75) or hilly areas (22), whereas just few are placed in the mountains (8).

Looking at the aspects of the acquisitions, higher point density is often found in central American projects (e.g., mean density by projects in Mexico: 20 pts/m^2; Belize: 17 pts/m^2) while lower mean density values are generally found in northern American studies (e.g., South Carolina, 5 case studies: mean density: 0.6 pts/m^2; Connecticut, 6 case studies: 2.2 pts/m^2).

With respect to the addressed time span, the majority of LiDAR-based American case studies are focused on the pre-modern and modern times (in particular, those considering the span between around 500 CE to 1500 CE; 44 studies), immediately followed by diachronic studies (41). This slightly differs from the European data, and it can be explained by the high number of publications focusing on the 'fossil' Mayan landscape revealed by extensive acquisitions carried out in Central America (in particular, Belize). Studies addressing other time spans, such as pre-200 BCE and from 200 BCE to 500 CE, corresponding to prehistoric and classical periods, are less represented (12 and 7, respectively; Figures 4d and 5c).

Like in Europe, site detection and landscape characterization are the principal scopes of LiDAR-based studies in America (respectively, 53 and 46 publications) while methodological, geological and monitoring scopes are less attested (respectively, 29, 8 and 4). This means that, despite the completely different material culture targeted by LiDAR projects in America and Europe and the much longer tradition of studies in European countries, the way archaeologists used LiDAR has been fairly comparable in both areas. This can also motivate why structures detected through LiDAR in the European continent are generally less monumental and less preserved (Figure 4e).

Techniques used in the American studies also do not differ significantly from those adopted in European projects. Data processing through different visualizations is the most attested technique (86 out of 104) followed by field check through surface surveys (62). Other ground based and machine learning techniques are also attested (32 and 17, respectively) while a minority of studies used other passive remote sensing methods (12). This is probably related to the application of LiDAR over thick forested areas, where the other techniques commonly used in different contexts (such as aerial imagery) are not applicable (Figure 4f).

4 | Discussion

Despite the exponential uptick of LiDAR applications in the archaeological field, this survey clearly shows that studies are not homogeneously distributed but cluster around Europe and North and Central America. With the remarkable exception of Cambodia, where the extensive Angkor Wat project took place, these three regions correspond to the areas where most of the LiDAR-based large scale projects have been carried out. The main reason for this odd distribution may be primarily related to the availability of LiDAR datasets. In these areas, archaeological investigations could rely on large open datasets acquired and shared by public agencies. This is well represented by both the high number of case studies and the extensiveness of LiDAR application in the United Kingdom, Spain, Italy (Europe), Pennsylvania and Michigan (USA) and Mexico. This trend is more evident in Europe than in the whole Americas: Considering all LiDAR datasets used in archaeology between 2010 and 2022, the percentage of open data in the former area is 46% versus 26% in the second one. Anyhow, the availability of open LiDAR datasets has been increasing globally since the early 2000s (Figures 6 and 7a–c).

Overall, it is very likely that the development of valuable expertise in the use of LiDAR for archaeological research at some places has been stimulated by the availability of open data freely provided by the institutions. This is reflected in the higher number of international papers published by scholars working in these regions. Trentino and Friuli Venezia Giulia regions (north-eastern Italy) provide a good example of this tendency. In fact, despite the longer tradition of studies in other Italian regions and their larger cultural heritage (e.g., Toscana and Lazio), almost one fourth of the Italian case studies come from these two regions (9 out of 33; see also Figure 3a). On the one hand, this clearly depends on the systematic use of LiDAR by some research groups working on this area since the early advent of this technology in archaeology (see, e.g., Bernardini et al. 2013, 2015; Cunial 2013; Forlin 2012). Also, this can be related to the availability of LiDAR data of the entire regions acquired by the local authorities for monitoring scopes and made fully available. The same can be proposed for Slovenia that, despite its limited extension, accounts for several studies using LiDAR (9), many of them authored by Benjamin Štular and colleagues (Lozić and Štular 2021; Štular et al. 2012; Štular, Eichert, and Lozić 2021; Štular, Lozić, and Eichert 2021). The impact of open data can be also measured by considering the largest scale studies. Most of the 30 largest case studies use open data, regardless the resolution is generally low or medium, with the final produced DTMs generally between 1 and 5 m, with only few exceptions (Table 1).

