MONITORING AND MAPPING URBAN SPRAWL OVER HERITAGE HOTSPOTS USING COPERNICUS LAND MONITORING SERVICES

The case of periurban large-scale, wind-powered water extraction mills in Palma (Mallorca)

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ABSTRACT: Among the varied group of human constructions of heritage interest are the old wind-powered water extraction mills that sometimes form large-scale sets in rural areas with high wind potential. On the Mediterranean island of Mallorca (Spain), up to 2,400 windmills dating from the 19th and early 20th centuries have been counted. The areas in which they are located are considered heritage 'hotspots', i.e., areas prone to specific problems, such as the progressive abandonment of ethnological heritage resulting from urban sprawl over areas with an agricultural orientation. This article aims to monitor urban sprawl in the municipality of Palma, to quantify and map its impact on a set of windmills located mainly in the plain of Sant Jordi, to the east of the city. The study has been carried out using methodologies and analysis techniques from the Copernicus Land Monitoring Service's *Urban Atlas* and *Imperviousness Density* products. The study shows that areas with agricultural land uses have been progressively transformed into urbanised ones. This transformation has impacted, above all, windmills located in peri-urban areas adjacent to the city. The analysis aims to show the analytical possibilities of Copernicus services and products, and their applicability in the planning and management of peri-urban agro-industrial heritage.

KEYWORDS: Copernicus Land Monitoring Service, *Urban Atlas*, *HRL Imperviousness*, urban sprawl, cultural heritage, windmills, Mallorca

1. Introduction

In a context of strong urban development, agro-industrial heritage elements that survive in the rural metropolitan peripheries are threatened by cities' expansion beyond their traditional limits. In certain regions of Europe, a significant part of this heritage is made up of old windmills, forming hotspots of great historical and cultural interest. As a tourist resource, the windmill farms of Kinderdijk and Zaanse Schans (Holland), Campo de Criptana (Spain), Öland (Sweden), Wielkopolska (Poland), Marsala and Trapani (Sicily, Italy) or Clayton (England) are well known, although the number of windmills in these regions is significantly less than the number found in islands like Mallorca or Crete.

In Mallorca, up to 2,445 windmills used for water extraction (windpumps) and up to 818 flour windmills have been catalogued (Cursach, 2005). These constitute a first-rate ethnological and agro-industrial heritage, since these constructions explain an important part of the agrarian history of the island, as they do in many other regions of Europe and the world (Kaldellis & Zafirakis, 2011). In the case of water extraction windmills, their easy visual verification as a "pheno-landscape" or surface echo of what is happening in depth (González-Bernáldez, 1981), hides the true purpose of their presence, which is the water stored in underground aquifers, that is, the "crypto-landscape". These windmills are the visible part of a water landscape whose deep structure is found in the subsoil of the island.

In Palma, the capital of Mallorca, the study area of this research, the hotspot for windmills originally located on the rural periphery to the east of the city is especially noteworthy. This periphery is today a peri-urban space where the old agricultural activity coexists with a large and growing number of tertiary infrastructures. This constitutes a threat to the preservation of the old windmills, especially when a few are still in operation. These agro-industrial infrastructures have attracted the attention of researchers concerned to recreate the original wind power landscape using low-level aerial photogrammetry techniques (Smaczyński *et al.*, 2022); to highlight their in situ and in open-air museumisation (Mosakowski *et al.,* 2020); or to map their original location from historical maps (Statuto *et al.*, 2017; Ostafin *et al.*, 2022) or iconographies (Arroyo, 2012).

Monitoring urban sprawl and its repercussions on the location of these old agro-industrial constructions is of crucial importance as an integral part of regional urban planning policies committed to the preservation of cultural heritage. In the agricultural areas surrounding the city, monitoring the urban sprawl processes is necessary to ensure that urban growth is planned in line with the custody of the agro-industrial heritage located in these areas. These are the reasons that have prompted the writing of this article, whose general objective has been to test the analytical possibilities of the products and services of the Copernicus Earth Observation program to monitor and preliminarily assess the impact of urban sprawl on a peri-urban area of agrarian tradition and its impact on an agro-industrial heritage complex formed by a thousand old windmills.

Although the use of satellite data and derived products for monitoring urban sprawl is not new (Besussi *et al.*, 2003; Herold *et al.*, 2003; Bhatta, 2010; Jaeger *et al.*, 2010; Aguilera-Benavente *et al.*, 2014; Lehner *et al.*, 2017), this article is original for two reasons. First, the application of Copernicus Land Monitoring Services (CLMS) to a study area such as Palma, capital of an island internationally recognised as a tourist attraction; and second, the unprecedented nature of the analysis of the impact of urban sprawl applied to a set of constructions of great heritage interest, i.e., traditional windmills. Moreover, the working method presented in this article can be used for the case of many other European peri-urban areas where isolated constructions with heritage value are deployed. My analysis is insightful for the formation of policies for the protection of agro-industrial heritage when it is widely distributed throughout a region and is also threatened by the growth of peri-urbanisation in areas formerly dedicated to agrarian activities.

2. Urban sprawl and its analysis using satellite imagery and derived products: Compernicus Land Monitoring Services (CLMS)

Urban sprawl has been defined as a measure of urbanisation when land is consumed at a faster rate than population growth (Churchman, 1999; Galster *et al.*, 2001; Squires, 2002). Conversely, when the population grows faster than the land consumed, the area is not characterised as "sprawling" but as "densifying" (Fulton *et al.*, 2001). In a broad sense, urban sprawl refers to any kind of suburban growth, although this usually occurs at a lower degree of building density than the existing density in the center(s) of the city (Galster *et al.*, 2001; Schwarz, 2010; Tsai, 2005; Artmann *et al.*, 2019). This suburban sprawl of urbanisation results in a known set of problems and impacts (Ewing, 1994; Brueckner, 2000; Ewing *et al.*, 2002; Johnson, 2001). One of the most obvious is the loss of agricultural land (Lennert *et al.*, 2020; Skog & Steinnes, 2016) and its ancillary infrastructure, including those that are part of the ethnological heritage of agro-industrial type. Agricultural land is often transformed into land for large shopping centers, residential or office buildings, as well as transport infrastructure between the metropolitan periphery and the city centre. Urban sprawl also increases the demand for investment in transportation infrastructure and services in general, resulting in higher energy consumption and increased dependence on automobiles (EEA, 2006). Urban sprawl and suburbanisation can also be understood as the initial phases of a more far-reaching urban sprawl. Initially, suburban areas are subject to low-density growth – and thus sprawl – whereas if the city continues to grow in this direction, the following phases will be characterised by the development of an increasingly dense urban fabric (Slaev *et al.*, 2018).

In recent years, the measurement of urban sprawl has gravitated towards the use of remote sensing data (Sudhira *et al.*, 2004; Jat *et al.*; 2008; Inostroza *et al.*, 2013). The main problem of remote sensing of urban and suburban environments is their thematic heterogeneity. Urban spaces are constituted not only by areas with buildings, but also by a wide spectrum of zonal types including road axes, bare ground areas, water surfaces and parks and gardens, as well as small forests and agricultural spaces. Because remote observation techniques are inevitably associated with problems of accuracy and scale, accurate recording of the heterogeneity and complexity that characterises any urban setting requires satellite sensors with high spatial resolution and wide acquisition coverage. The data provided by these satellites enable a wide set of applications, including the analysis of urban and suburban canopies (Bhatta, 2010; Rogan & Chen, 2004; Lefebvre *et al.*, 2016), or the analysis of urban sprawl from proprietary indicators and metrics (Herold *et al.,* 2003; Seto & Fragkias, 2005; Wu *et al*., 2011; Prastacos *et al*., 2017). These analyses often integrate remote sensing and Geographic Information Systems to work together (Fuladlu *et al.*, 2021), making them an effective tool for monitoring land use and land cover changes (LULC) (Liu & Yang, 2015).

