remote sensing

Review Paper

Monitoring of damages to cultural heritage across Europe using remote sensing and Earth observation: assessment of scientific and Grey literature

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Abstract: This research is part of a wider framework of index literature studies that have been conducted in the past few years. Some of these had a focus on specific remote sensing (RS) technologies, while others have tackled specific threats to cultural heritage and landscapes. By considering both damages to heritage sites and technologies used for documentation and monitoring of such occurrences, the paper unveils the current trends on a global scale in the study of the threats to heritage, caused by both human-induced and natural hazards. Papers published by Europe-based researchers over the last 20 years using RS and Earth Observation (EO) techniques were surveyed, alongside recommendations and programmatic documents issued by institutions in charge of heritage protection and management of several countries in Europe. Around 300 documents among scientific articles (published from 2000 until 2022) and Grey literature (from 2008 and 2022) were analysed. The data collection and analysis were undertaken by a group working that was intentionally composed to bring together diverse perspectives and expertise, i.e., requirements of heritage professionals when using RS and EO technologies; knowledge on technologies and their use in the field; expertise in methodology implementation to support heritage management. The results highlight: the type of hazards mostly considered and the geographical distribution of the archaeological sites and monuments targeted by these studies; the country affiliations of the researchers; types of RS and specifically satellite-based technologies (and hence type of data) used; what are the tendencies of satellite data usage: visual interpretation, image processing, employment of machine learning and AI; what are the mostly applied technologies by public institutions and practitioners; and many others. Recommendations and future trajectories are then outlined to efficiently reframe discrepancies between types of damage that received the greatest attention in the literature and the most impacting ones in terms of number of sites damaged.

Keywords: Remote Sensing; Satellite data; Literature assessment; Cultural Heritage; Damage; Hazards; White papers; Grey literature

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1. Introduction

The management cycle of tangible cultural heritage – either archaeological findings, buried and open-air sites, monuments, historical buildings or movable objects – includes at least the following phases: discovery, documentation, study, conservation and promotion. Remote sensing (RS) is nowadays an acknowledged technological asset contributing to each of these phases and a means to collect digital data and records allowing not only non-invasive measurements at a given accuracy, but also replicability and reproducibility of the features' and sites' geometry, of their context and of their location in space. These properties are key features to support monitoring activities from remote, at various spatial and temporal scales, in both ordinary and crisis times. For conservation purposes, monitoring through RS techniques enables assessment of potential threats before harmful events occur, as well as documentation of damages and impacts once an incident, due to either natural or anthropogenic process, has happened. As such, RS – via sensors mounted onto terrestrial, airborne and satellite platforms – offers an instrument to institutions and organizations in charge of heritage conservation and promotion, alongside the scientific community, to undertake a variety of tasks including regular monitoring of the on-the-ground condition, risk assessment and damage mapping.

However, the extent to which RS and Earth Observation (EO) technologies are effectively and systematically exploited by end-users outside the scientific research field and, if so, whether this use applies to all (or at least a broad range of) hazards and types of damage, or instead there is a polarization towards a certain specific use-cases and scenarios, is yet to be fully unveiled.

Therefore, to fill this gap, in this paper we will first provide in-depth state-of-the-art analysis of the previous research and literature assessments on the topic, from which current issues and limitations will be highlighted. Based on these findings, in the second part we will illustrate the specific objectives (i.e. the three research questions) and the methodology developed. The latter will have a dedicated section about the terminology used in the paper followed by the step-by-step processes of analysis for both the Indexed literature assessment and the Grey literature assessment. The third part of the article will be dedicated to the results. Here, we will separately describe the trends emerged from both the Indexed literature assessment and Grey literature assessment. Within each type of assessment, the results will be distinguished on the basis of the research questions, focusing on the one hand on the types of hazards and damage and on the other hand on the geomatic technologies used. In the Discussion we will evaluate the results separately, thus showing the main findings for the Indexed literature and the Grey literature. The conclusive section will underline the common problems that emerged from the two analyses and consequently the possible recommendations and way forwards.

1.1. State-of-the-art on RS of satellite imagery for monitoring hazards and damages to CH

The interest towards the use of RS of satellite imagery for monitoring hazards to CH increased significantly over the past decades [1–5], as confirmed by the growth of academic articles, white papers, policy documents and more generally in the Grey literature [4,6]. The application of RS to the field of cultural heritage encompasses the use of manual, semi-automatic and automatic methods as well as tools including satellite imagery, aerial photography, geophysical prospection, and Unmanned Aerial Vehicles (UAVs), all used for discovering, safeguarding and monitoring new or existing archaeological sites, monuments and cultural landscape worldwide [7].

As such, RS opened a new season on the protection and safeguarding of cultural and natural heritage, with many stakeholders, from academic scholars to practitioners, involved at different levels. The relevance of this topic expanded well beyond the scientific sphere, reaching international agendas (e.g., as a dedicated target in the United Nations' 2030 Agenda for Sustainable Development Objective #11.4) and triggering the creation dedicated working groups at least at the European level (e.g., Copernicus Cultural Heritage Task Force). The wealth of both academic and Grey literature publications (referred to as "Grey Literature" in compliance with the definitions published in [8, 9]) allowed to develop practical tailor-made solutions for many damages, thus significantly contributing to improve the quality of documentation, prevention and monitoring of endangered heritage at a global level.

However, recent indexed literature assessment [10] suggested a discrepancy between the types of damage that received attentions by scientific research and white papers and the most impacting ones in terms of number and extent of sites damaged. As a result, this albeit preliminary analysis underlined the necessity to conduct a more in-depth study of this issue, and eventually to reframe scientific research focus in proportion to the type of hazard and its level of impact.

1.2. Background on previous literature assessments, including findings, recommendations and limits

This study is part of a line of research that aims to monitor the evolution of research and knowledge in the field of cultural and natural heritage safeguarding, using satellite RS technologies. As such, this line of research reconstructs the long-term trends in the use of specific methodologies and tools as well as in the evolution of the geographical area of analysis and the types of heritage places considered. Studies in the field eventually provide recommendations on how to redirect the analyses, introduce new tools and approaches, and possibly improve the quality of protection and safeguarding of cultural and natural heritage.

The exercises aimed to monitor the evolution of the literature focusing on this topic developed over the last decade, with the first studies conducted by [7] on the impact of RS on the wider archaeological field, up to the most recent research one carried out by [10] from which this research takes its cue.

Table 1 collects the literature assessments mentioned above and a summary of the outcome/s achieved. However, it must be kept in mind that, in many cases, the goal of these studies was to measure the entire range of RS applications for archaeology and cultural heritage (such as sites or landscape features detection), and therefore it is not possible to extract the trends relating to studies on hazards to cultural heritage.

Table 1. List of literature assessments regarding the use of remote sensing for cultural heritage for hazard and monitoring. Notation: RS – remote sensing; SAR – Synthetic Aperture Radar; InSAR – Interferometric SAR; WHS – World Heritage Sites.

Publication	Main topic	Time range	Geographic area	Outcomes
[7]	Remote sensing in archaeology	1999-2015	Europe	1. Substantial increase of RS for archaeology. 2. Need for common repository to share knowledge.
[12]	SAR for cultural heritage	1985-2016	World	1. SAR as an increasingly accessible and practical technique for monitoring multiple threats.
[13]	InSAR data for hazard assessment on UNESCO WHS	2000-2017	Europe	1. InSAR increasingly used in Europe with large amount of data for heritage stakeholders. 2. Necessity for more public consultation exercises and workshops, and user engagement at early stages of InSAR implementation.
[4]	Looting of archaeological sites	2000-2017	World	1. Substantial body of different satellite image-based processing methods. 2. Lack of common practices, needs for more dissemination and user uptake.
[6]	Air/spaceborne imagery for cultural heritage	1907-2017	World	1. Different RS image techniques for different applications. 2. Increase of access archive and novel data
[5]	Google Earth application for cultural heritage	2005-2016	World	1. Google Earth as a basic efficient and open-access tool for cultural heritage monitoring.
[14]	Machine intelligence approaches to archaeological remote sensing	1995-2017	World	1. Data sharing and collaboration between different disciplines.

				2.Need for machine intelligence applications for processing datasets and replicating complex calculations.
[11]	SAR and InSAR for cultural heritage	1992-2020	World	1. Combining all radar technologies. 2. Multidisciplinary collaboration is crucial. 3. Including frontier information technologies to better manage data that radar technologies can provide
[10]	Most endangered types of cultural heritage	1969-2021	World	1. Substantial discrepancy between damage documented and damage studied.

Of these papers, some focused on the advances in the use of specific types of satellite imagery and/or techniques for their processing and generation of value-added products, such as radar and maps of structural deformation [6,11–13], while others investigated the potential of online platforms like Google Earth [5]. Several studies also evaluated the role and validity of big data repositories to organize and manage large quantity of satellite imagery [7,11,13]. In other cases, the main focus was the relevance of multidisciplinary collaborations [7,11], as well as the importance of establishing common practices for data processing and investing on dissemination and capacity building [4,12,14]. Towards such ambitious goal of effective user uptake, engagement of end-users in designing and implementation of RS/EO-based solutions is frequently called for. However, limited evidence was found in the scientific literature [4, 13] and most of the successful use-cases of technological transfer relied on mediation by scientific champions [4, 11, 13]. Finally, it is worth highlighting that a recent study [10] highlighted a third significant element, meaning the discrepancy between the types of damage that received the greatest attention in terms of scientific research and policies and the most impacting ones in terms of number of damaged sites. Basically, several common hazard factors are well known to cause damage and require significant investments by heritage bodies and institutions in charge of daily maintenance and conservation (e.g., local conditions encompassing micro-organism, wind, rain or humidity, urban sprawl or agricultural practices). However, there are only few examples of evidence in the scientific literature that these were the primary threats for which RS and EO technologies were used, compared those damages of which impacts result to be more disastrous and devastating, albeit limited in time and linked to specific extraordinary events (e.g., earthquakes, landslides).

The outcomes of these studies may be summarized according to three main recommendations:

1. Necessity to pay more attention to match the properties of current and future satellites with the needs and questions of archaeological research and built heritage conservation practice.
2. Necessity to raise awareness among the multiple stakeholders revolving around the wider field of heritage on the range of uses of available satellites via more investments in training and capacity building.
3. Necessity to expand and share the available datasets to widen the types of analyses that can be undertaken.

Over the years, these recommendations helped reframing this field of study in several ways including:

1. Slow increase (albeit still underdeveloped) of the level of engagement of non-experts of remote sensing [11];
4. Development of international capacity building and training projects, as confirmed by numerous international initiatives run on a global level like Space2place [15] or EO4GEO [16], or in Europe such as JPI-CH Prothego [17,18], in the Mediterranean and Near East like EAMENA [19,20] and EDUU [21] as well as in Central Asia with the CAAL project [22];

5. Launch of new (or the improvement of existing) satellite imagery archive platforms like the Sentinel-Hub (https://www.sentinel-hub.com/) or USGS (https://earthexplorer.usgs.gov/) ones.

However, despite the substantial positive impact of these studies in the improvement of this line of research, some limitations and open questions still remain. In the case investigated in this paper, i.e., damage to cultural heritage caused by both human and natural-induced hazards, these limitations include:

1. A lack of a clear reconstruction of the trends in the study of hazards and resulting damage to cultural heritage encompassing both scientific research and Grey literature.
2. A lack of a concise understanding of the RS methods and tools that can be used for each type of hazard.

This last limitation is crucial to provide end-users such as national authorities, international organizations (e.g., UNESCO) as well as private consultants with a suite of well-defined methods and tools to be used to efficiently document and monitor each type of hazard. This paper aspires to contribute to bridging these gaps through a tailor-made literature assessment regarding more than 20 years of research in the field.

Building on three main necessities emerged from the previous assessment as well as on the current limitation, in the present paper we analyse the current trends in the study and assessment of damages to cultural heritage in Europe caused by both human-induced damage and natural hazards using RS and EO techniques. In particular, our research provides a fresh and ample look at the long-term evolution of both the indexed scientific and Grey literature regarding hazards and damage to archaeological sites, monuments and cultural landscapes conducted by European-based researchers and heritage professionals from 2000 until today using RS technologies and techniques. To do so, and following previous recommendations [7,11], we developed a multidisciplinary collaboration to investigate the current trends and suggest improvements in processes of documentation, safeguarding and monitoring of cultural heritage and cultural landscape under threat. To address this scope, the group who worked on this research was intentionally composed to bring together some of the main (although not exhaustive) perspectives and expertise, i.e.: concrete requirements of the heritage professionals that are the final end-users of RS and EO technologies; knowledge of these technologies and their use in the field; methodologies and practice for implementation to support tasks of cultural heritage management cycle.

2. Research aims, materials and method

2.1. Research questions

The present study is underpinned by the following research questions:

1. What are the types of hazards to cultural heritage that have been studied using satellite imagery so far?
2. Are all the types of hazards equally addressed?
3. Is there a correlation between a specific type of damage and satellite-based technology?