However, the use of LiDAR open data has some important drawbacks that go beyond the generally lower data resolution and deal with the lack of control on the acquisition process. This means that acquisition dates do not follow the 'leaf-off' season but are random or planned by the institution according to other criteria. Moreover, ground filtering is often not possible as it requires access to the unfiltered point-cloud and other information generally not provided by the institutions. All these factors make the potential of open datasets for the identification of features much more variable than that of the restricted datasets ad hoc acquired for archaeological purposes. Notwithstanding

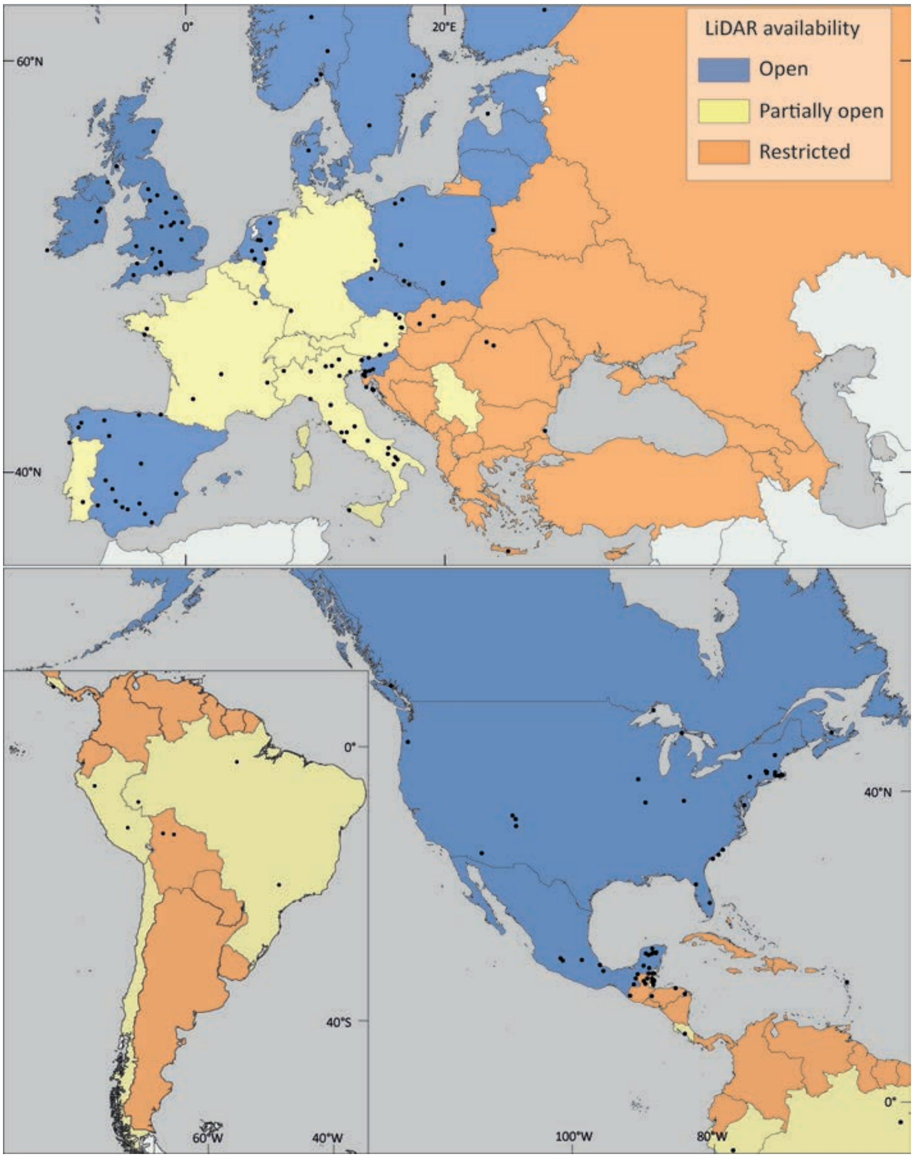

FIGURE 6 | LiDAR data availability in European and American countries at the end of 2022. Partially open data include countries for which LiDAR is only available for certain regions and/or through case studies acquisitions.

this, collected information shows that, wherever available, open data has greatly expanded the general knowledge of the past in many areas, allowing for the detection of many previously unreported features.