In Europe, the main challenge to applying remote sensing to the study of urban sprawl is dealing with the (non-)availability of harmonised datasets (Soukup *et al.,* 2015). To effectively address such a challenge, the Copernicus Land Monitoring Service (CLMS) offers a set of open access satellite imagery-derived products and services (as established by the EU Regulation No 1159/2013 of 12 July 2013). Such products and services support applications in a variety of domains such as spatial planning, forest management, water management, agriculture, food security or emergency management, among others. The CLMS portfolio is distinguished by its three components Global, Pan-European and Local, each offering a particular set of products. The Pan-European component products are *CORINE Land Cover, CORINE Land Cover Plus*, *High Resolution Layers*, *Biophysical parameters*, *European Settlement Map* and *European Ground Motion Service*. The Local component products are the *Urban Atlas*, *Riparian Zones, Natura 2000* and *Coastal zones*. In addition, Copernicus includes two groups of satellite images: *High Resolution (HR*) image mosaics and *Very High Resolution (VHR*) image mosaics.

2.1. The Urban Atlas

In 2009, the European Space Agency (ESA) launched the Global Monitoring for Environment and Security (GMES) with the publication of the *Urban Atlas* (UA) (EC, 2016), a pan-European dataset on land use and land cover of Functional Urban Areas (FUAs) with more than 100,000 inhabitants. FUAs are the spatial unit considered to assess the spatial structures of urban sprawl and suburbanisation. The first *Urban Atlas* database referenced 2006 and contained 319 FUAs. The subsequent one referenced to 2012 and contains 785 FUAs with more than 50,000 inhabitants (in addition to the 2006-2012 change product). The latest UA database is from 2018 and contains a dataset for 788 FUAs plus the 2012-2018 change product (EU, 2020).

Together with *CORINE Land Cover*, the *Urban Atlas* is one of the most widely used databases at the European level for urban cover monitoring and characterisation and has greater thematic richness than CORINE. The built-up classes are combined with *Imperviousness Density* (IMD) information, a high-resolution layer that provides more detail regarding the density of the urban fabric. It is also complemented with functional information (road network, services, facilities, etc.) using auxiliary data sources such as local urban maps or online mapping services. The spatial resolution of the *Urban Atlas* is 0.25 ha, while its temporal resolution is 6 years –2006, 2012 and 2018. These characteristics allow the product data to be used as indicators of urban sprawl. The complete definition of Land Use (LU) and Land Cover (LC) classes for the *Urban Atlas* 2006 and *Urban Atlas* 2012 at all hierarchical levels can be found in the official documentation (EU, 2020). The *Urban Atlas* database contains information on the distribution of land use in the 305 largest European cities. Twenty different land use types are recognised, six of which represent the urban fabric. The data has been used to generate a time series of percentages of urban coverage in Palma, as a basic input to monitor the impact of this coverage on the existing windmill heritage.

2.2. The High Resolution Layer (HRL) Imperviousness

The *High Resolution Layers* (*HRL*) of the Copernicus program are a type of pan-European high-resolution raster-based datasets, created for five themes or cover types: degree of soil sealing (Imperviousness), Forest, Permanent grassland, Wetlands, and Water bodies. All of these are available for 39 countries in Europe, with the most recent data being for the year 2012. Specifically, the *High Resolution Imperviousness* Density Layer captures the spatial distribution of artificially sealed areas, including the degree of soil sealing per unit area (EC, 2016; EU, 2020). The degree of imperviousness (0-100%) is determined by a semi-automatic classification, based on the calibrated NDVI (Normalized Difference Vegetation Index). These are classified images of sealed soil, generally consisting of structures that prevent or hinder water from infiltrating into the subsoil – basically, roads, driveways, sidewalks or parking lots with asphalt pavements, as well as rooftops. It is therefore an artificialised land type, which can indirectly be taken as a measure of the percentage of effectively urbanised land (EC, 2016; Weng, 2012; Drašković, 2021) since built-up areas are characterised by the substitution of the original (semi-)natural ground cover or water-bearing surfaces with an artificial, often impermeable cover, which is also usually maintained for long periods of time.

The *HRL Imperviousness* provides more detailed sealed surface data (20 × 20 m = 0.04 ha resolution) than the *Urban Atlas* data (0.25 ha). Copernicus provides two types of Imperviousness change products: a) a simple layer mapping the percentage of sealing increase or decrease for those pixels that show real sealing change in the period covered; and b) a classified change product that maps the most relevant categories of sealing change (unchanged, new cover, loss of cover, unchanged sealed, increased sealing, decreased sealing).

3. A case study in a peri-urban agricultural plain (Palma, Mallorca)

The study area of this research is the Spanish municipality of Palma (Mallorca, Balearic Islands) (Figure 1). With an area of 195.3 km^2 and 419,366 inhabitants in 2021, its population density is 2,147 inhabitants/km^2. Conquered by Rome in 123 BCE, this territory has a long history of land use and concatenation of cultures, which have given rise to a rich heritage of different periods and typologies. Due to its economic and demographic dynamics, the city has a rururban periphery that is relevant to study the effects of urban sprawl. One of the characteristics that make it relevant is the existence of traditional windmills, which were built between the 19th and early 20th centuries in the eastern sector of the municipality. This area was previously a typical location for providing agricultural services to the city. This sector constitutes a coastal plain known as Pla de Sant Jordi and is in the process of being transformed into a metropolitan agricultural park (Figure 1). The windmills of Pla de Sant Jordi would not be of great interest if it were not for two reasons: first, because of their heritage value; second, because of their high number – 1,055 units – which surely represents one of the highest densities of windmills in the Mediterranean region and probably in the world.