The outcomes consist in a comprehensive reconstruction of the current trends and limits in the application of RS and EO techniques by European-based researchers over the last 20 years to document human and natural-induced damage to archaeological cultural heritage. This will be useful to 1) indicate the best tools and methodologies for each specific type of hazards, 2) to suggest recommendations and future trajectories for properly reframe discrepancy between those types of damage that received the greatest attentions and the most impacting ones in terms of number of sites damaged, so as deepen the preliminary findings discussed by [10].

2.2. Methodology

To provide a closest possible answer to the query of "*what are the most studied damages on cultural heritage across Europe and what are the technologies used*", our method was based on assessment of scientific and Grey literature presented in previous cited experiences. In this paper, however, we went a step further with an attempt to compare these two domains that could have very different final users (audiences). The main reason for such approach was the assumption that there could be some discrepancies in the interdisciplinary interaction: while remote sensing scientist are not always fully aware of the needs of the cultural heritage sector, scholars involved in heritage study and preservation are not always up to date with the recent technological advancements. In line with previous research [10], we felt that such a scenario might contribute to a divulgation of an unseemly narrative of the most relevant damages monitored using advanced technologies. In this respect, the focus of this paper is placed on the demonstration of the potential of advanced geomatics technologies, specifically on space-based solutions for a number of expert and non-expert end-user, particularly in the field of archaeology and cultural heritage.

The reason for this choice is that the information processed for monitoring of damage to cultural heritage relies on different sets of data often managed in Geographical Information Systems, especially for extended areas or larger archaeological sites. Such complex sets of data must be organised, processed, and managed considering an appropriate representation of both construction/monument/site and often its territorial surroundings. As the processing of such information is increasingly requiring an interdisciplinary and interoperable environment, we thought that geomatics technologies satisfy such requirements. As recalled by Gomarasca [23], the term geomatics was based on the concept that the increased potential of electronic computing was revolutionizing surveys and representation sciences, and that the use of computerized design was compatible with the treatment of huge amounts of data. Among the different geomatics techniques and disciplines able to assign a geospatial location to each object on the planet, we considered as a specific point of interest those of satellite-based Remote Sensing Earth Observation. Also, other technologies were taken into consideration because widely employed in, i) practices of heritage documentation and monitoring like photogrammetry, laser-scanning, GPS or RS ground sensor technologies; ii) information management like GIS and WebGIS.

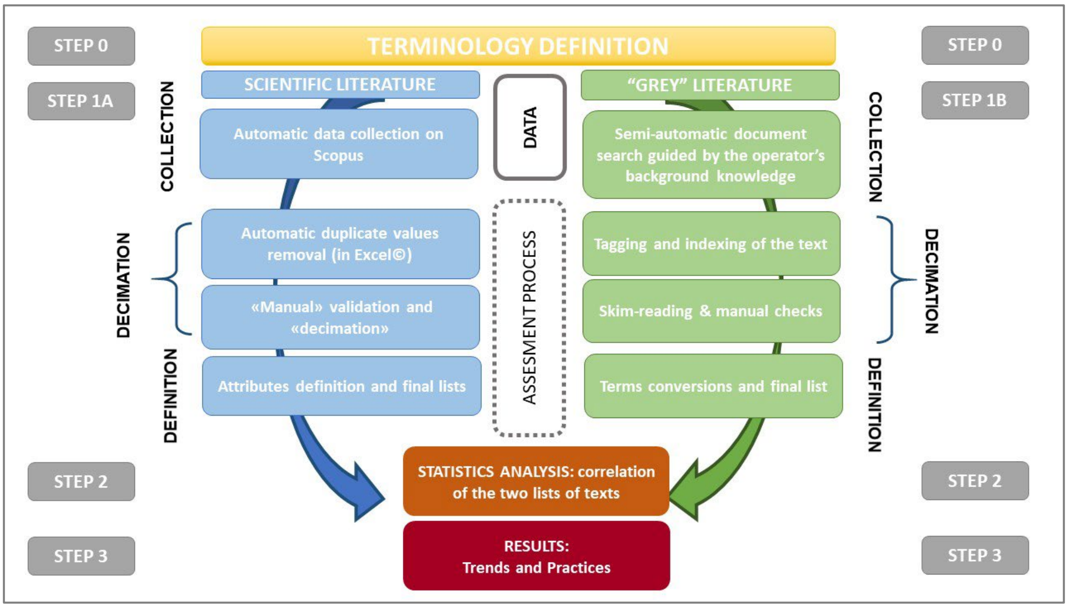

Figure 1. Literature assessment: overall methodology workflow

From a conceptual and methodological points of view, there are further reasons to include a dedicated analysis of the Grey literature. As observed in previous studies [12,13], the scientific literature alone cannot provide an exhaustive representation of demonstration activities involving or made directly by users and stakeholders. Journal papers are mostly focused on applied research, methodological developments and tests, as well as proof of concept or case studies, thus it is sometimes unfeasible to grasp the real impact of RS and EO technologies on daily heritage practice. Moreover, policy, programmatic and institutional documents issued by organisations and bodies in charge of heritage preservation are more likely to provide insights into the status of RS and EO technology uptake and embedding in operational workflows than journal papers.

Hence, we have decided to act in two directions:

a. To investigate scientific literature that is a testimony not only of the base research but often of applied research activities conducted during projects or pilot demonstrative initiatives.
b. To consider the Grey literature, i.e. materials and research produced and published in the form of Report, Guidelines and White papers outside of the traditional academic publishing and distribution channels, catalogues and repositories.

The decision for such two-fold approach was to: i) grasp scientific advancements in the domain of cultural heritage monitoring presented by the solutions that are objectively technologically possible; ii) to illustrate the best practices "on the field", that is to say operations that are needed and that are being implemented by public administrations and private entities in their common practice of heritage preservation.

The overall methodological process is presented in Figure 1 and it is organised into four main steps:

- Step 0: Terminology definition
- Step 1: Data collection and literature assessment, divided into Step 1A and 1B
- Step 2: Correlation of the two literature assessments
- Step 3: Analysis of findings regarding trends and best practices.

This section deals with description of the Step 0 that sets the terminological definition and Step 1 that regards data collection, data structuring and first analysis. It is important to note that the outcomes of Step 0 (i.e., terminology development) can be further used and replicated on other cases studies; Steps 1 to 3 refer specifically to this exercise.

2.1.1. Terminology definition

To be able to "normalise" the results from the two batches that might appear heterogeneous and make them comparable, it was necessary to build a common Terminology of reference. We have referred to this phase as a "**Step 0: Terminology definition".** On one side, for the definition of damages and type of heritage, we have referred to the official UNESCO terminology based on a two two-tier system of damaging factors consisting of a list of 14 primary hazards from which more 150 types of hazards (secondary) derive (https://whc.unesco.org/en/factors/) [24]. The UNESCO terminology is nowadays the most complete and shared document regarding the definition of heritage hazards and all types of damage considered by the papers analysed in the present research well fit either UNESCO primary or secondary hazards. To have a statistically significant sample, we considered the 14 primary factors proposed by the UNESCO report [24] as sufficiently exhaustive. In fact, if we had also considered the secondary factors, we would not have obtained a statistically significant result. For each paper selected we normalized the types of damaging factors described according to the UNESCO terminology, so as to produce a coherent dataset to be analysed.

On the other side, for a definition of terminology of geomatics technologies employed, we have built a nomenclature reference, as presented in Figure 2. To provide a comprehensive list of technologies and their sub-categories we have referred to the current structure adopted by the International Society of Photogrammetry and Remote Sensing (ISPRS). The list of Commissions and sub-commissions of ISPRS was hence used to define a structure and correlations between different technologies, sensors and their future technological perspectives within a specific applications framework of cultural heritage and cultural landscapes monitoring.

Some adaptations were anyway required. In addition to the list of geomatics technologies, it resulted necessary to indicate "Machine Learning/Artificial Intelligence (AI)" as possible relevant terms for this exercise.

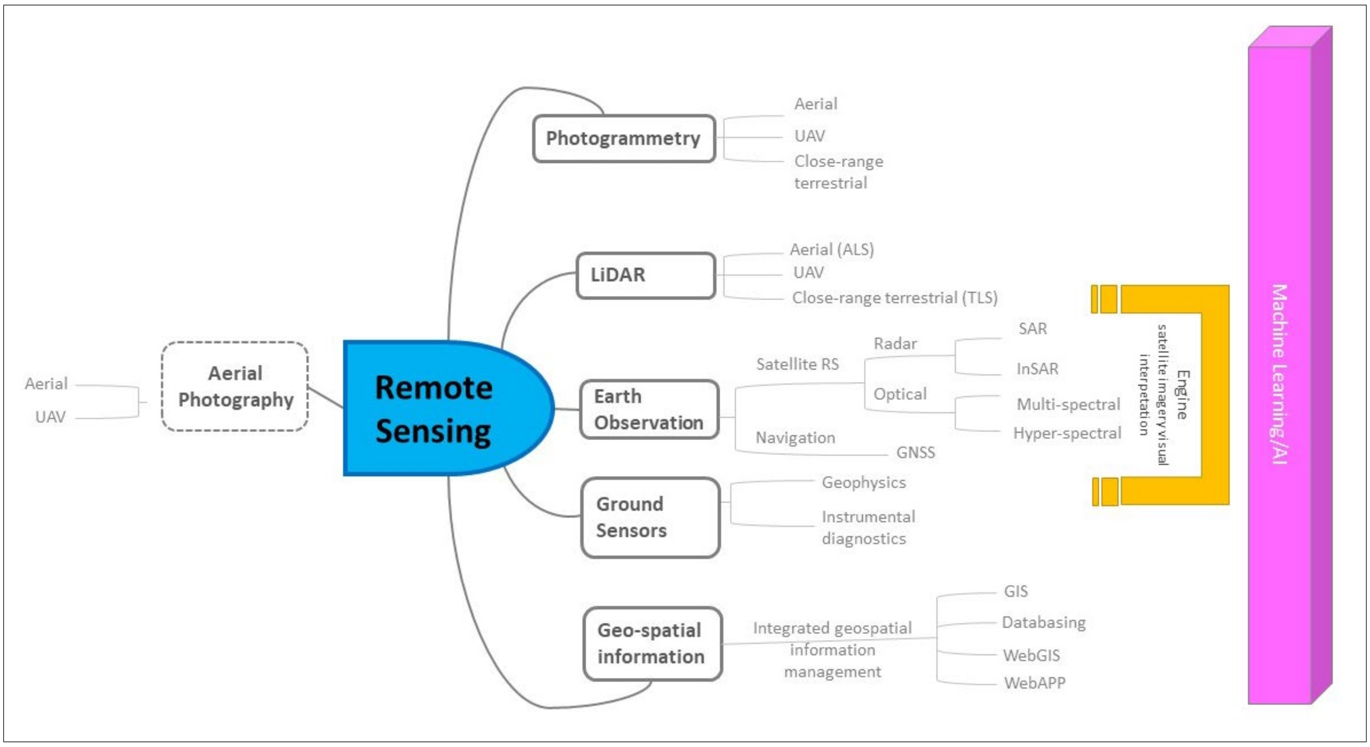

Figure 2. Terminology for Remote Sensing technologies.

At the same time, "Photography", either from Aerial or UAV (but also balloon or other specific types) platforms was taken into account as a relevant term because the use of photographs from above is common practice by CH professionals since several decades. Similarly, the use of satellite imagery consultation within maps search engines without further processing of the images themselves (e.g. through Google Earth or Bing) was considered under the general term "Engine". Both examples have been used for literature assessment (Step 1, Data collection and literature assessment) as they indicate awareness of technological potential and specifically that of satellite imagery. However, articles from the scientific literature and documents from Grey literature that only mentioned this kind of practice without a specific reference to actual data processing or way to further process and analyse satellite images were not considered in order to answer question n. 1. The concept is that the simple mention of maps search engines cannot be taken as a proof that this technology is effectively exploited in daily practice. Similar consideration was made for any other RS reported in Figure 2 and, in that case, the textual occurrence was disregarded to the scopes of the final statistics of the present assessment.

The time period of the scientific and Grey literature analysed in this study spans from 2000 and 2022, thus providing a sufficiently long timeline to assess trends and current perspectives.

2.2.2. Literature assessment

- **Step 1: Data collection and literature assessment of scientific and Grey Literature**

Scientific literature batch was obtained from Scopus©, a world-wide acknowledged abstract and citation database of peer-reviewed literature, that was also exploited by most of the previous publications listed in Table 1. In order to select the most significant papers, we took into account products by both Remote Sensing experts that applied their knowledge on heritage assets and by Cultural Heritage scholars that have employed remote sensing techniques in their research activities. As far as Grey literature batch is considered, a list of significant titles was built according to our experience and background, with a specific reference to the "Terminology" defined for the purposes of this study (see also Appendix A and B). Hence, Step 1 was further subdivided into Steps 1A and 1B to allow a separate, but parallel assessment of the two Batches.