The second interesting aspect regards the vegetation cover. Though some large-scale studies include open areas, most case studies targeted forested ones, in Europe as much as in the American continent. This is due to the lucky coincidence that makes LiDAR a perfect *trait d'union* between woodlands and archaeology. In fact, in these contexts, the presence of dense vegetation allows the conservation of both archaeological and natural landforms by hindering soil erosion and detrimental effects of agriculture. Moreover, as some of these areas are protected by countries' regulations, forested areas indirectly guarantee further protection from urban development. Finally, as archaeological survey in woodlands are generally arduous and time-consuming, no or little archaeological information has emerged and, consequently, has high potential for new discoveries (Campana 2018, 13–14; Chase, Chase, and Chase 2017; Crow 2004; Crow et al. 2007; Doneus et al. 2008; Howey et al. 2016; Schindling and Gibbes 2014, 412–413). All these reasons make LiDAR the most powerful tool in forested environments.

As known, outstanding results have been achieved in densely forested areas covered (i.e., the tropical rainforests), where the ruins of many monumental standing structures have been recorded under the tree canopy. However, also in the other forested areas of the world as the temperate ones, the impact of LiDAR was significant and led to the identification of many features, generally embedded in the landscape. In both tropical and temperate forests of Mesoamerica and northern Europe, the minimum scale unit of the recognized features was generally higher than 5 m, up to some hundred metres. This means that, to date, many project have mainly targeted large-scale objects of tens of metres in size (e.g., the Mayan temples or the European prehistoric enclosures) that are much easily detectable compared to other smaller features (e.g., Roman and Medieval farmsteads, small irrigation ditches and