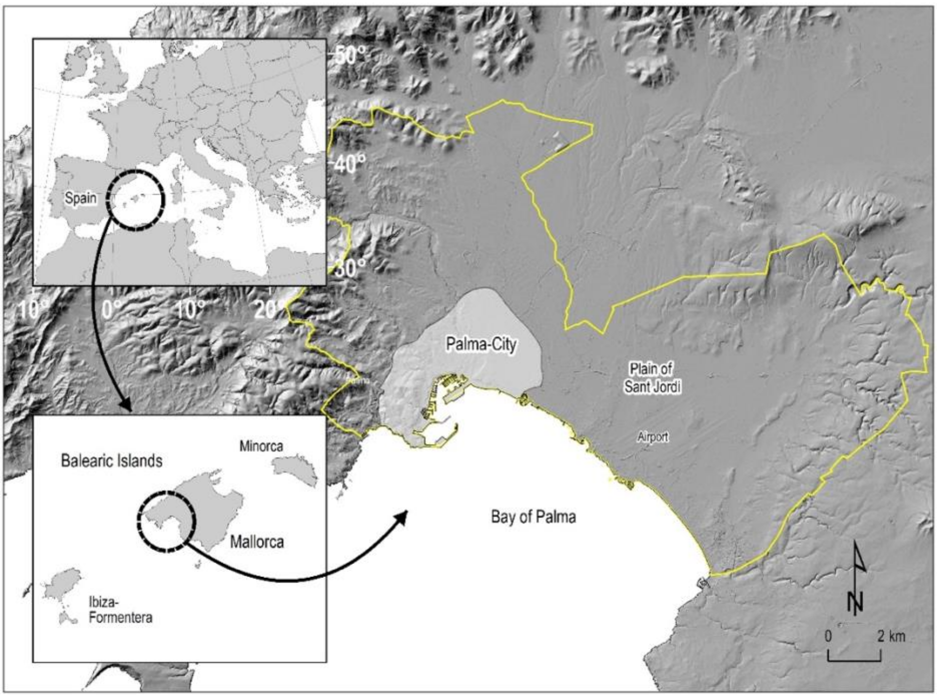

Figure 1 - The study area: the municipality of Palma and the plain of Sant Jordi in the context of the Balearic Islands, Spain and Europe.

From a geographical point of view, the Pla de Sant Jordi is a subsident and endorheic sedimentary basin formed by post-orogenic materials (from the Serravallian to the present day), with thicknesses that can reach 450m, and that is surrounded by the Tramuntana mountain range and by hills of much lower altitude scattered around the inland area of Mallorca (Rodríguez-Perea & Grimalt-Gelabert, 1994). The existence of two main aquifers – one superficial, formed by Plio-Quaternary materials, and the other deep, from the Upper Miocene – has been decisive for the historical transformation of this basin into an irrigated area, although as such only the upper Plio-Quaternary aquifer is exploited. Before its transformation into an agricultural area, the Pla de Sant Jordi was a wetland, drained and reclaimed since the mid-19th century (Rosselló, 1959). The plain is open and oriented to the coastal winds generated in the bay of Palma, where in spring and summer frequent and very regular sea breezes are generated, essential to move the wheels of the windmills still in operation (Alomar-Garau & Grimalt-Gelabert, 2022). Together with the presence of the aquifer, these breezes have been decisive for the massive placement of the windmills to extract water from the subsoil, and their configuration as an aerolic hotspot of large dimensions.

Access to water in Mallorca is an highly relevant issue, since the particularities of the Mediterranean climate – irregular rainfall, summer drought – make water a scarce resource on the island, or at least highly subject to the seasonal component. Rainfall regime, soil permeability, and the relatively small size of watersheds contribute to the fact that the island hardly has any permanent surface water courses. Instead of rivers, there are torrents, i.e. intermittent water courses that are only operative during torrential rainfall episodes, typically in autumn. Isolated and scattered across the territory, there are also springs (where water emerges from the substrata), of which two representative types exist: those that naturally emerge or are brought forth through a short excavation, and what are referred to in Mallorcan Catalan language as *fonts de mina* or *qanat* (dry stone fountains, which are methods of groundwater collection involving an underground gallery that leads to the point where water flows).

A third important water resource is that of the aforementioned underground aquifers, which are a characteristic example of the island's *karst* geography, a word of Serbo-Croatian origin that designates the set of geological formations typical of places where calcareous rocks predominate. Over thousands of years, these rocks dissolve upon contact with rainwater, forming carbonic acid and eventually creating exokarstic features such as limestone pavements, sinkholes, poljes, and karst canyons, as well as endokarstic features like caves, underground conduits, and karst aquifers. These aquifers fill with water as it infiltrates the subsurface and have a large storage capacity.

Both torrents and springs, along with karstic aquifers, have historically been exploited through the development of sophisticated systems of regulation, capture, distribution, and water storage over the centuries: *qanats*, waterwheels, drainage and irrigation channels, dams, reservoirs, basins, cisterns, bucket hydraulic mills, and wind-powered water extraction mills. This anthropogenic hydraulic network overlays the natural system, integrating and adapting to the physical and topographic characteristics of the terrain, shaping a water landscape whose virtue lies in the balanced integration of human activity with the environment.

The agricultural dedication of the eastern plain of Palma is reflected in the classified land cover data provided by the *Urban Atlas*. Figure 2 shows the predominance of the agricultural footprint both to the north and east of the large urban center of Palma, represented, above all, by the land covers Arable land (annual crops), Permanent crops and Orchards. In the eastern sector, a vast part of the agricultural footprint is literally annihilated by the presence of the large airport infrastructure of Son Sant Joan – some 730 ha – whose construction in the 1960s and expansion in 1997, meant the progressive artificialisation and rigidification of the original agricultural space.

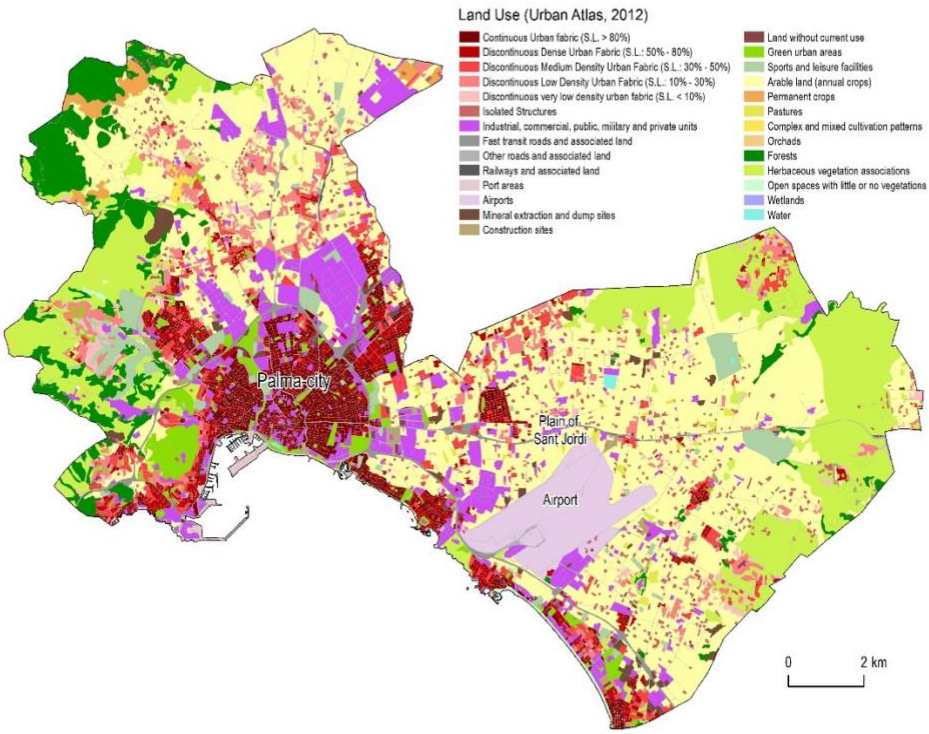

Figure 2 - Land Use/Land Cover (LU/LC) in the municipality of Palma (Mallorca), according to the 2012 *Urban Atlas* (UA) categorisation. The complete definition of the LU/LC classes for UA at all hierarchical levels can be found in official documentation (EC, 2016; EU, 2020)

3.1. The standing windmills

In Mallorca, the use of wind power to extract groundwater from the aquifer in the agricultural sector of the Sant Jordi plain dates back to the mid-19th century, with the construction and strategic installation of the first windpumps on this coastal plain. Their primary function was to pump water from wetlands to dry them out and transform them into agricultural land, thus eliminating an endemic source of malaria. It was not in vain that in 1816 King Ferdinand VII had promulgated a Royal Decree that sought to promote irrigated agriculture in Spain, and served, along with other legal instruments, as a catalyst for a series of initiatives for the agricultural colonisation of the Sant Jordi plain.