- **Step 1A: Indexed literature assessment. (collection, decimation, definition)**

Collection: As a result of the Terminology definition, several combinations of keywords were applied on the scientific batch to perform the articles search (see Supplementary materials: List of scientific articles obtained through Scopus – Step 1A). The focus was placed on archaeological heritage monitored using satellite technologies, while six (6) different terms for damages were employed. The combinations were hence proposed as follows:

– "satellite" AND "heritage" AND "archaeology" AND "hazard"
– "satellite" AND "heritage" AND "archaeology" AND "disaster"
– "satellite" AND "heritage" AND "archaeology" AND "threat"
– "satellite" AND "heritage" AND "archaeology" AND "risk"
– "satellite" AND "heritage" AND "archaeology" AND "damage"
– "satellite" AND "heritage" AND "archaeology" AND "destruction"
– Such combinations have produced a total of 1966 relevant articles.

Decimation. The first list of papers was initially checked for double results by running an Automatic duplicate values removal (Excel©). This step was followed by a manual check for detecting duplicate missed by the automatic duplicate removal due to grammar or lexical errors that may have prevented their identification. This process led to an intermediate result of 849 single papers and 1117 duplicate.

Definition. To perform "Attribute definition", all articles were manually checked for categories "Title", "Authors Keywords" "Index Keyword" and "Abstract". In multiple cases, in order to be certain of the contents i.e., technology employed, or damage treated if any, the full-text of the papers has been consulted. Thanks to this procedure, 412 paper as matching the requirements. At the end of the process, all articles were "tagged" for: 1) type of heritage studied; 2) type of damage or damages studied on the illustrated case study; 3) type of technology or technologies employed for damage assessment and monitoring. Through this process, 102 papers were found to be not relevant for this survey, while 15 works were not in any way accessible to the authors, so they were not evaluated. The total number of articles selected for the statistics evaluation amounts to 295.

- **Step 1B: "Grey" literature assessment. (collection, decimation, definition)**

Collection: Unlike the indexed literature, there were neither national nor international repositories or catalogues to browse that provided access to the whole body of documents that heritage organisations and institutions, or practitioners have produced on the studied subject. This is intrinsic to the definition of "Grey Literature" (see section 2.2). The main categories of documents that were searched for included: guidance documents, standards, recommendations; organisation/institutional documentations; national plans; management plans; technical reports; non-indexed conference proceedings.

To put together the database to analyse, it was decided to run a semi-automatic document search guided by the operator's background knowledge. In practice, two main routes were followed. On one side, documents falling in the above categories were searched directly by browsing the institutional websites and publication repositories of the public heritage bodies of the European countries. The rationale was to search for evidence of the use of RS and EO by heritage institutions "directly from the source". The search was not restricted to central administrations only, but also encompassed regional to local administrations. Furthermore, to provide the most comprehensive picture, we considered texts published in different languages (English, Italian, Polish, German etc.).

For example, for Spain Ministerio de Cultura y Deporte - Gobierno de España and Instituto Andaluz del Patrimonio Histórico in Spain; for Italy the Italian Ministry of Culture and the Archaeological Park of Colosseum; for Germany the State Office for Cultural Heritage Management Baden-Württemberg. This choice was under the assumption that, depending on the specific governance and administrative hierarchy and associated roles and mission (that may vary from country to country), policy, guidance and technical documents may be issued at different levels. Therefore, the search aimed to be as much inclusive as possible.

On the other side, an automatic search by keywords (same combinations as per the indexed literature) was run through Google search engine. This route mainly enabled the collection of a body of technical reports and non-indexed conference proceedings.

For the period 2008 – 2022, the total amount of documents retrieved was up to 77 documents. As expected, these documents were found to be very heterogeneous in typology and content, and the technical terminology therein was quite diverse, even to mean the same type of RS or EO technology or damage or threat.

<u>Decimation.</u> Therefore, it was needed to run two tasks, i.e. tagging and indexing of the text and, afterwards, "skim-reading" and manual checks. In practice, the text of each document was screened to tag the technical terms (see also Appendix B) specifically related to: "Type of heritage", "Technology" and "Threats/factors/hazard". Each tagged term was recorded in its original form, alongside the number of its occurrences in the various sections of the document. The latter quantitative information was already indicative of the relevance to the scope of the present assessment. As mentioned in section 2.2., isolated textual occurrences without any clear evidence of dedicated narration or discussion were disregarded during the skim-reading task. This task required an in-depth reading of the documents so to contextualise the tagged terms and indexed text. At the end of this process, 19 documents were kept to input into the statistics evaluation.

<u>Definition.</u> Finally, to solve the terminology heterogeneity and make the Grey literature comparable with the indexed literature, the tagged terms were converted to match and fall within the terminology for RS technologies adopted in the present study (Figure 2) and UNESCO categories of factors affecting properties [24]. This step was also helpful to address the redundancy in the terms used within the same document. Although different terms are descriptive of different types of heritage or technology or threats, and thus express the variety of real-world conservation situations and the specifics of the employed technologies, for the purposes of this study their conversion to main common categories makes the assessment more effective, without compromising the key information. Appendix A reports an example of terms conversions and categorisation to explain the process.

2.3. Geographic framework of the sample selection

Our research considered all the countries studied by researchers affiliated to institutions in the European Union. Additionally, given the geographic horizon of the "grey" literature considered, the findings of the assessment relate to discovery, documentation, study, conservation and promotion of cultural heritage across Europe. This choice has been made for a number of reasons including the more coherent geographic area, the wider and more uniform exploitation of RS tools and methods across European countries as well as the greater coordination at continental level of initiatives (e.g. the Copernicus program) compared to other areas of the world, and lastly, the possibility of comparing results with all the previous literature assessments (two of which focused only on Europe, see Table 1).

As stressed by previous studies [4,6,12], although the use of RS and EO for archaeology and cultural heritage applications is older, it is from the early 2000s that we observe a more systematic use of satellite images, from both commercial providers, data license mechanisms or institutional agreements or freely accessible platforms. Therefore, we decided to focus our attention on the last two decades, specifically between 2000 and 2022.

3. Results

This section illustrates the results of the methodological **"Step 2 Correlating the two literature assessments".** Step 1 resulted in two distinct lists of scientific articles and Grey papers that were now referenced and tagged according to a common methodology. This gave a possibility to perform statistical enquiries on two lists separately, searching for possible trends and best practices to be further discussed.

3.1. Results of the literature assessment

3.1.1. Overview on the types of damages considered. Unbalanced concentration on specific types of hazards and regionalisms

The analysis of the indexed literature of academic studies on hazards affecting cultural heritage sites worldwide and performed between 2000 and 2021 by European institutions using remote sensing techniques revealed some important trends.

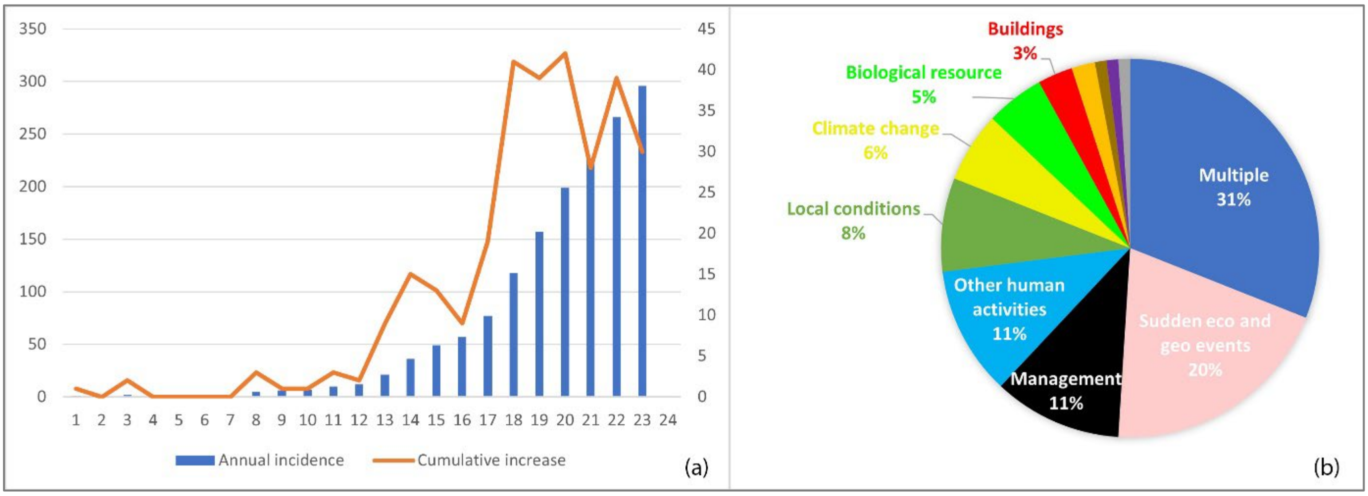

Figure 3. (a-b) Distribution of the studies between 2000 and 2022 (a, left) and percentage of the types of hazards mostly analyzed by the indexed literature, as defined according to UNESCO's official terminology (2010).

Figure 3a suggests that, from a quantitative point of view, the temporal evolution of the studies published over the last 20 years can be divided into four main phases. During the first six years of the new millennium (2000-2006), the application of remote sensing technologies for monitoring hazards to cultural heritage is almost absent in the scientific research catalogues that have been searched. Then, a growing interest emerges starting from 2007 (second phase) with an average of two studies per year. From 2012 to 2016 (third phase) the number of publications on this topic underwent a sharp increase, reaching an average of 15 publications per year. Then, in 2017 the scientific production in this field entered a fourth phase where the number of studies focusing on global damage to cultural heritage reached 40 per year, thus doubling the 2012-2016 trend.

However, when looking at the types of hazards considered in the published studies, we observe that the substantial increase of scientific literature associates with an uneven distribution with most of the publications focusing on some hazards only (Figure 3b). Indeed, while one third of the 295 publications considered in this paper (i.e. 98, accounting for 32.1%) tackled multiple hazards (i.e. often up to 10-15), those focusing on a single type chose only a selected number of them. For example, 'Sudden ecological and geological events', namely earthquakes, landslide and floods, represent the most investigated hazards by single-topic publications (58, 20.1%). 'Other human activities' (37, 12.5%) which is a broad and diverse category including conflict, looting and vandalism, together with 'Management activities' (34, 12.2%) follow quite closely. In this scenario it is noteworthy that certain UNESCO factors like 'Climate change', 'Pollution' or 'Physical resource extraction', which are currently on top of the agenda in other research sectors and beyond (i.e. the UN SDGs), found little space in the current debate around the main hazards affecting cultural heritage.

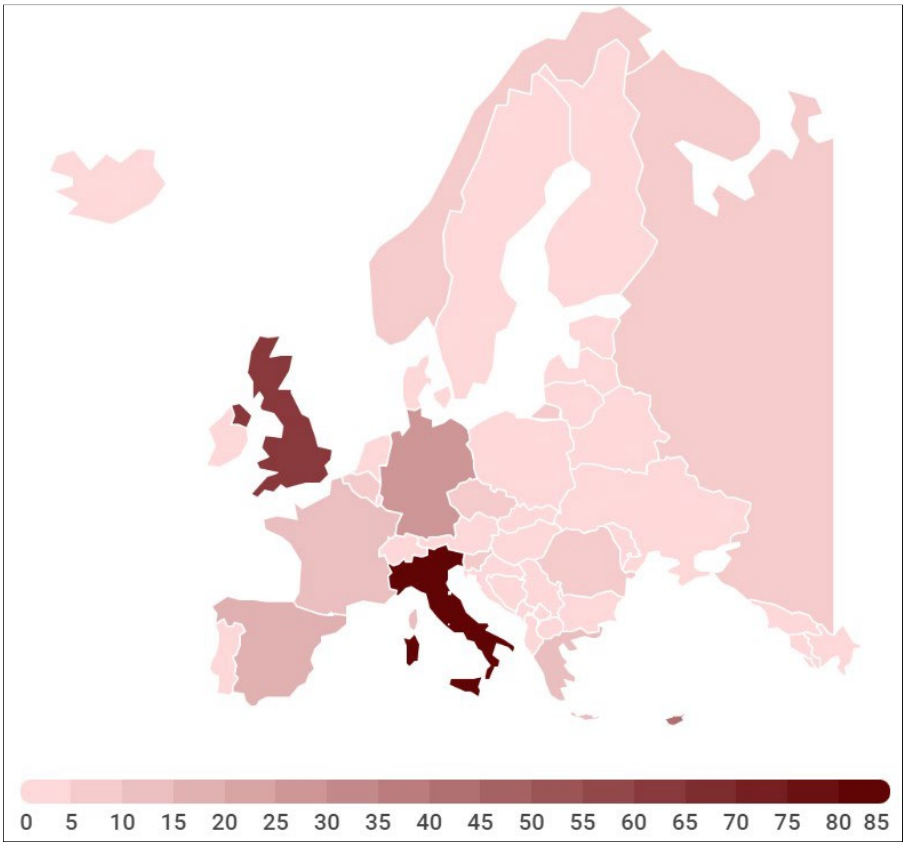

Figure 4. Map showing the geographical distribution in Europe of the researchers who authored the analyzed publications through the proxy of their declared affiliations.