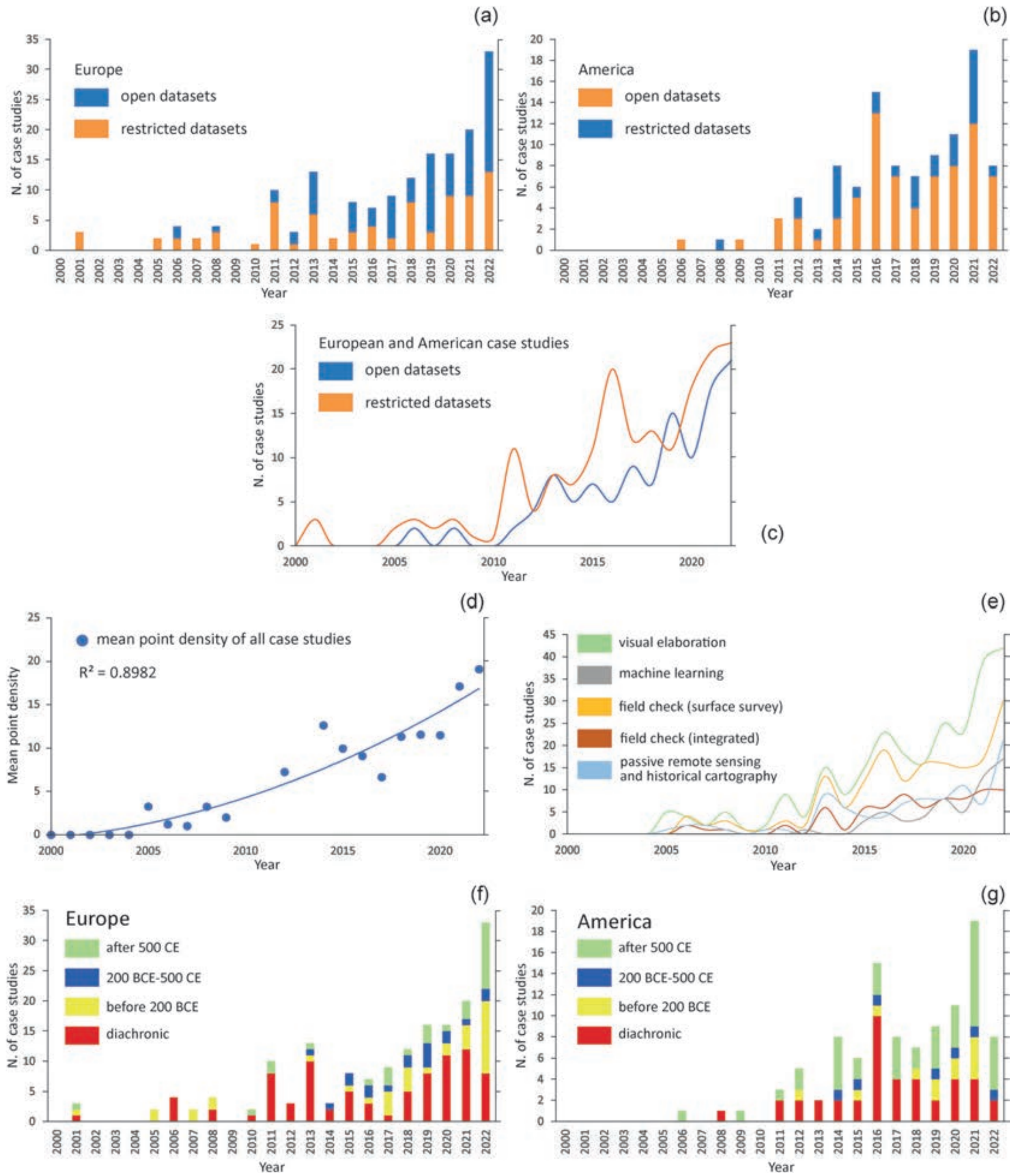

FIGURE 7 | (a and b) Histograms showing the frequency distribution of open source and restricted LiDAR data in Europe and America over the period 2000–2022; (c) line graph showing the global trend in open source and restricted data over the period 2000–2022; (d) global mean point density (pts/m^2) of all case studies in the considered period; (e) line graph showing the global trends in methods and techniques integrated with LiDAR in the considered period; (f and g) histograms showing the frequency distribution of time period targeted by studies in Europe and America between 2000 and 2022.

land divisions). This leaves space for a significant increase in the identification of features in the near future. Štular (2022) estimates a 5-fold increase in known archaeological features through LiDAR in forested areas. As for Europe, where about 43% of the area is covered by forests and the availability of LiDAR datasets is widespread, an increase of 215% in finding new archaeological features in the next few years would be likely.

So far, most European case studies applied LiDAR in deciduous and coniferous woodlands and only a smaller number in Mediterranean maquis, typical of southern Europe and northern Africa. This can be related both to the generally less availability of open datasets in this region and to the less penetrability of Mediterranean shrubs and bushes, which probably require LiDAR acquisition at higher resolution than those mostly carried so far. Nonetheless, the situation is likely to change in the next few years with the progressive enhancement of sensors and the reduction in costs. However, despite the case studies in forested environments are most attested worldwide, a good number of studies applied LiDAR to mixed landscapes (woodlands interspersed with grasslands) or open lands (croplands and grasslands).

With regard to the specifics of single acquisitions, as global trends indicate, density of points per square metre has been progressively increasing since the early 2000s and so was the final resolution of the DTMs (Figure 7d). This is principally due to advancements in technology from single wave to full waveform, which allows up to several hundred returns to be recorded per laser beam (Doneus et al. 2008). Alongside, visualization techniques, ground point filtering and archaeology-specific data processing have been progressively refined or developed (Hesse 2010; Kokalj, Zakšek, and Oštir 2011; Doneus, Mandlburger, and Doneus 2020; Lozić and Štular 2021; Štular, Lozić, and Eichert 2023 with references; Figure 7e).

Together with the progressive growth of case studies, we also envisage a steady expansion of both methodologies and objectives. From around 2010, the integration of LiDAR with other techniques has been not only limited to surface survey and 'shovel tests' (i.e., trial pit excavations and corings) but has been increasingly including other techniques such as aerial and imagery, the analysis of historical cartography, 3D photogrammetry and ground-based methods (in particular geophysical ones, such as magnetometry and Ground Penetrating Radar) to detail geometry, age and characteristics of specific landforms (Campana 2018; Forte and Campana 2017; Leucci 2019; Opitz 2013). In this direction, it is worth mentioning the growing diffusion of 'home-made' combined photogrammetric and LiDAR-based acquisitions from UAVs and smartphones, which allow for accurate low-cost topographic surveys (Campana 2017; Luetzenburg, Kroon, and Bjørk 2021; Risbøl and Gustavsen 2018). In particular, recent experiences of UAV-based LiDAR acquisitions from UAV collected through high resolution sensors (e.g., mini-RIEGL) demonstrate the great potential of these combined technologies even in densely forested environments, such as the Mediterranean macchia (e.g., Mazzacca et al. 2022). Other opportunities fully available in the near future derive from LiDAR data taken from satellite (Kokalj and Mast 2021).