The drainage project was undertaken in 1847 by the Dutch engineer Paul Bouvy von Schorremberg (1807–1868), together with the French geologist Paulino Vernière (1818–18?) and culminated with relative success in 1849. Two years earlier, the first windmill with hydraulic purposes had been installed in Mallorca, probably a type of windmill with sets of triangular sails at either end of the windshaft. The installation of as many windpumps for the purpose of pumping water and draining it to the sea was combined with the creation of a network of drainage channels, mainly the so-called *síquia de Sant Jordi*. From this point on, the drained and fertilised lands were systematically converted into irrigated crop fields. Irrigation was undertaken through the construction of new windpumps, this time used to extract water from the aquifer, store it in reservoirs located next to the windpump – *safareigs*, in Catalan vernacular – and then use it to irrigate the crops. Since 1871, when Archduke Ludwig Salvator of Austria counted 36 windmills in the new, large agricultural area of the plain of Sant Jordi (Ludwig Salvator, 1897), their number increased until 1891, when Pedro de Alcántara Peña (1891, p. 195) counted 200 windmills "of sail and varied systems". This considerable increase coincided with the intensification of irrigation in this coastal plain. According to Valdés (1951), the census of windmills had reached 897, and by 1959 it had reached 1,308.

The proliferation of windmills on the eastern side of the municipality of Palma occurred along with the process of segregation and segmentation of this territory into small, agricultural plots –starting with the one initiated by Antonio Rotten Gual, Marquis of Campofranco, in his estate of Son Sunyer, between 1905 and 1909 (Horrach, 2013). In Mallorca, these rural plots are designated with different local names, in the Catalan language: *hort*, *possessió* and *sementer*. The result is a strongly fractionated and ultimately anthropised agrarian landscape. The massive installation of windmills changed the sanitation conditions of the environment, promoting improvements in access to the city and to the coast, which in the long run encouraged its urbanisation.

The decline in the construction of windmills began in the 1960s, as the use of electric and combustion engines for pumping water was introduced, replacing wind power. The decline is also explained by the gradual salinisation of groundwater caused by excessive extraction, in addition to the abandonment of agricultural activity in favour of tertiary/service sector activity. In acknowledgement of the agricultural tradition of the eastern plain of Palma, in whose development the construction of windmills played a decisive role, the Consell de Mallorca –the island's government administration, acting through the Foment al Desenvolupament de Mallorca (FODESMA), presented an inventory of windmills in 2002 in which a total of 2,445 units were counted for the whole of Mallorca (Cañellas, 1993). The municipalities of Palma (1,055), Campos (629), Sa Pobla (298), Muro (181) and Ses Salines (92) together accounted for 92.3% of the total number of water extraction windmills on the island.

The map in Figure 3 shows the spatial distribution of water windmills in the municipality of Palma, where 43.2% of the island's total is concentrated. This distribution coincides, in general, with agricultural land cover. In addition, the windmills are distributed forming a border around the large airport infrastructure of Son Sant Joan. Its construction meant not only the rigidification of the original agricultural space but also the physical destruction of many of the windmills located in the area where the airport is located today. Inside the airport area, there are still 27 windmills, some in ruins, and others that have been restored. Of the 1,055 windmills catalogued in Palma, most only have the stone tower is preserved, although sometimes the wheels and blades are still standing, although they are immobile.

These are, therefore, largely periclitated and fossilised constructions, which is why my research is largely synchronic in nature. However, an unquantified number of windmills are still in operation, and many others have been restored with government funding (Figure 4).

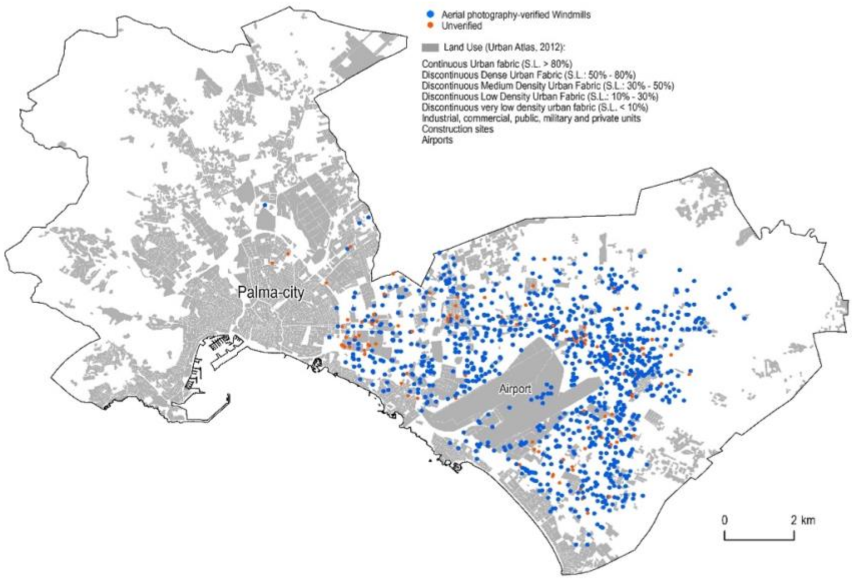

Figure 3 - Distribution of windmills throughout the municipality of Palma (Mallorca), from the catalogue of ethnological elements of the Spatial Data Infrastructure of the Balearic Islands (www.ideib.es).

3.2 The windmills heritage

In Mallorca, windmills have played a decisive role in the development of agricultural activity since the mid-19th century, as well as in the configuration of the irrigated agricultural space. In addition to this, their impact as landscape creators, specifically a wind power landscape, has made them a part of the territorial and tourist brand image of the coastal plains of Mallorca (Buswell, 2013). Promotional campaigns for Mallorca as a tourist destination often feature photographs of these windmills. Some of them have been part of a cultural cooperation project of the Pyrenees-Mediterranean Euroregion entitled 'Windmills: Another Look' (EGTC, 2014). This project comprises a didactic itinerary that covers various milling areas in the plain of Mallorca. Its purpose is to revitalise the milling heritage of this Euroregion and prevent its disappearance by creating a cultural tourism product. The Consell de Mallorca and the Association of Friends of the Windmills of Mallorca, are actively involved in disseminating the historical and cultural heritage of the windmills of Mallorca. The latter is integrated into the association Hispania Nostra. The scenic allure of the Mallorcan windmills, especially those of Pla de Sant Jordi, has also attracted numerous artists, such as the panoramic view provided by the Mallorcan painter Jaume Mercant (1908-1999) (Figure 5), which showcases the diverse array of wind-powered water extraction mills in this coastal plain in 1963. At that time, many of the water windmills were still in full activity.