The tendency of scientific research to focus on few hazard types is also confirmed by analyzing the temporal trend of publications. Since early 2000s publications mostly focused on ‘Sudden ecological and geological events’, ‘Management activities’ and ‘Other human activities’. Only Climate change registered a substantial increase from 2017, becoming the fourth macro-factor mostly investigated by the scientific literature.

The geographical location of the case studies from the 295 papers selected showed significant patterns (Figure 4). The findings show that, while around 21% (64) of the case studies took into consideration one or two countries, almost 50% (147) of case studies revolve around nine (9) of them (Figure 5). These include mostly European countries like Italy (37, 12.5%), Cyprus (28, 9.4%), Russia (8, 2.7%), Greece (9, 3%) and UK (9, 3%), although also few extra-European countries received extensive attention from EU scholars, as in the case of Peru (21, 7.1%), Egypt (15, 5%), Iraq (10, 3.3%) or Syria (10, 3.3%).

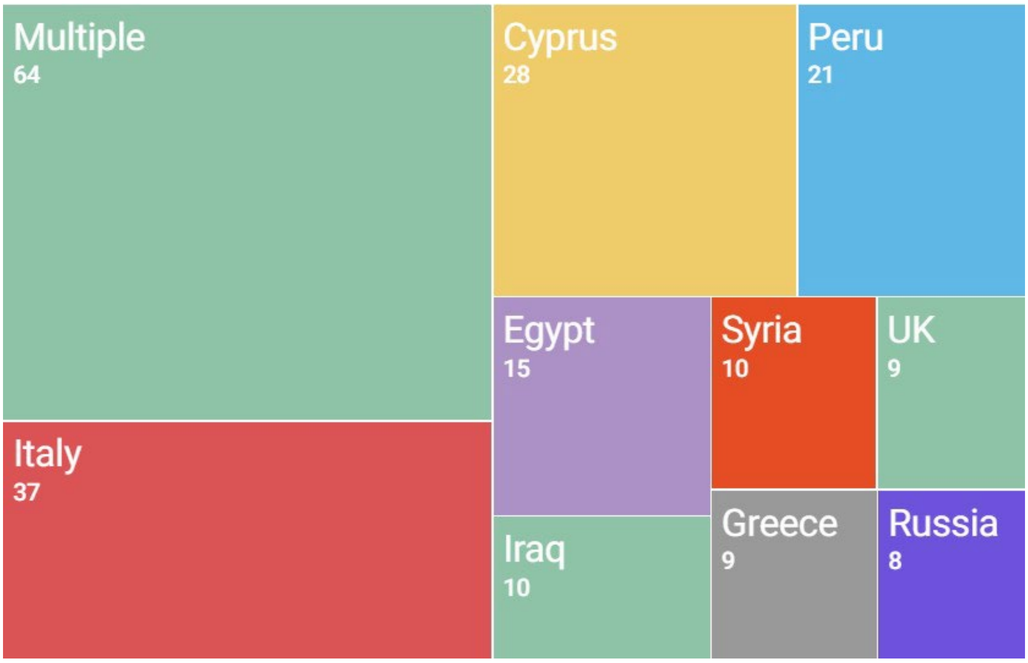

Figure 5. Tree-map of the geographical location of the case studies from the 295 papers selected.

Unlike for the Grey literature papers (paragraph 3.1.3) where the expertise of the authors are explicit, in the analysis of scientific literature, the presence of articles with multiple authors with different expertise and affiliations did not allow to perform analysis of the distribution by role/mission/function/type of authors' affiliation/organization that issued the analyzed documents, and by match with author's expertise.

3.1.2. Overview on the technology use in scientific literature. Focus on the articles relying on satellite remote sensing

When examining the use of geomatics technologies for monitoring of damages on cultural heritage, the progress in the use of satellite Remote Sensing technologies in Europe can be noticed. The trend observed regards articles relying not (only) on the visual interpretation of changes but on the processing of satellite-based data (in this section "satellite RS"). We notice that, in the last decade, there is an acceleration in scientific production; in particular, the two peaks that are very similar to analysis on "damage" factors (Figure 3), occurring in similar years, 2013 and 2017 (Figure 6a).

When observing closer into specific imagery of the specific space programs (Figure 6b), a steady trend of use of Landsat and, although variable, a still consistent presence of Corona imagery is noticed. It can be argued that these two satellite programs are by now "traditionally" used in the domain of cultural heritage monitoring.

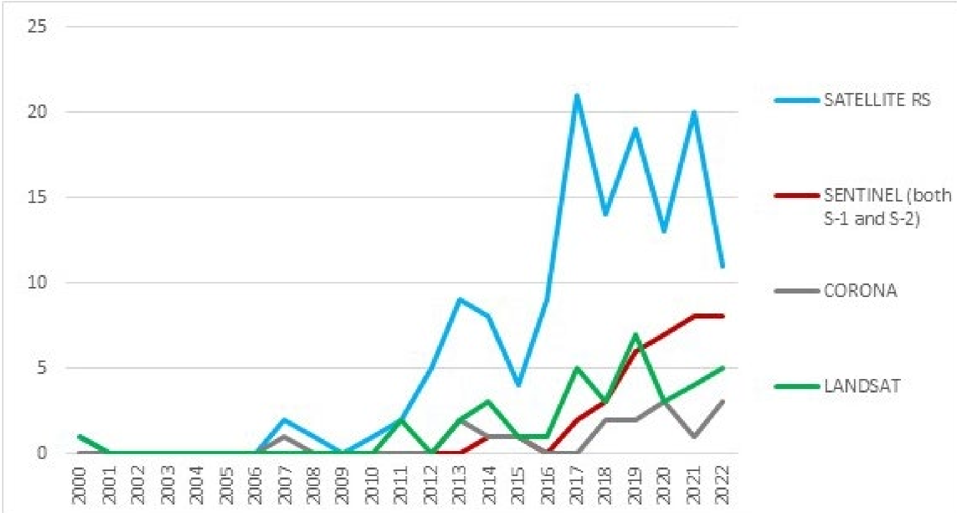

Figure 6. Articles relying on the use of satellite RS data processing for monitoring hazards and damage caused to CH: period since 2000 to 2022. Use of all types of satellite imagery and of satellite imagery considering the type of three satellite data/programs mainly used by CH community, namely Sentinel 1 and 2, CORONA and Landsat imagery.

As illustrated in Figure 7, what is on the rise is the employment of Sentinel imagery (here both S1 and S2 data), which is even more noticeable, if temporally contextualized. The first satellites of the Copernicus program were launched in April 2014 (Sentinel-1A) and June 2015 (Sentinel-2B). Shortly after, several scientific articles are already providing inputs of Sentinels' suitability for CH damage monitoring: already in 2014, authors from Cyprus propose an evaluation of S2 potentials [25], while some first examples on damage studies are provided for looting using SAR S1 imagery in 2015 [26] and for urban growth and land use changes using multi-spectral S2 imagery in 2017 [27].

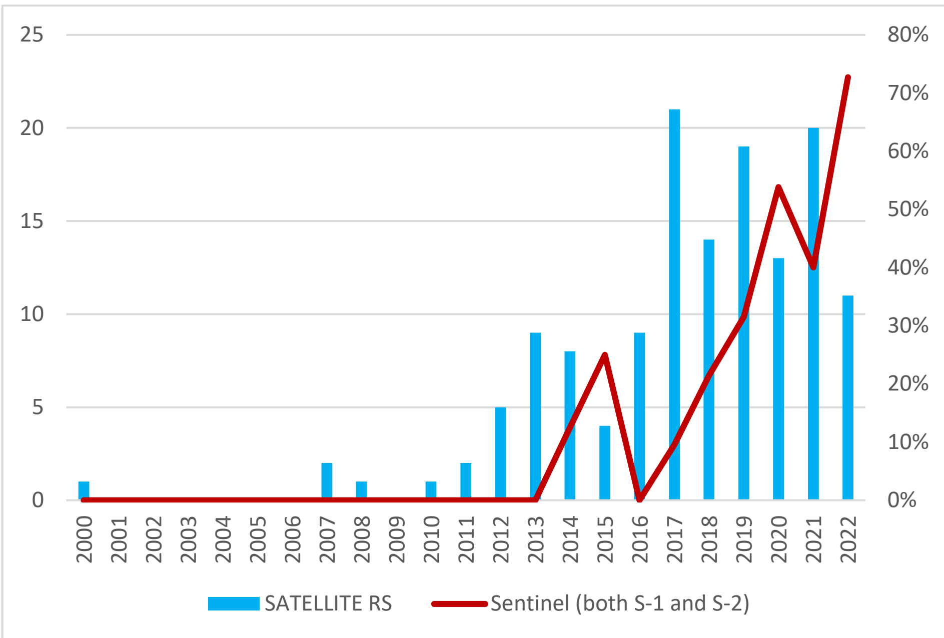

Figure 7. Percentage of articles using Sentinel data across the absolute number of papers relying on satellite RS data processing: period 2000 to 2022.

Further, it can be noticed that within the batch of articles relying on satellite image processing that increases, the percentage of articles employing Sentinel (either S1, S2, or both) is on the rise as well. For example, in 2022, 31 articles reported studies on the damages to cultural heritage. Eleven (11) of these articles were based on processing of satellite imagery, including 8 articles treating Sentinel imagery. In fact, while zero publications before 2014 are an obvious fact, an increase since a couple of years later was not necessarily expected. Hence, we could conclude that Full – Open – Free (FOF) policy and the technical properties seem to have made Copernicus satellite imagery extremely appealing and manageable data for monitoring of damages of cultural heritage, specifically for archaeological sites [28].

In addition, an interesting comparison was made between the articles tagged as "Satellite RS" i.e., articles that were based on the use of satellite image processing vs. those tagged as "Engine" i.e., articles based on consultation and visual interpretation of the satellite imagery (Figure 8). There is a significant peak in satellite imagery consultation using search engines in 2019, and again in 2022. The reason for this could be suggested in the new source of freely available information at a moderate spatial resolution of 10m terrain pixel i.e., Sentinel-2 data, available for consultation through various platforms (e.g., ESA's ones or those affiliated such as EO Browser; Google Earth Engine).

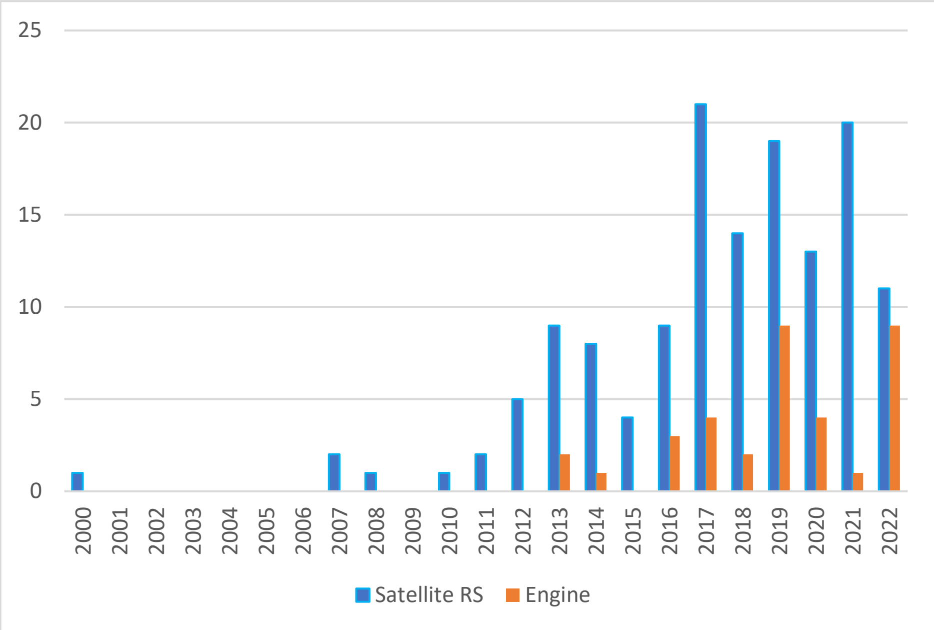

Figure 8. Number of scientific articles relying of satellite data processing (series "satellite RS") compared to the number of articles relying on visual interpretation of satellite imagery (series "Engine").

Looking closer into the employment of machine learning (Figure 9), it is noticed that, with respect to the total of satellite "Satellite RS"-tagged articles, such phenomena are still contained but present. Such an indication at the moment probably denotes a "niche" that could still be explored in the years to come.