It is also worth noting the increasing development of machine learning algorithms for the automatic detection of anthropogenic features within large LiDAR datasets. Overall, all this gathered information is of paramount importance not only for research scopes but also to plan effective measures for heritage management, monitoring and valorization (Boschi 2016; Bunting et al. 2014; Cowley 2011; Cowley et al. 2020). As proof of this, the sharp increase in studies targeting site detection, landscape characterization and methodological contributions corresponds to a slower but steady increase of publications using LiDAR for monitoring scopes (Figure 7e).

Finally, from a more theoretical perspective, the use of LiDAR has been gradually becoming part of the global study of landscape. This is well depicted by the increasing number of LiDAR-based diachronic studies with respect to those targeting a specific chronological period. With this regard, it is worth considering the chronological period targeted by single case studies. It appears that, although the number of diachronic case studies has significantly increased in both Europe and America, in recent years, there is an increase in projects that focus on a specific chronological period. This would suggest that the use of LiDAR has entered the archaeological practice and that overall vast analysis of landforms are followed by more specific studies, in both chronological and spatial aspects (Figure 7f,g). With this regard, some authors recently emphasized the long-term evolution of landscape and used terms as 'palinsept' and 'archaeological continuum' to define the complex sequence of materialized actions that needs to be deciphered (Campana 2018; Johnson and Ouimet 2018). LiDAR has an active role in this new wave of landscape studies, not only in widening the available tools to study the past but also in contributing to change the approach of scholars to the cultural landscape itself, by addressing new issues and rethinking the old ones. Just like what happened with the introduction of GIS in early 1990s and the following 'tool or science' heated debate (for a summary, see Wright, Goodchild, and Proctor 1997), the adoption of a new technology such as LiDAR in the archaeological field is contributing to shaping not only the archaeological practice but also the theory.

5 | Conclusions

Some final remarks from this review can be briefly summarized as follows.

- The application of LiDAR in archaeological studies is growing at global scale but, to date, has been by far more extensive in Europe and America (especially north and central). Its impact was more significant in some areas of Europe and North America where the availability of open data provided by the institutions has encouraged scholars to apply this technology, no matter whether the investigated area was forested or not. This is clearly indicated by the higher number of both case studies and large-scale projects in these regions. Conversely, areas where LiDAR datasets are not open require massive economic efforts to conduct LiDAR surveys that only a limited number of institutions are capable of sustaining. It is worth mentioning, as an exemplary case, the extensive survey carried out in Cambodia by the Cambodian Archaeological Lidar Initiative (CALI), considerably funded by the European Research Council (ERC-2014-STG, project n. 639828). Ultimately, this disparity underscores the great divide between industrialized and developed countries. In the near future, the increasing use of UAVs will facilitate the creation of custom LiDAR acquisitions at reduced costs, potentially providing a way to bridge this gap.
- Despite some disadvantages compared to restricted archaeology-oriented acquisitions, the availability of open datasets has anyway yielded important results and contribute to the development of valuable expertise in the application of this technology for cultural heritage. Moreover, this strongly suggests a further increase in the number of LiDAR-based studies, as soon as more open data become available, most likely in the next few years.
- Most studies still adopt airborne LiDAR to detect and characterize archaeological sites in their landscape context. However, a progressive trend towards a diachronic and interdisciplinary analysis of past landscape is noted.
- Due to the capability of LiDAR to peek through the vegetation, greater results are yielded in forested environments, reflected in a higher number of publications. Outstanding results achieved by LIDAR-based projects in tropical environments can be first explained as a consequence of the characteristics of the material culture occurring in that region and its preservation. This often consists of large standing features of some hundred metres in size, located in very inaccessible areas, yet archaeologically largely unknown. In

contrast, in other parts of the world, such as central–northern Europe, most detected features are completely embedded in the present landscape and are generally smaller in both planimetric and altimetric dimensions. This can also explain the poor results so far obtained by LiDAR applications in several areas of long-term settlement that are currently covered by thick vegetation. Among these are several sectors of the Mediterranean in which the outcropping archaeological evidence, albeit vast and widespread, is generally less preserved and not easily detectable through LiDAR data at low-medium resolution. In these regions, the availability of high-resolution data can dramatically change our knowledge of the past.

- The increasing availability of LiDAR data over vast areas will produce more granularity in the acquisition and analysis of data and could lead to enormous advances in the investigation, monitoring and protection of the cultural heritage worldwide.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at 10.5281/zenodo.8174095.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.