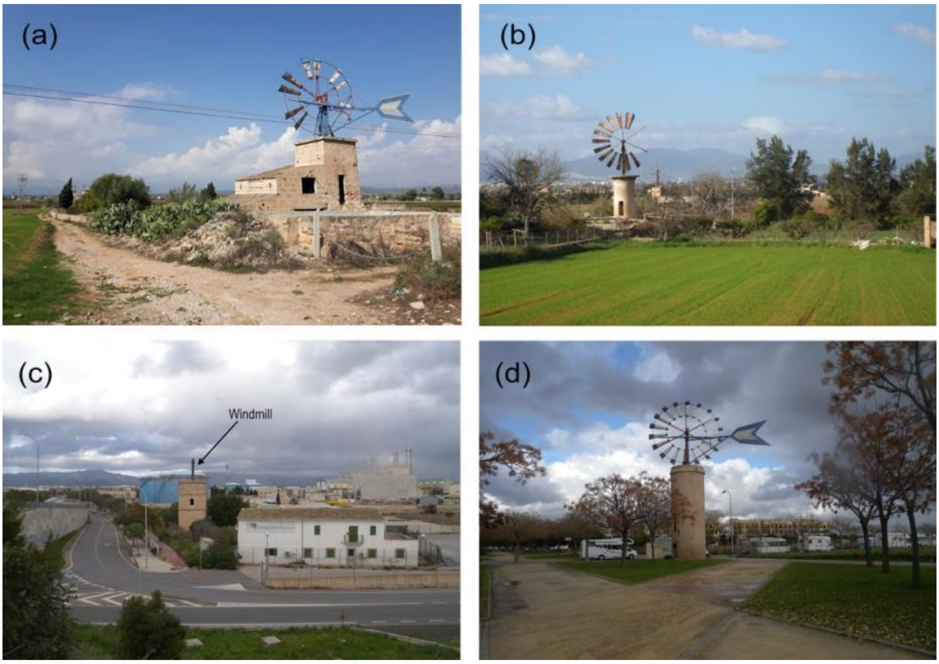

Figure 4 - Examples of windmills located in the eastern sector of Palma: (a) and (b), windmills abandoned in the interior of the agricultural plain of Sant Jordi; (c) an old windmill tower without its wheel, located and fossilised in a strongly tertiary urban sprawl area; (d) restored windmill located in an urban sprawl area. (Photos: Gabriel Alomar-Garau.)

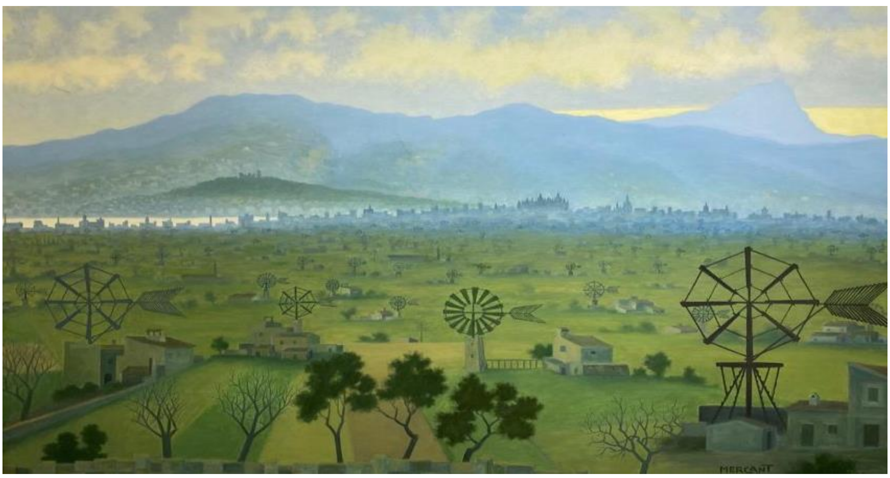

Figure 5 - View of the plain of Sant Jordi (eastern Palma) in 1963, by the painter Jaume Mercant (1908-1999), showing an active windmilling complex. In the background, the city of Palma and its bay, at the foot of the small mountain range of Na Burguesa with the medieval castle of Bellver.

The recognition of the historical and landscape value of the windmills (Sanchis, 1955), together with their progressive abandonment and deterioration, have led to the recognition of their heritage value, specifically in the category of agro-industrial heritage. Shortly before the current century, this interpretation led the insular government institutions to promote a systematic inventory and cataloguing of the windmills, with the aim of examining and describing their typology, their constructive characteristics, their territorial distribution, and their state of conservation. Inventory methods for traditional rural constructions play a key role in preserving cultural heritage. Such cataloguing has served as a basic instrument for decision-making in protecting and conserving the industrial and agricultural heritage of Mallorca, and by extension, of Spain and Europe.

In Mallorca, the instruments through which this protection is made effective are the municipal catalogues of heritage, which complement the General Urban Development Plans (PGOU) of the respective municipalities. These catalogues are drawn up in accordance with the provisions of the Territorial Plan of Mallorca, Article 2.2.5.5 (Rural ethnological elements), which establishes that the general planning of each municipality must include in its catalogue those elements of an ethnological nature that, due to their cultural or landscape value, deserve special protection.

The windmills of the plain of Sant Jordi are protected by virtue of the classification of this plain (termed the Molinos del Pla de Sant Jordi) as a Site of Geological Interest (LIG) under Law 42/2007, December 13, 2007, concerning Natural Heritage and Biodiversity. This designation is somewhat misleading, because although this plain is of clear hydrogeological interest, what is being protected are windmills for the extraction of groundwater from the Plio-Quaternary aquifer of Sant Jordi (now in disuse due to salinisation).The revision of the General Plan of Palma (Ajuntament de Palma, 2021) foresees the creation of Areas of General Interest (AIN) and Zones of Landscape Interest (ZIP) on rural land. The latter refers to landscapes rich in cultural significance, reflecting the traditional balance between agricultural use, natural resources, and conservation. The aforementioned General Plan of Palma (Ajuntament de Palma, 2021) declares the "rural zone El Molinar" (ZIP-EM), integrated in the future agricultural park of the plain of Sant Jordi, a Zone of Landscape Interest. Likewise, the General Plan also stipulates that protection for the windmills will be implemented through cataloging in the Detailed Management Plan for the most significant wind-mills, and through the Special Plan of the Agricultural Park for the others (Ajuntament de Palma, 2021).

The windmills are considered both architectural and civil engineering structures, and the PGOU assigns them a level B protection, which do not possess the architectural, historical, or environmental qualities of higher categories, but have significant historical or artistic value. This proposal for protection is based on the 2002 inventory of water-extracting windmills prepared by the Consell de Mallorca, and is made for a total of 979 water extraction windmills, which are those that architecturally, technically, or in terms of landscape, have preserved their original characteristics and have not undergone significant alterations.