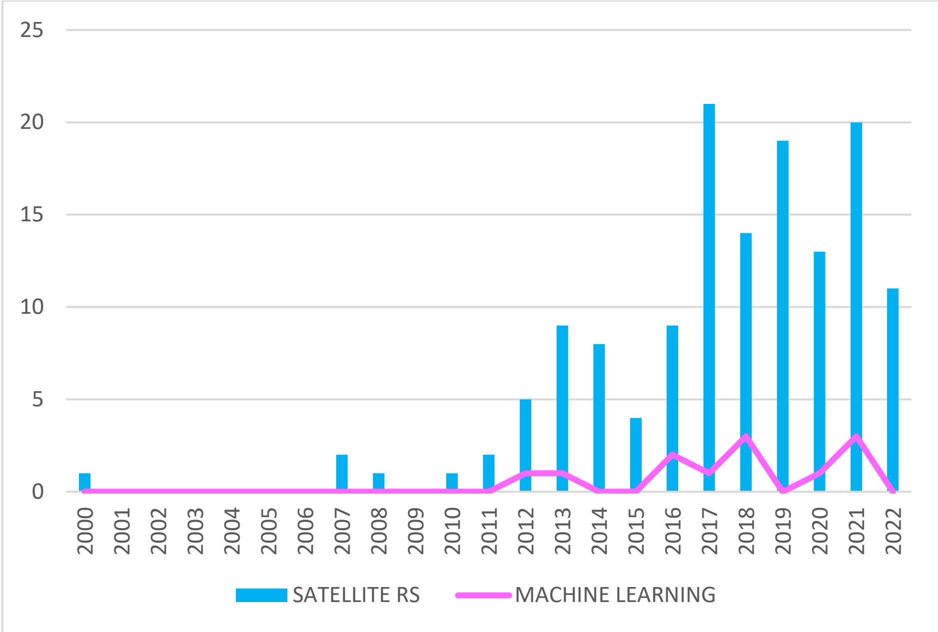

Figure 9. Number of articles using machine learning across the number of those relying on general satellite RS data processing: period 2000 to 2022.

The last inspection of the Step 2 regarded an analysis of other geomatics technologies disciplines used simultaneously with satellite imagery. Out of 295 papers studied, 140 papers describe using some kind of data processing conducted on satellite remote sensing ('Satellite RS') while 35 articles refer to visual inspection of satellite imagery using resource ('Engine'). With regard to 'Satellite RS' and the use of geomatics technologies, the absolute main technology macro-category is 'Geospatial information Environment' (26%), followed by several categories with almost equal distribution namely: 'Ground sensors" (9%) , 'Aerial (including UAV) photography' (9%) and 'Aerial (UAV) photogrammetry' (7%; Figure 10a). For 'Engine' category, 'Geospatial information Environment' also stays predominant for even 40% of cases, followed only by 'Aerial (including UAV) photography' in 29% of cases. Other, more technically specific technologies like 'Ground sensors" and Aerial (UAV) photogrammetry account for lower percentages, respectively 6% and 9% that is to say 2 and 3 articles (Figure 10b).

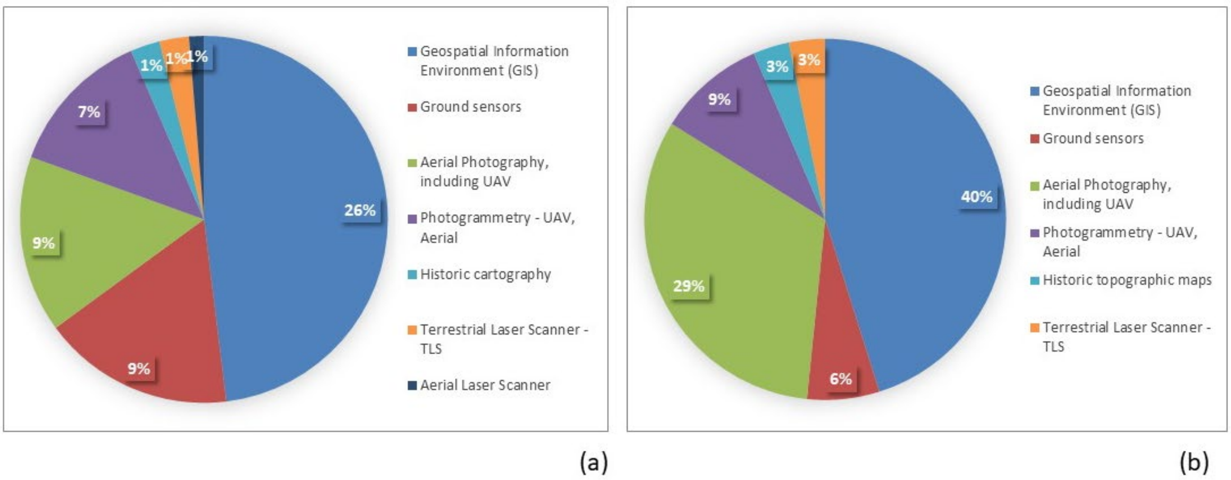

Figure 10. Inspection in use of other technologies simultaneously with satellite remote sensing imagery when (a) satellite data processing is involved ("Satellite RS") and (b) satellite imagery is consulted for visual inspection ("Engine").

3.1.3. Grey Literature

Figure 11 shows the distribution of the analyzed Grey literature accounting for the following two parameters:

1. 'authors' expertise' as inferred from the 'affiliation's discipline', i.e., the main field of the department/institution/organization/body which the authors are affiliated with. In absence of personal information about the specific expertise of each individual author that could be known exclusively from their curriculum vitae (which was not available for this research and, however, is beyond the remit of the present study), we could only rely on the reasonable assumption that who compiled the analyzed documents had an expertise fitting with the main field of their organizations and/or that the described activities implied that the authors had the needed expertise (or a matching one). Therefore, with appropriate care, the affiliation's discipline can be used as a proxy. The found classes encompass: Archaeology; Cultural Heritage; Remote Sensing; GIS; Geo-information; Information and Communication Technologies (ICT); and Archive, with the latter meaning building, curation and management of archives.
2. Role/mission/function/type of authors' affiliation/organization as per their official statutory duties. The found classes encompass: Institutional/public authority; Research body; Foundation; Academic/University/Higher Education; Private company.

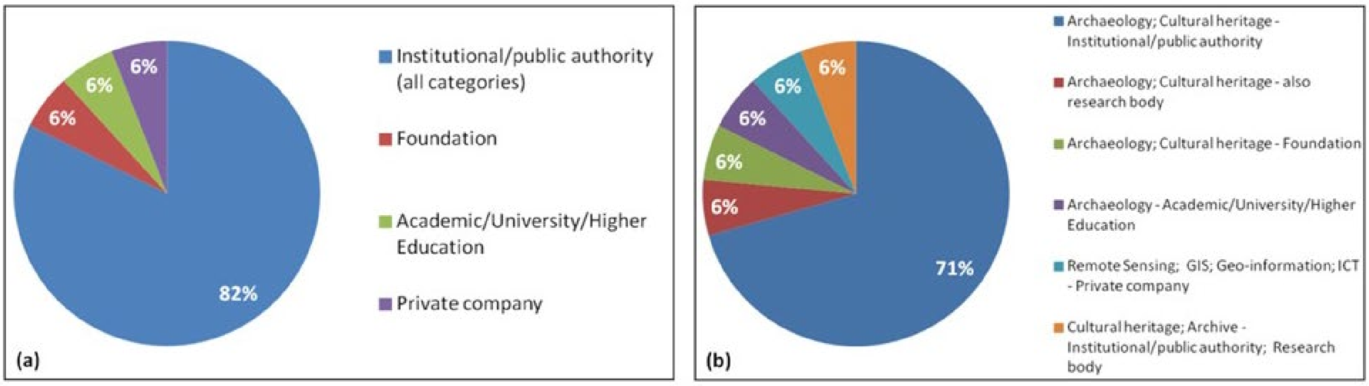

Figure 11. Distribution of Grey literature by (a) role/mission/function/type of authors' affiliation/organization that issued the analyzed documents, and by (b) match with author's expertise.

The main conclusion is that the relative percentage distribution in Figure 11a reflects the type of searched documents (namely guidance documents, standards, recommendations; organisation/institutional documentations; national plans; management plans; technical reports; non-indexed conference proceedings) and, thus, the type of organizations that, due to statutory duties, are expected to issue these documents. Therefore, it does not surprise that the majority of the Grey literature documents are issued by institutional/public authorities (82%), i.e., the bodies that in the hierarchy of heritage governance are those typically in charge of heritage preservation (Figure 11a). Curiously, the analyzed Grey literature shows an equal distribution between Foundations, Academic/University/Higher Education, and Private companies (6% each).

If the two above parameters are jointly analysed with no aggregation (Figure 11b), it can be found that no distinction between Archaeology & Cultural Heritage applies to Institutional / public authority and Foundation. This result means that the issuing bodies indistinctively operate across the typologies of heritage and their documents do not necessarily refer to a preferential scope e.g., archaeological investigation as opposed to heritage preservation, but often address manifold purposes. On the contrary, documents issued by authors affiliated to Academic/University/Higher Education seem to highlight more specialization towards archaeological disciplines and topics. Finally, the documents that were contributed to by private companies embed an explicit ITC expertise brought by the commercial professionals collaborating with academia and/or public authorities.

With regard to RS and geomatic technologies, the three main technology macro-categories in the analyzed Grey literature are, in order: 'Geo-spatial information' (23%), 'Photography' (17%) and 'Satellite Remote Sensing' (17%; Figure 12).

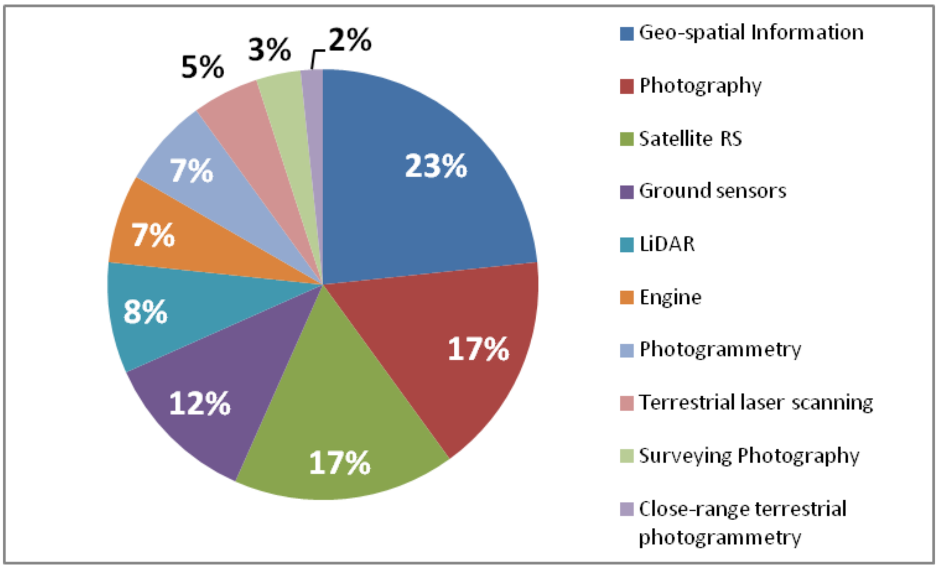

Figure 12. Distribution of Grey literature by technology macro-categories as defined in Figure 2.

Being the first macro-category, 'Geo-spatial information' suggests a cross-cutting awareness among heritage bodies of the importance of skills in capture, storage, analysis, and use of spatially referenced information to support ordinary duties such as documentation, diagnosis and inventorying of cultural heritage, condition reporting and hazard assessment. This comes out very clearly from the detailed analysis of the tagged texts. Except for 7% of the total occurrences when the macro-category 'Geo-spatial information' is not associated to a specific technology, technique of data capture/handling or type of activity falling within the sub-categories reported in Figure 2, Grey literature documents explicitly refer to 'databasing' (11%), 'GIS' (7%), 'georeferencing' (4%) (Figure 13), 'GPS' (3%), 'ground sensors' (2%), 'webGIS' (1%), 'geophysics' (1%) and 'GPR' (1%).

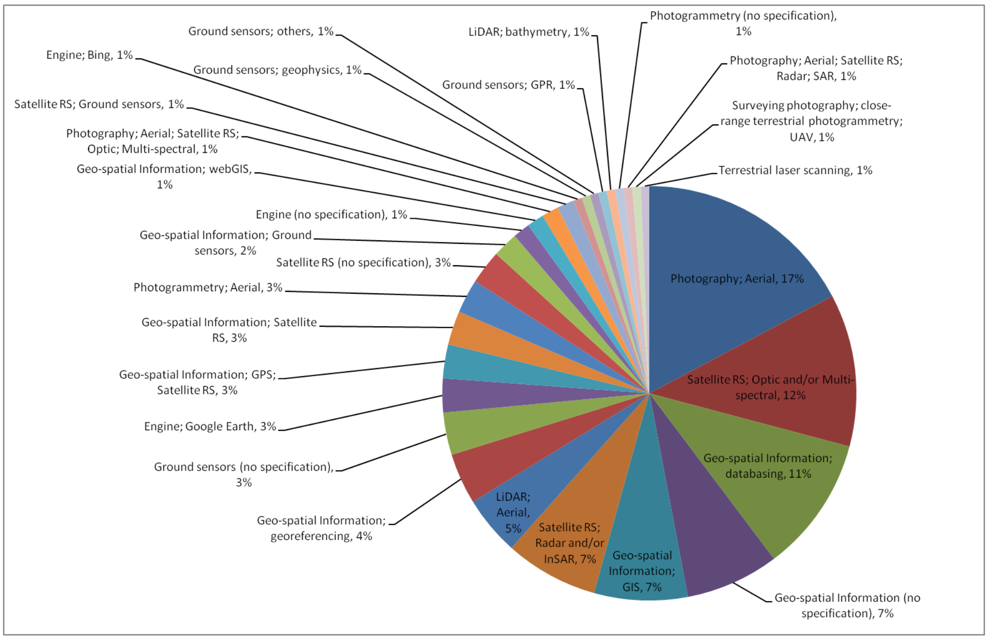

Figure 13. Distribution of Grey literature by combination of technology macro-categories and sub-categories as defined in Figure 2.

For example, in the Historic England Aerial Investigation and Mapping (formerly National Mapping Programme) Standards Technical Review [29] the use of GIS is acknowledged for *"increasing sophistication and efficiency in gathering information, recording, sharing data, and comparative analyses"*. Furthermore, among the collected feedback, users highlighted that Historic Environment Record (HER) is *"an extraordinary resource available in a format that is easily usable in GIS platforms"*. This evidence reassures about the impact that heritage collections and databases compiled in a way that geolocated and spatial information can be extracted and handled in GIS are advantageous, not only for the officers themselves to undertake their daily work, but also for dissemination to and further exploitation by the user community. This functionality provided by GIS also enables the exploitation of other type of RS data. For example, the footprint of aerial photography is recorded within GIS, so the full geographic extent of the available scenes is known. Not to forget that GIS and its processing functions are very helpful for digitalization, post-processing, precise positioning and distortion correction of old photographs and historic maps.

Reading through the tagged and indexed texts, it is apparent how common the use of GIS is nowadays across European heritage organizations and bodies, up to the point that specific guidance documents and technical recommendations, albeit issued in different countries, show several commonalities in illustrating how to use this geospatial technology. For example, in its technical recommendations [30] the Instituto Andaluz del Patrimonio Histórico (2011) provided detailed instructions on how to undertake documentation process, select the geodetic reference system, implement the correct way for geospatial and geolocation data capture, georeferencing, representation geometries, archiving formats, and check metadata quality. The overall aim is to establish a normalized protocol for processing cartographic documentation of heritage, to be used to build registers and inventories. Such programmatic objective and technical guidance to achieve it are echoed in the Spanish National Emergency Risk Management Plan for Cultural Heritage [31], wherein generation of the geo-referenced cartographic inventory of assets of cultural interest is among the responsibilities of the Management Group belonging to the Emergency and Risk Management Unit of the Ministry of Education, Culture and Sport. This national document states that *"the generation of Cultural Heritage Risk Maps requires the promotion of documentation programmes in the various autonomous regions of Spain, with the aim of geo-referencing all movable and immovable cultural assets, in all categories, along with other assets which, although they might not be classified as such, represent a distinct value in terms of identity, emotion or evocative meaning for a particular community of citizens"*.

When space technologies are explicitly mentioned, GPS is the most cited satellite-based positioning system. However, in some documents other constellations are also mentioned and described such as the Russian system GLONASS, the European system Galileo and the Chinese system BeiDou, as well as the Global Navigation Satellite System (GNSS) and more generally navigation (NAV) technologies (see e.g., the technical recommendation by the Instituto Andaluz del Patrimonio Histórico, 2011 and the guidance published by Historic Environment Scotland, 2018) [30,32]. This evidence would suggest that these technologies are adopted in heritage documentation practice.

Finally, GIS, georeferencing and more generally geo-spatial information are considered crucial also for planning purposes, and to deal with the pressure due to modern development. For example, in its review of aerial archaeology in Ireland for the Heritage Council [33], Lambrick (2008) recommends that *"further development of mapping (rectification, transcription, image enhancement and integration with terrain models) should be encouraged, and a strategy developed for strategic mapping of the results of aerial reconnaissance in areas under pressure of development, especially where subject to Strategic Environmental Assessment (SEA)"*. Undertaking GIS-based mapping of existing and new imagery of sites is necessary in particular in the areas under significant pressure of development or other land-use change. This specification is interesting given that development and land conversion are among the first sources of concern for heritage bodies (see below results).

Regarding the second-ranked technology macro-category, i.e., 'Photography', the analysis of the sub-categories highlights the predominance of 'Aerial' photography (17%; Figure 13). This outcome does not surprise given the well-known long-standing tradition of aerial reconnaissance and mapping archaeological features by archaeologists. This, in turn, explains the reason by which aerial photograph collections are nowadays valuable historic resources for users and, to be stored and accessed effectively, various initiatives for digitalization as geo-spatial information have been launched by heritage institutions in different countries (see above for the evidence of the association between 'Geo-spatial information' and 'Photography').

On the contrary, 'Surveying photography' and documentation from 'Close-range terrestrial photogrammetry' and 'UAV' are much less represented in the analyzed Grey literature, both when aggregation is made by macro-category and individual sub-categories are detailed (Figures 12-13). In the case of 'UAV' this low representation is explained by the drone technology being relatively new still being experimented (mostly by academia and commercial sector). In addition, it is important to mention that licensing can be an issue for a systemic uptake of drone use, especially in emergency situation. In that reference, it is only since 2019 that there are some shared instructions at European level provided by European Union Aviation Safety Agency (EASA) [34] which can be further refined on national level. All these factors contribute to the fact that UAVs have not been fully embedded yet in the common practice by heritage bodies and organizations. Instead, the low statistics found for 'Surveying photography' and 'Close-range terrestrial photogrammetry' need to be better contextualized. Proximity and terrestrial RS measurements are indeed quite spread in the Grey literature, with 'Ground sensors' counting to 12%, 'Photogrammetry' 7%, and 'Terrestrial laser scanning' 5%. These percentages would therefore contrast with those found at sub-categories level. The hypothesis is that this outcome could an effect of the diversity in specific terminology used in the analyzed texts. So, in reality, the representation would be much higher than the above statistics would show. Indeed, the careful reading of the indexed texts highlights that overall, despite the specific terminology used, a wide variety of technologies are currently known and employed in the heritage practice.

Regarding 'Satellite Remote Sensing' ranking third among macro-categories (17%, Figure 12), it is worth noting that it ranks second when technology sub-categories are accounted for (12%, Figure 13). In particular, the latter percentage refers to the use of 'Optic and/or multi-spectral' satellite images that predominates on the use of 'Radar and/or InSAR' data (7%, Figure 13). This outcome aligns with similar observations reported in previous reviews [4] and confirms the general consensus that archaeologists, heritage scientists, practitioners and heritage officers are much more acquainted with data collected in the optical portion of the spectrum. Insights into whether these statistics correspond to an actual use of satellite data in the daily practice are provided in the discussion (see Sec. 4).

In the Grey literature RS and geomatic technologies are described in relation to a broad spectrum of threats and factors affecting the properties that in the present research are analysed as per the definition complying with the UNESCO's lexicon. Figure 14 shows the distribution of threats and factors, from which it is clear that in the Grey literature there is a no predominant factor or a group of factors significantly distancing the others. This is a substantial difference from the situation observed in the scientific literature (cf. Figure 3b). In particular, the statistics suggest that the first sources of concern include: human actions; impacts due to modern development; agriculture and use of natural resources. These are followed by: climate and severe weather events and their cascading processes such as flooding, desertification, changes in weather parameters (e.g., temperature, pH); factors related to maintenance and management of site.

Some caution should be paid in the interpretation of the lower ranking of 'Local conditions affecting physical fabric' (6%) – which include erosion, weathering, rain, water table rise, micro-organisms. These threat factors, which are highly relevant for ordinary maintenance and conservation, are mostly addressed by heritage bodies and organizations by means of other types of technologies than those of interest in the present research and, for sure, than the top-ranked macro-categories (see Figure 12).

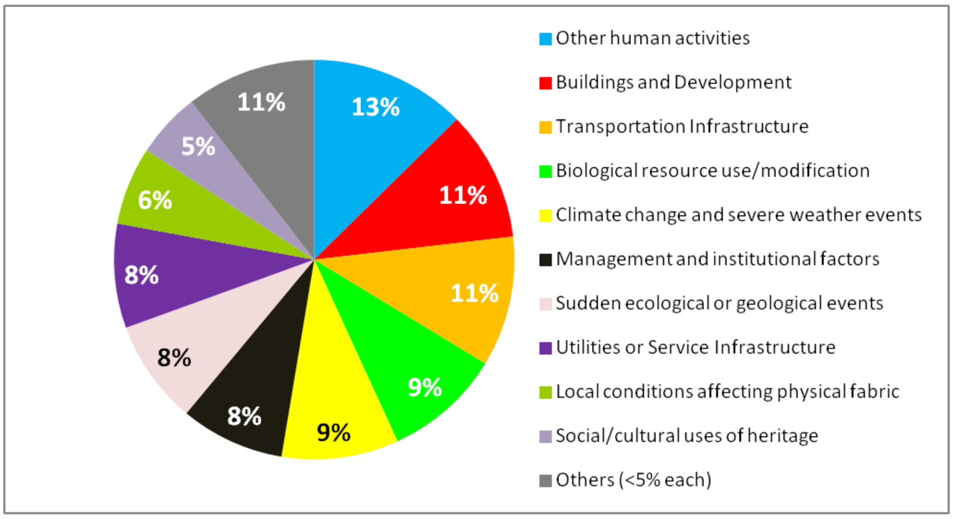

Figure 14. Distribution of Grey literature by hazards and damage factors as defined according to UNESCO's lexicon [24]. For the sake of visualization, "Others" category aggregates factors that account for less than 5% each.

A temporal analysis of the Grey literature highlights that the threats that appear to be the first sources of concern (see above), as well as climate and severe weather events, are consistently present through time (Figure 15). No specific trend is observed. These statistics reflect that the analyzed documents mostly cover more than one factor. The key evidence then is the confirmation of the plurality of threats that heritage bodies and organizations need to account for and mitigate. Therefore, diverse factors are addressed by different RS and geomatic techniques, depending on their technical specifics and proved capabilities.

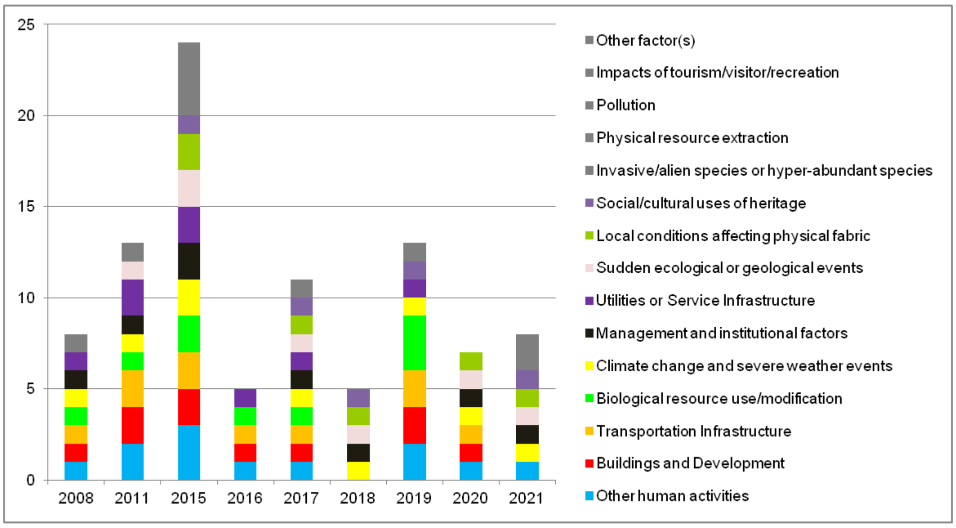

Figure 15. Temporal distribution of hazards and damage factors as defined according to UNESCO's lexicon (citation), in the analysed Grey literature. Factors accounting for less than 5% each (cf. Figure 14) are all grey-colored.

Finally, with specific regard to 'Satellite Remote Sensing', the majority of Grey literature documents refer generically to 'satellite images/imagery' to mention Earth Observation data. Nevertheless, some exceptions are to be noted. The most cited Earth Observation imagery encompass those collected from commercial very high-resolution missions such as Quickbird, IKONOS, GeoEye-1, WorldView, as well as from satellite constellations such as Pleiades and SPOT [33, 35]. In one instance, Landsat ETM and ASTER are mentioned [33]. As expected, mentions of Copernicus data are found only in documents issued after 2014 [36, 37] , but the number of explicit citations in the analysed body of Grey literature is less than 11%.