4. Method and Data

This article aims to exploit the advantages of Copernicus products and services to monitor the recent expansion of the city of Palma and asses the spatial impact of this growth on a heritage site composed of 1,055 windmills. Assessing this impact involves three types of interconnected analysis, which in turn have involved the use of Copernicus satellite datasets and derived products:

i) The areas of low-density urban development in the city of Palma (Mallorca), commonly known as "urban sprawl", have been mapped and quantified using the *Urban Atlas* Land Use-Land Cover (LULC) change layer from 2006-2012, a specific product of the Local component of the Copernicus Land Monitoring Service. This layer uses 2006 and 2012 orthorectified VHR satellite imagery to detect changes in comparison to the 2006 LULC *Urban Atlas*. The *Urban Atlas* 'Change 2012-2018' layer could not be used as it is not yet validated data. Although the *Urban Atlas* 'Change 2006-2012' layer covers a non-recent period, it allows for the observation of certain spatial trends of urban growth in the study area.

ii) Soil sealing or imperviousness is another parameter considered in the analysis, and it has been used as a complementary method to measure the increase in artificialised (and thereby urbanised) surface area in the study area. For this purpose, two Imperviousness Change Classified Change (IMCC) products have been used: 'Imperviousness Classified Change 2006-2012 (CLC Synchronous)', and 'Imperviousness Change Classified (IMCC) 2015-2018'. Both products are 20m resolution raster datasets that map changes in imperviousness (new cover, loss of cover, increase, and decrease in densities), based mainly on NDVI analysis. 2006-2012 has been chosen as the first period, as it coincides with the period of analysis of the *Urban Atlas* changes layer used in the first step. 2015-2018 has been chosen as an additional period because it offers an advantage when analysing recent changes related to soil sealing and its impact on the current location of windmills. However, the European Environment Agency has warned that the reliability of the increase in imperviousness mapped for the period 2015-2018 is currently under investigation as the change products show a significant increase in the rate of soil sealing compared to previous periods.

The analysis uses raster images in GeoTIFF (*.tif) format that have been adjusted to the study area using the boundary layer of the municipality of Palma as a clipping layer. The layer shows the most relevant categories of sealing change: 0: unchanged areas with imperviousness degree of 0; 1: new cover-increased imperviousness density, zero IMD at first reference date; 2: loss of cover-decreasing imperviousness density, zero IMD at second reference date; 10: unchanged areas, IMD>0 at both reference date; 11: increased imperviousness density, IMD>0 at both reference date; 12: decreased imperviousness density, IMD>0 at both reference date; 254: unclassifiable in any of parent status layers (EEA, 2018).

iii) The point entities used to locate the 1,055 windmills were geometrically intersected with the area vector entities containing the *Urban Atlas* land-use categories (2006-2012), and the pixels of the 2006-2012 and 2015-2018 imperviousness classified change layers. Intersect is a geoprocess typically used in Geographic Information Systems, which computes the geometric intersection of two input entities, in this case, the windmills represented by point entities, with the land covers represented by area entities. Both intersections have allowed for the quantification of the degree of direct impact of urban sprawl and soil artificialisation on the inventoried windmills.

4.1. Windmills database

To map the heritage hotspot of the inventoried windmills and compare them with areas of urban sprawl, we used the geolocated windmill dataset mapped in the plans of protected buildings and spaces of the Detailed Management Plan (POD) of the revision of the General Urban Development Plans (PGOU) (Ajuntament de Palma, 2021). These data are also available from the catalogue of the Spatial Data Infrastructure of the Balearic Islands (www.ideib.es). This availability made it unnecessary to use automatic object detection techniques from Earth observation images, as Tertre and Laurençot (2022) or Mridula and Sharma (2021) have done, using deep learning techniques applied to satellite images. The experimental base of windmills in Palma consists of 1,055 units, whose first inventory was conducted in 2002 by the Public Administration (Consell de Mallorca). To evaluate the degree of updating of this inventory, a visual verification of the inventoried windmills was carried out using updated aerial photographs from the Spanish National Orthophoto Program (PNOA). This confirmed the presence of 935 windmills in the study area, 88.6% of the total originally inventoried. Due to the operational difficulty of verifying the presence of all the windmills through fieldwork, for the purposes of this research, we have considered the 1,055 officially inventoried by the Public Administration.

4.2. Aerial Photos

To visually interpret the results, aerial images were used to monitor the evolution of urban sprawl over the windmill hotspot closest to the consolidated city. These are aerial orthoimages from different flights and historical orthophotos from the Spanish National Orthophoto Program (PNOA) and the Historical PNOA project. Both plans are part of a cooperative project involving the General State Administration and the Autonomous Communities of Spain that began in 2004 with the objective of obtaining digital aerial orthophotographs of the entire Spanish territory, with a fixed updating period, currently 3 years. For this investigation, the Serie B flight from 1956, as well as the flights from 1981, 1997, 2006, 2012 and 2018 were used. The orthoimage of the last flight was used for its high spatial resolution (0.15 m) to visually identify windmills, and to contrast this identification with the windmill inventory map.

5. Results

5.1. Application of the Copernicus Urban Atlas *to the detection of land cover change and urban sprawl*

The analysis of the *Urban Atlas* changes layer for the period 2006-2012 in the municipality of Palma shows the progress of extensive urbanisation between these two dates. The layer has a total of 788 polygons (904.4 ha) corresponding to areas whose land uses have changed. These changes are illustrated in Figure 6 and summarised in Table 1. In 2006, 54.4% of these areas (530.2 ha, 429 polygons) were classified as "Agricultural, semi-natural areas, wetlands" and 23.0% (234.7 ha, 181 polygons) were classified as "Construction sites". The remaining 22.6% corresponded to various other land cover types.

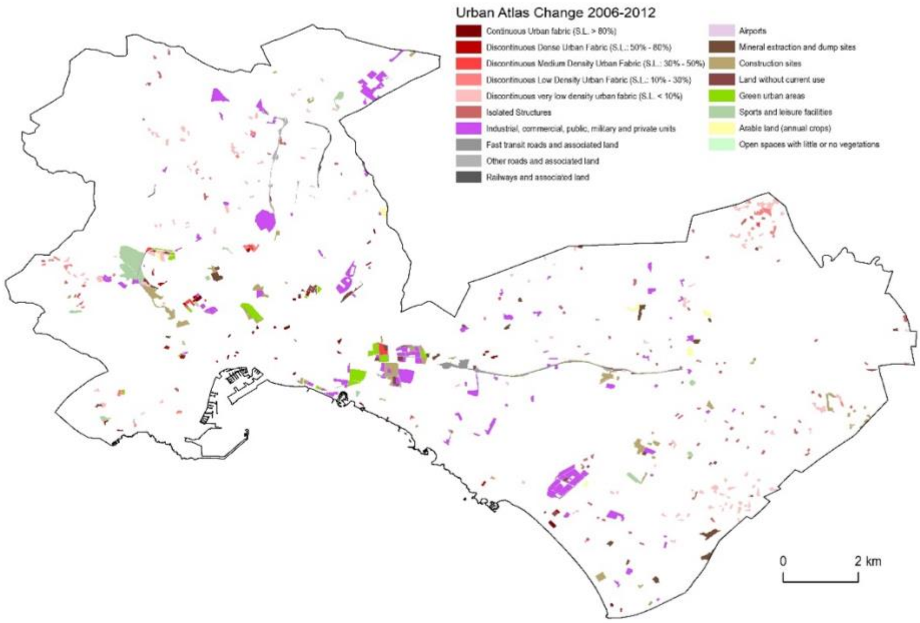

Figure 6 - *Urban Atlas* Change 2006-2012, applied to the municipality of Palma (Mallorca).

In 2012, 30.4% (274.8 ha, 149 polygons) of the areas that had undergone changes were classified as "Industrial, commercial, public, military and private units" land. 11.9% (107.4 ha, 67 polygons) of the changed surfaces were classified as "Construction sites", and 11.6% (105.1 ha, 147 polygons) as "Discontinuous very low density urban fabric (S.L. : < 10%)". The data shows that none of the areas that changed in use or coverage between 2006 and 2012 became "Agricultural, semi-natural areas, wetlands" or "Forest". Quite the contrary, since the 530.2 ha of surface area that in 2006 were agricultural land, semi-natural areas and wetlands, in 2012 had been transformed, primarily as "Industrial, commercial, public, military and private units" (165.2 ha), into "Construction sites"" (80.2 ha) or into "Discontinuous very low density urban fabric (S.L. : < 10%)" (80.0 ha).

Table 2 shows the numerical data of the changes that occurred in 2012 to areas classified as "Agricultural, semi-natural areas, wetlands" in 2006. The three main types of land cover indicated, "Industrial…", "Construction sites", and "Discontinuous very low density urban fabric", account for 61.4% of the changes. These primary data reveal two aspects of interest: first, that the most transformed land cover is agricultural and semi-natural areas; second, that this change has led to the replacement of these areas with urban land, indicating an artificialisation of the land.

UA CODE 2006	Land Use 2006	COUNT 2006	Area (ha)	UA CODE 2012	Land Use 2012	COUNT 2012	Area (ha)
12400	Airports	7	12,4	12400	Airports	1	0,7
				21000	Arable land (annual crops)	16	22,3
13300	Construction sites	181	234,7	13300	Construction sites	67	107,4
11100	Continuous urban fabric (S.L. : > 80%)	4	2,6	11100	Continuous urban fabric (S.L. : > 80%)	24	14,2
11210	Discontinuous dense urban fabric (S.L. : 50% - 80%)	18	8,1	11210	Discontinuous dense urban fabric (S.L. : 50% - 80%)	19	12,1
11230	Discontinuous low density urban fabric (S.L. : 10% - 30%)	13	5,2	11230	Discontinuous low density urban fabric (S.L. : 10% - 30%)	32	29,9
11220	Discontinuous medium density urban fabric (S.L. : 30% - 50%)	18	7,7	11220	Discontinuous medium density urban fabric (S.L. : 30% - 50%)	20	16,1
				11240	Discontinuous very low density urban fabric (S.L. : < 10%)	147	105,1
				12210	Fast transit roads and associated land	31	34,9
14100	Green urban areas	16	16,1	14100	Green urban areas	22	51,7
12100	Industrial, commercial, public, military and private units	18	17,5	12100	Industrial, commercial, public, military and private units	149	274,8
11300	Isolated structures	22	10,3	11300	Isolated structures	75	45,1
13400	Land without current use	33	27,1	13400	Land without current use	48	32,4
13100	Mineral extraction and dump sites	6	11,9	13100	Mineral extraction and dump sites	22	38,0
				33000	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	1	0,2
12220	Other roads and associated land	8	1,3	12220	Other roads and associated land	79	38,7
				12230	Railways and associated land	11	7,8
14200	Sports and leisure facilities	9	14,2	14200	Sports and leisure facilities	24	73,0
20000	Agricultural, semi-natural areas, wetlands	429	530,2				
30000	Forests	6	5,1				
		788	**904,4**			**788**	**904,4**

Table 1. Numerical translation of Land Cover changes for the period 2006-2012 (*Urban Atlas* Change 2006-2012), in the municipality of Palma (Mallorca).

Land Use 2006	UA CODE 2012	Land Use 2012	COUNT 2012	Area (ha)	%
Agricultural, semi-natural areas, wetlands (Code 20000)	12100	Industrial, commercial, public, military and private units	80	165,2	31,2
	13300	Construction sites	41	80,2	15,1
	11220	Discontinuous very low density urban fabric (S.L. : < 10%)	114	80,0	15,1
	14200	Sports and leisure facilities	13	52,6	9,9
	11300	Isolated structures	68	40,0	7,5
	13100	Mineral extraction and dump sites	15	29,9	5,6
	12220	Other roads and associated land	35	21,0	4,0
	11230	Discontinuous low density urban fabric (S.L. : 10% - 30%)	19	19,7	3,7
	13400	Land without current use	17	14,2	2,7
	14100	Green urban areas	2	8,0	1,5
	12210	Fast transit roads and associated land	7	6,6	1,3
	12230	Railways and associated land	7	6,4	1,2
	11220	Discontinuous medium density urban fabric (S.L. : 30% - 50%)	9	5,1	1,0
	11210	Discontinuous dense urban fabric (S.L. : 50% - 80%)	2	1,1	0,2
			429	**530,2**	**100,0**

Table 2. Numerical translation of the transformation of the coverage "Agricultural, semi-natural areas, wetlands" into 14 different coverages during the period 2006-2012 (*Urban Atlas* Change 2006-2012), for the municipality of Palma (Mallorca).

5.2. Application of the Copernicus HRL Imperviousness to the detection of artificialised ground and urban sprawl.

The changes identified through the analysis of the *Urban Atlas* change layer between 2006 and 2012 can be compared to data on soil sealing ("Imperviousness"). For this purpose, the layers of classified imperviousness changes for the reference periods 2006-2012 and 2015-2018 have been used. The former has been selected to make it coincide with the period of analysis of the changes observed from the *Urban Atlas*. By applying these data to the study area, the results of the analysis are presented in Figure 7, which shows the progress or permanence of impervious surfaces in the municipality of Palma. A summary of the results for both reference periods is presented in Table 3.

First, the percentage of unaltered areas with a degree of imperviousness of 0 was 76.38% in the 2006-2012 period and 70.39% in the 2015-2018 period, indicating that the recent period had a greater increase in transformed surfaces. These transformations resulted in an increase of new coverages, leading to an increase in imperviousness density in certain areas of the study area. Thus, in the 2006-2012 period, sealed soil increased by 84.3 ha, while in the 2015-2018 period, it increased by 170.4 ha. Increases in imperviousness density in areas where the IMD was already greater than 0 are also observed during the most recent period of analysis, with 89.7 ha having gained density. Percentagewise, these increases appear insignificant for a large territory like Palma. However, the significance of these increases lies not in their absolute or relative values, but in the location where they occur. Thus, for the period 2006-2012, new areas of sealed land could be observed, above all, in the sector to the north of the main urban core, but also, to a lesser extent, in the eastern sector closer to this same core. During the 2015-2018 period, the increase in sealed land was particularly notable in the eastern sector of the municipality, particularly in areas in direct contact with the consolidated city towards the east (Figure 7b). It is also worth noting the increase in imperviousness density in the area surrounding the airport runways, suggesting an increase in paved surfaces in this area. The eastern sector of the municipality has the most windmills and is most affected by urban sprawl in all its variety of forms. Therefore, windmills in this area are the most exposed to the impact of urbanisation. This impact is described in the following section.