4. Discussion on the results analysis: first findings on trends and best practices.

This section refers to the "STEP 3. First findings resulted in analysis of the trends and best practices" based on the results presented in Section 3. The solid base obtained allowed to highlight similarities and discrepancies between the two literature assessments, keeping in mind the differences in nature of analyzed documents, size and level of detail of the two analyses. With this final exercise, we tried to identify possible gaps to be filled and to propose some ad-hoc instruments that could allow further in-depth analysis.

4.1. Main findings for the scientific literature sample

In the past few decades, ordinary management has become one of the fields of application where not only RS and geomatics, but also non-invasive diagnostics of cultural heritage has proved to be of interest to public and private heritage protection bodies in support of conservation procedures. In support to this finding, we identify the suggestions for an overall non-invasive approach also from the cultural heritage community itself, that is to say the requests established by Valetta convention of 1995. Over the years there has been quite transversal evidence of such employment of such practices across Europe, from Italy to Spain, from Poland to the United Kingdom.

The community of geological sciences is one of the first that historically had the need to monitor important environmental phenomena on territorial scale, and hence the access to satellite remote sensing information for civil purposes. In fact, US Landsat program and European Global Monitoring for Environment and Security GMES program were planned for monitoring of the environmental changes and their possible impact of the society as a whole. It is in this context that several communities have historically been interested in applications on cultural heritage. This interest has translated into an increasing use of RS and EO techniques to document and monitor Sudden ecological and geological events, such as earthquakes, floodings or fires. This is well visible in our analysis with the corresponding UNESCO primary factor being the second most considered over the last 20 years.

As a result, one of the first to reach a maturity in the use of satellite RS for cultural heritage, to the point of publishing results and use cases with a certain temporal continuity, is the community of geological sciences focused on damage assessment, followed by the geomatics technologies sector focused on the geometric documentation and change monitoring. Evidence for this is reflected in studies reported at European level on the use of satellite data for geohazards in cultural heritage sites [13].

Furthermore, it has been identified that, during monitoring of hazards to cultural heritage, quite a few geomatics technologies are used simultaneously with satellite imagery, be it by the remote sensing specialists, by heritage experts or both. Suggestion for this can be found in our analysis of additional technologies used simultaneously with satellite imagery for both "Satellite RS" and "Engine" technologies (shown in Figure 10). It can be noticed that in both cases geospatial framework (in terms of GIS environments for different purposes) is the predominant choice for data integration. This only indicate the most recent trends in EO domain to link even more closely the remote sensing imagery processing with geospatial information world, with examples that can be found in addressing user communities like the Copernicus user uptake within EO4GEO [16] or more official legislative instruments such as Open Data Directive tackling public sector information (a successor to PSI Directive) [38].

Furthermore, another technological category common to both uses of satellite imagery is aerial photography, especially the branch increasingly relying on UAV-born imagery. This could be explained by the fact that UAV devices, and the licenses needed to pilot them, have had an increasingly more accessible costs comparing to the same technology a few years ago, or even more so, comparing to the photogrammetry depending on airplane flights. Similar consideration can be made for UAV-photogrammetry as well: because commercial software with robust algorithms for stereo-models and orthophoto production have stable costs and ever improving user-friendly interfaces, UAV photogrammetry is increasingly being used by non-geomatics experts.

'Ground sensors' category seems to be making a more substantial difference in simultaneous use with remote sensing imagery: while this kind of sensors are used only in two cases employing "Engine" modality, it amounts for almost 10% of use, with "Satellite RS" modality. Such behavior indicates that 'Ground sensors' are still more employed when processing of satellite imagery is required, often to complement such statistical analysis or to serve as ground-truth for satellite imagery calibration [39, 40]. Additionally, often the cost of employment of Ground sensors such as spectrometers or Ground Penetration Radar (GPR) together with RS expertise requires larger collaboration frameworks e.g. specific dedicated projects [41-44].

The growing interest of the scientific community in using satellite imagery to study 'Other human activities' factor (e.g., conflict, looting etc.) can be explained in relation to the media attention that recent events such as wars and collateral damage have received in multiple countries worldwide [45,46]. The reason for this can be found in the fact that for specific events such as armed conflicts, the employment of remotely acquired high and medium-resolution satellite imagery was often the only way of establishing that the damage has occurred and, hence evaluating its extent. As a result, this has probably encouraged the scientific community to deal with other types of "human activities" also occurring in times of non-crisis (e.g.. looting). However, this does not necessarily constitute a temporal association between events and studies, as observed in recent studies [4].

As already mentioned, what remains surprising is the almost absent analysis of the impact of large-scale damage such as Buildings and development, Transportation infrastructure, and biological resource use/modification (e.g., agriculture). Indeed, these factors represent a daily threat to cultural heritage if not adequately regulated. This is confirmed by the growing number of reports issued by national and international institutions and NGOs including UNESCO, ICCROM and ICOMOS. Furthermore, they can be easily documented and monitored thanks to RS and EO technologies [47– 49].

With reference to the geographical distribution of affiliations, it is not surprising that the four (4) most represented countries (Italy, UK, Cyprus, Germany) are also among the European countries that exhibit most of the following characteristics: (i) Long heritage conservation history (e.g. dedicated regulations and public facilities responsible for conservation); (ii) Research centers, institutes, universities and a national scientific community with well-known heritage related expertise (also able to attract researchers of different nationalities and developing new technological solutions); (iii) High exposure to different risk factors given the geo-topographic and territorial conformation (e.g. a number of case studies of Italy and Cyprus).

4.2. Main findings for the Grey Literature sample

The statistics related to Grey Literature showed in Section 3.1.3 can help to achieve an understanding of the current state in the use of RS and geomatic technologies across Europe if a careful reading of the indexed texts is also undertaken. While the found numbers reassure that 'Photography' and 'Satellite Remote Sensing' are increasingly established technologies – and in particular the use of 'Aerial' and 'Optic and/or multi-spectral' data, respectively –, there are however some considerations to make to highlight commonalities and differences across the analysed documents, and thus across the European countries.

4.2.1. Aerial Photography: commonalities and regionalisms

With regard to 'Aerial Photography', the use of aerial documentation, either vertical or oblique, from either historical collections or new surveys, is fairly common to northern (e.g. England, Scotland, Ireland, Denmark), central (e.g. Germany, Poland) and southern (e.g. Italy, Spain) European countries. Nevertheless, it is to be noted that detailed discussion of the different typologies of aerial photographs, and how to undertake photointerpretation, is found only in the Grey literature documents that are issued by heritage bodies and organisations that have an established technical expertise and/or in-house services or departments for collection, storage, processing and dissemination of aerial photographs. For example, all the documents issued in the northern countries included in the analysed sample fall in this category. Instead, more generic mentions are found in the other documents analysed.

In some instances, documents include technical considerations that highlight a higher level of awareness, by users and practitioners, of imagery that is collected in other wavelengths of the electromagnetic spectrum than the mere visible bands. For instance – albeit referred to satellite imagery, but the concept is basically applicable to aerial photographs too –, the Short Guide on applied digital documentation in the historic environment [32] issued by Historic Environment Scotland (2018) mentions the existence of multispectral sensors including additional infrared bands that "*can provide further information about the surface captured, identifying otherwise hidden features, helping to 'classify' areas (e.g. as urban, water or vegetation) and even showing emitted thermal radiation*". More detailed is the discussion dedicated by Lambrick [33] who highlighted the sensitivity of the infrared portion of the spectrum to changes in vegetation, and the consequent benefits for detection of subsoil archaeological remains. The author also recalled that *"the infrared spectrum has been shown to be particularly useful in identifying and interpreting coastal features and assessing vegetation type and health (a stronger red/orange hue is related to vegetation health and growth)"*. However, in [33] the author also acknowledged that, at that time, infrared imagery was not used very commonly. While this statement may seem nowadays to be obsolete given the time-lapse from when the document was published, it actually finds matching evidence in the fact that very few of the Grey literature documents explicitly mention infrared aerial photographs. Even less is the interest in thermal imagery. Again, among the analyzed Grey literature, Lambrick is the sole author to comment on the usefulness of thermal imagery for archaeological applications [33].

Therefore, the final impression is that, apart from some exceptions (particularly when the level of available technical expertise is highly specialist), the use of aerial photography is mostly confined to imagery collected in the visible and, secondarily, in the near-infrared bands.

One potential limitation that may occur if only technical recommendations and guidance documents are analyzed, is that such Grey literature is by definition programmatic. Therefore, it does not necessarily provide sufficient evidence that the best practices and technologies recommended therein are effectively implemented and followed by practitioners and officers, and thus exploited in the daily practice. In this respect, better evidence can be found in the management plans. For example, the Management Plan of the UNESCO World Heritage List Archaeological Area and the Patriarchal Basilica of Aquileia [50] explicitly lists photointerpretation of aerial photographs (either already available or collected on purposes) among the operations needed to prepare the required documentation to implement the safeguarding of areas of archaeological interest. In particular, photointerpretation is used to detect anomalies and thus characterize the 'archaeological risk', i.e., the likelihood that buried archaeological remains are present in the landscape and may be exposed to threats such as development and anthropogenic activities.

Similar evidence is found in other documents, e.g., from other locations in Italy and Spain, to corroborate the hypothesis that commonalities can be found across at least some of the European countries. This, however, does not ensure that regional differences may be present and in some other countries the situation could be more uneven across the respective national archaeological and heritage communities. This seems to have been the case of Poland. In [51], Rączkowski reported that, *"despite the presence of aerial photographs in Polish archaeology since the 1920s and 1930s, it is still not present in the consciousness of archaeologists as an effective method of uncovering the past. Very often the role of aerial photographs is simplified to an illustration of the location or presentation of the geographic terrain. […] As a* *result, even though the AZP programme* [i.e., the Polish Archaeological Record] *foresaw the use of aerial photographs this has never actually happened in practice* [52]".

4.2.2. Satellite Remote Sensing

Same situation seems to have applied to 'Satellite Remote Sensing', given that the same author [51] also reported that in Poland *"satellite images are known only via Google Earth™ and are not deemed to be especially useful"*. Most of the users limited *"their understanding of the data to the observational level and consequently their expectations are mostly intuitive"* and, as a consequence, for years there was *"a lack of deeper understanding of the potential and limitations of remote sensing methods and data"* [35]. A proof that the situation is anyway gradually evolving, and the national community may be quite diverse in the adopted methodological approaches and technological maturity can be found in recent publications wherein satellite RS data have been used in support to heritage management [53].

With respect to the degree of users' uptake of 'Satellite Remote Sensing' and the embedding in their daily workflows, the same limitation as the one described above for 'Aerial Photography' applies to the technical recommendations and guidance documents that were analyzed. However, some documents are quite informative, also to understand the barriers that users perceive as an obstacle to access and use satellite data. For example, in [29] Evans states that as of 2019 satellite images were not used in the Aerial Investigation and Mapping (AI&M) projects carried out by Historic England (and its predecessors). The author highlights, in order, the following barriers: spatial resolution, image purchase cost, and challenges in collecting cloud-free images. It is therefore evident that the author is exclusively referring to very high-resolution satellite images collected in the visible bands. Evans [29] acknowledges that *"the key advantage of satellite data, over and above the possibility of capturing data over very large areas at any given time, is the fact that most of the recent satellites possess sensors beyond the visible spectrum"* and envisions the potential to use multispectral imagery to detect cropmarks. Nevertheless, the conclusive remark is that, even if satellite imagery were *"incorporated into AI&M projects in the future […], this will require an assessment of the cost and time outlay compared with the usefulness of this source […] and a degree of training"*. This end-user perspective is highly interesting, given that it echoes similar considerations that are found across several scientific papers published by archaeologists and heritage professionals [54, 55, 56]. Furthermore, the above barriers and actions that are supposed to facilitate an effective user uptake substantially match with those that previous review papers have highlighted [4, 6, 11,12].

In this respect, another enabling mechanism towards user uptake of satellite and geomatic technologies is multi-disciplinary collaboration. The analysis of the Grey Literature proves the role that experimentations and technological transfer may play, especially when heritage bodies are receptive to (new) technological solutions. A demonstrative example is provided by the Archaeological Park of Colosseum in Rome. As reported in its dissemination publications [36,37], the Park implemented a dedicated program of satellite InSAR monitoring to combine with the in-situ network of diagnostic instrumentations to assess the condition of monuments and archaeological structures and, based on this information, plan maintenance and restoration activities. The InSAR deformation measurements showing either stability or motions of the monitored structures were included in the Web App system, namely SyPEAH, that was developed by the Archaeological Park itself as a tool for an effective activity of programmed conservation of cultural heritage [57]. Not surprisingly, this successful experience of advanced satellite technology that are fully embedded in the end-user workflow is found in a heritage site like the central archaeological of Rome, where since 2008 experimentations with satellite RS have been undertaken in the framework of close collaborations between the heritage authorities and the national academia. The latter, indeed, acted as the technological champion facilitating the conduction of the experimentations and the technological transfer process [58]. The fact that similar evidence is found for other Italian sites including Pompeii World Heritage Site [59], and that the experience at the Archaeological Park is paving the way for the setting of a national plan towards a multi-sensor monitoring system also including satellite RS [37], enhances how Italy is among the European countries at the forefront in this field.

4.2.3. Trends in heritage practice

The above use cases and situations revolve around specific types of applications, given the match that is established between the specifics of the single or multiple technologies used, the observables/measurable parameters and properties, and the given hazards or damage factors to address. Therefore, according to this rationale, for instance: photo-interpretation of old and recent aerial photography is exploited for discovering and inventorying buried sites; InSAR satellite RS is searched for by users to monitor structural deformation and characterize the impact due to 'Sudden ecological or geological events' such as ground motions, landslides, impact of local tectonic; change detection based on optical imagery is suitable for monitoring (and potentially preventing) new urban development and infrastructure construction that may affect landscapes with known archaeological potential.

Nevertheless, the analysis of the Grey literature has not highlighted a predominant factor or a group of factors that are more addressed with RS and geomatic techniques than others. One of the reasons that can plausibly explain this apparently contrasting evidence with the scientific literature is the diversity in mission, scope and type of activities between academia and heritage bodies. Almost 70% of scientific research (and thus scientific papers) focuses on one (or up to 3-4) topic, whereas the institutional duty of safeguarding and preserving heritage implies that a plurality of threats and factors of potential damage needs to be addressed. While on one side the specificity of the sites or monuments may emphasize a series of threats (e.g., coastal sites may be more exposed to erosion, flooding, impacts due to climate as opposed to inland urban monuments that may be more exposed to pollution, weed vegetation, vandalism, graffiti), on the other side it is very likely that different sites, monuments, landscapes share similar threats. Not to forget that key duties of site managers (e.g., management, protection from human activities and interactions with surrounding natural environment and weather conditions) are definitely common.

The characteristics of the geomatics discipline are based on the study and application of a series of (usually remote sensing) technologies. Therefore, such studies usually refer to one predominant technology (for example, satellite remote sensing examined by this paper) in combination with one or a few additional technologies. Such an approach is also oriented by the very nature of geomatics scientific literature that is required to emphasize novelties and new achievements in the technological domain, rather than the proof of an "all-inclusive" approach for monitoring the case study archaeological site. Hence, such discrepancy should not be seen as a flaw of the scientific literature, but rather an emphasis of the different needs of different communities, one being the content and another being the timing. Specifically, when operating in domains of scientific advancement, it is appropriate that the scientific community provides the focus on the highest existing achievements in their own sector and that such important advancements are promptly shared and discussed with the community. Specifically for the purposes of our study, the evidence for this is found in the increased number of publications based on the processing of satellite imagery in recent years, as discussed in section 3.1. On the other side, when collaboration between the technological scientific community with public administration is established, it is imperative that the user needs (and hence their skills and final expectations) should be met. From the examples of Grey literature, it can be noted that a more holistic approach to site and monument preservation and promotion is desired by the Public Administrations. Hence, the scientific contribution should consider the already established common practices as fertile ground to then propose innovation action on identified activities, such as the use of satellite imagery for monitoring of specific phenomena could be. The process for such action might be longer than the usual timing required and employed in scientific literature, while at the same time, these should serve as a reference for good practices to be conducted over a significant arch of time (years or decades) and usually regard a set of technologies used to provide a desired application and/or service. In conclusion, it should be of no surprise that the number of Grey Literature documents is less frequent and that it usually considers, as comprehensively as possible, the full list of technologies and of concrete benefits of their applications.

In our view, an important bridging activity would be the continuous promotion of the technological solutions that are developed together with the final user, hence out of the "service-provider – client" mode but rather in "service-provider – informed customer" environment. The major benefits could be achieved if this kind of exchange took place at the local level and hence in a local language, where possible. In such a practice, the users (even site managers) could actively take part in the development of the applications and services that meet the purposes of their specific site and possibly in their own language, in a closer coherence with terminology of their local and national legislation.

5. Conclusions

In this review of the current scientific and Grey literature focusing specifically on monitoring hazards to cultural heritage across Europe through remote sensing and Earth Observation technologies, we tried to answer a few fundamental questions: (i) What are the types of hazards to cultural heritage that have been studied using satellite imagery so far? Are all the types of hazards equally addressed? and (ii) Is there a correlation between a specific type of damage and satellite-based technology? While we acknowledge that the issues affecting this field of application are broader than those sampled by these research questions, they had not been previously investigated in the literature and the results presented in this paper highlight findings and observations that could not be necessarily predicted. Thus, the results corroborate the working hypothesis and that it was appropriate to start investigating these subjects.

From the results presented we can conclude that the most studied types of hazards do not truly reflect the hazards that represent the major threats to the monuments that have been monitored, with a significant unbalance towards "Sudden ecological and geologic threats", "Management" and "Other human activities" (e.g., looting or war). Hence, one recommendation coming out from this research would be that, together with the heritage stakeholders, the scientific community should consider a more balanced focus on less considered damage categories and/or hazards factors. The present gap may be due to the limited understanding and use of satellite images by multiple end-users to tackle different types of factors agriculture and urban sprawl. This assumption well-fit previous research studies on this and other related topics [4, 12, 13]. The construction of multidisciplinary collaborations, including satellite image specialists and non-specialists from different application fields, may certainly help to fill this gap and test the full potential of satellite technologies for documenting and monitoring endangered heritage. This can be implemented through capacity building and training sessions as demonstrated by recent examples [13-20].

Another issue regards the terminology. The literature is currently characterized by a wide variety of terms, even to indicate the same or similar threats. Using common terms facilitates comparisons and research replication. As demonstrated in this study, a significant effort has been done for normalizing terminologies regarding threats to cultural heritage. One possible solution could be that of relying upon the UNESCO terminology (2010) used in this paper, representing nowadays the most comprehensive attempt to map the whole repertoire of factors affecting cultural properties worldwide.

The separate analyses of both scientific and Grey literature highlight that there is no direct correlation between type of hazard and potential RS technology used to monitor them. On the other side, the analysis of both the literature batches reveals how geospatial environment is the most suitable framework for data integration for both RS expert and non-expert users. Also, aerial photography (increasingly through UAV devices) is another common ground for both scientific and Grey literature. These results suggest that users sampled in the Grey literature are familiar with managing photography, orthophotos and satellite imagery for consistent visual interpretation. However, although acknowledged, the full benefits of satellite data processing, and especially in combination with specific technical solutions such as ground sensors, still remain unlocked for the larger public.

Looking closer into the numbers, the analysis of this study shows how there is apparent successes of the Copernicus programme and Sentinel imagery (predominantly Sentinel-1 and 2). With their FOF access policy, the Sentinels have had a significant impact in the studies regarding in the cultural heritage sector in the past ten years. The reasons for this could be found in a three times higher spatial resolution of VIS and NIR bands achieved progressively from the older to the newer missions; a higher maturity of end-users regarding the availability and use of geo-spatial information and technologies – following the requirements of the INSPIRE Directive [60]; and this type of data becoming systematically integrated in the daily practice. Furthermore, the results suggest that, in damage monitoring of cultural heritage, the Sentinel data predominate over Landsat because, with equal accessibility, they have better technical properties (in terms of both spatial and temporal resolution). In addition, in Europe (the geographical area of our interest) there is a greater awareness of this program and consequently a greater interest and a more facilitated access through dedicated platforms that make it easy and appealing to access and use.

In this respect, it is worth acknowledging the effort that, at European level and across many countries, is currently being made to promote the integration of Earth Observation technologies in cultural heritage management and find a better match between what the satellite assets provide and the actual requirements and needs of the users of satellite data. Towards this direction, for example, the "Copernicus Cultural Heritage Task Force" was established in order to assess the current and future potential of Copernicus data, services and products in support of monitoring and protection of cultural heritage. While not focusing exclusively on monitoring hazards and damages to cultural heritage, the final report and the associated journal paper [61,62] analyze how existing Copernicus data, services and products could satisfy those requirements, identify possible enhancement and customization of Copernicus products within already operational Core Services, and analyze possible synergies with National, European or International space related solutions to fill the gaps. How this user needs' analysis would impact the future generations of satellite missions and services delivered based on their data and contribute to an enhanced exploitation to monitor hazard and damage to cultural heritage and for condition assessment, could be an interesting avenue of research.

Finally, the investigation of the heritage practice through the lens of the Grey literature highlights that the user-uptake of any RS and geomatics technologies is a complex process. It usually takes time, and often is not as fast as the mechanism by which researchers develop new methods and techniques and disseminate them within scientific publications. Even if researchers bring the technology to users (specifically experts involved in heritage maintenance, monitoring and promotion) and even if there is an attempt to make the users aware of novel solutions, this does not necessarily mean that the innovative technologies will then be exploited by the users (see for example the issues found in some of the Polish literature [51]). As demonstrated by previous studies [63], users need to see the technology as relevant to them, suiting their working purposes, and accessible. Not surprisingly, RS technologies that became part of the working flow and decision-making process are those that have been demonstrated via a direct engagement of the users (e.g., InSAR deformation measurements). The Grey literature provides examples of the benefits achieved from multidisciplinary collaboration, especially in governmental and international initiatives (see for example the archaeological area of Rome [36-37, 57-58]), and proves the role of "facilitator" / "accelerator" that scientific partners or specialist consultants can play to help heritage administrations to take advantage of EO technologies. Therefore, a further recommendation coming out from this review of the current scientific and Grey literature is that applied dedicated research projects in this domain should try and respond to bottom-up user-focused necessities (raised for instance by superintendence and site managers) rather than being shaped and conducted mainly according to top-down (usually technology-driven) academic approaches.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1 : *"List of scientific articles obtained through Scopus – Step 1A"*.

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Data Availability Statement: Data used for the analysis of the scientific literature have been retrieved from Scopus© search engine (https://www.scopus.com/home.uri). The specific data presented in this study are available in supplementary materials of this paper (List of scientific articles obtained through Scopus – Step 1A).

Appendix A

Table A.1 List of UNESCO factors (2010).

UNESCO factors
Buildings and development
Transport infrastructure
Utilities or service infrastructure
Pollution
Biological resource use/modification
Physical resource extraction
Local conditions affecting physical fabric
Social/cultural uses of heritage
Other human activities
Climate change and severe weather events
Sudden ecological or geological events
Invasive/alien species or hyper-abundant species
Management and institutional factors
Other factors

Appendix B

Table B.1 Example of terms conversions and categorization applied to one of the "grey" literature documents, as per the methodology proposed in this paper.

Type of heritage (original terms)	**Type of heritage (conversion to UNESCO categories)**
Historic Environment	Sites
Cropmarks	Monuments
Earthworks	Monuments
Soil marks	Monuments
Structures	Groups of buildings
Buildings	Groups of buildings
Landscape	Landscape
Townscape	Sites
Coastal	Natural sites
Marine	Natural sites
Maritime	Natural sites
Extant features	Monuments
Relict features	Monuments
Rural	Natural sites
Shadow marks	Monuments
Underwater	Underwater monuments
Shallow waters	Geological and physiographical formations
Wetlands	Geological and physiographical formations

Industrial archaeology	Sites

Technology (original terms)	Technology (conversion to selected lexicon, including sub-categories)
Aerial photography	Photography; Aerial
GIS	Geo-spatial Information; GIS
Satellite imagery	Satellite RS; Optic; Radar
Low-altitude aerial photography	Photography; Aerial
Orthophotography	Photography; Aerial
Infrared imagery	Photography; Aerial; Satellite RS; Optic; Multi-spectral
Thermal imaging	Photography; Aerial; Satellite RS; Optic; Multi-spectral
Multispectral scanners	Photography; Aerial
Radar	Photography; Aerial; Satellite RS; Radar; SAR
Sonar (bathymetry)	Ground sensors; sonar (bathymetry)
Google earth	Engine; Google Earth
Very Low-level Aerial Imagery	Photography; Aerial
Stereoscopic photography	Photography; Photogrammetry; Aerial
Lidar (aerial)	LiDAR; Aerial

Threats/factors/hazards (original terms)	Conversion to Primary factors affecting properties (UNESCO lexicon)
Development	Buildings and Development
Land-use change	Biological resource use/modification
Agriculture	Biological resource use/modification
Forestry activities	Biological resource use/modification
Scrub encroachment	Biological resource use/modification
Fisheries	Biological resource use/modification
Farming	Biological resource use/modification
Environmental change	Climate change and severe weather events
Limited resources	Management and institutional factors
Destruction	Other human activities
Minerals	Physical resource extraction
Peat extraction	Physical resource extraction
Coastal erosion	Sudden ecological or geological events

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