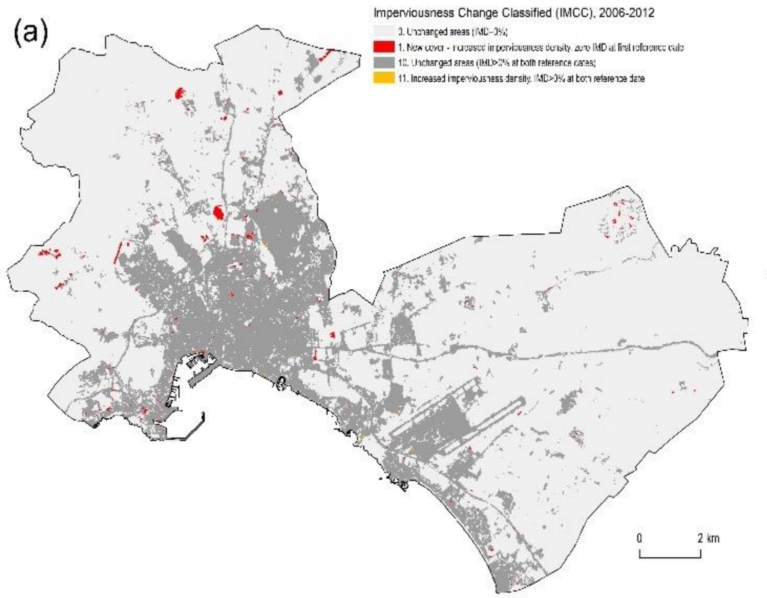

Figure 7a - Degree of Imperviousness Change (IMCC 20 m: Imperviousness Change Classified) in six-year period from 2006 to 2012, for the municipality of Palma (Mallorca).

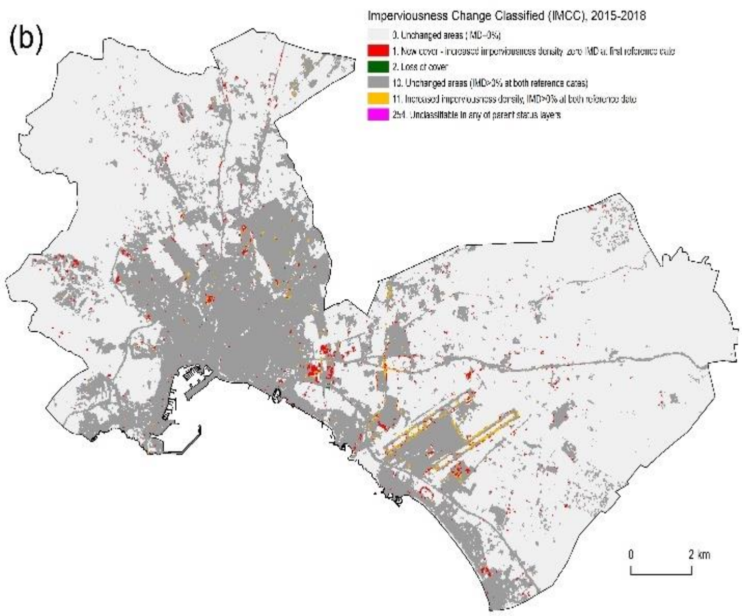

Figure 7b - Degree of Imperviousness Change (IMCC 20 m: Imperviousness Change Classified) in three-year period from 2015 to 2018 for the municipality of Palma (Mallorca).

Code Imperviousness Change Classified (IMCC)	Description	% 2006-2012	Ha 2006-2012	% 2015-2018	Ha 2015-2018
0	Unchanged areas	76.38	14,936.2	70.39	13,768.1
10	Unchanged areas, IMD>0 at both reference date	23.17	4,531.2	28.24	5,524.3
11	Increased imperviousness density, IMD>0 at both reference date	0.02	3.1	0.46	89.7
2	Loss of cover			0,01	2.2
254	Unclassifiable in any of parent status layers			0.02	4.0
1	New cover–Increased imperviousness density	0.43	84.3	0.87	170.4
		100,0	**19,556**	**100,0**	**19,558**

Table 3 - Summary of the area (ha) and percentage (%) of changes for each category of the Imperviousness Change Classified (IMCC) layers, corresponding to the reference periods six-year 2006-2012 and three-year 2015-2018.

5.3. *Impact of urban sprawl over the heritage windmill hotspot*

After examining urban sprawl and the increase of sealed soil in Palma from two different analytical sources over several time periods, it is possible to measure the direct spatial impact of new urbanised surfaces on heritage windmills. This measurement is performed by geometrically intersecting point entities corresponding to the windmills with the change layers of the *Urban Atlas* and HRL *Imperviousness*. This allows for an evaluation of the extent of loss of the original rural vocation of the agro-industrial heritage affected by new urbanisation.

In the case of the first intersected dataset (*Urban Atlas* 'Changes 2006-2012'), it was found that 46 windmills that were located on surfaces classified as "Agricultural, semi-natural areas, wetlands" in 2006 (Table 4 and Figure 8), were located on surfaces indicating a loss of agricultural land in 2012. Although the number of windmills affected by land use changes between 2006 and 2012 is much smaller (84 mills out of a total of 1,055, or barely 8%), the short, 6 year period of time in which these changes took place can be interpreted as a sign of subsequent changes of greater scope. Moreover, it is not so much the number of windmills affected by such changes, but the new types of land cover on which they have ended up settling. Thus, what is significant is that the 46 mills that were settled on agricultural and semi-natural areas in 2006, after six years, were settled on areas where agriculture or the naturalness of the site had been replaced by land cover types without agricultural vocation: mainly, "isolated structures" (15 windmills), "industrial, commercial, public, military and private units" (10) and "discontinuous very low density urban fabric" (8) (Table 5). These three main land cover types also indicate a type of urbanisation that typically characterises urban sprawl, such as the low density of new buildings.

Land Use 2006 (*Urban Atlas*)	Number of Windmills
Construction sites	12
Discontinuous low density urban fabric (S.L. : 10% - 30%)	8
Isolated structures	7
Discontinuous medium density urban fabric (S.L. : 30% - 50%)	4
Airports	2
Discontinuous dense urban fabric (S.L. : 50% - 80%)	2
Industrial, commercial, public, military and private units	2
Land without current use	1
Agricultural, semi-natural areas, wetlands	46
	84

Table 4 - Types of land cover (*Urban Atlas*) on which the windmills were located in 2006.

Land Use 2012 (*Urban Atlas*)	Number of Windmills
Isolated structures	15
Industrial, commercial, public, military and private units	10
Discontinuous very low density urban fabric (S.L. : < 10%)	8
Construction sites	4
Sports and leisure facilities	4
Land without current use	2
Green urban areas	1
Mineral extraction and dump sites	1
Other roads and associated land	1
	46

Table 5 - Land cover types resulting from the transformation of land cover classified as "Agricultural, semi-natural areas, wetlands" in 2006, and number of windmills corresponding to each type of land cover classified in 2012.

In the case of the second intersection (*HRL Imperviousness*), the results show similar problems to those we noticed when overlaying the geolocated windmill data with the *Urban Atlas* change layer. Thus, between 2006 and 2012, only 4 of the 1,055 windmills were affected by being located on new surfaces with sealed soil, whereas between 2015 and 2018 the impact was more rapid, as 22 windmills (2.0% of the total inventoried) had come to be located on new surfaces with sealed soil (19 windmills) or on surfaces where the density of imperviousness had increased (3 windmills) (Table 6 and Figure 9a). Thus, if during the period 2015-2018 the area of new sealed soil had increased by 170.4 ha (Table 3), this increase had impacted a limited number of windmills. Even so, areas of agricultural vocation continue to be the main ones affected by soil sealing and, ultimately, by the expansion of urbanisation in a broad sense. Since the location of windmills is originally and typically rural, it can be seen that these heritage infrastructures can be more easily affected by the transformation of the original agricultural land into urbanised land.

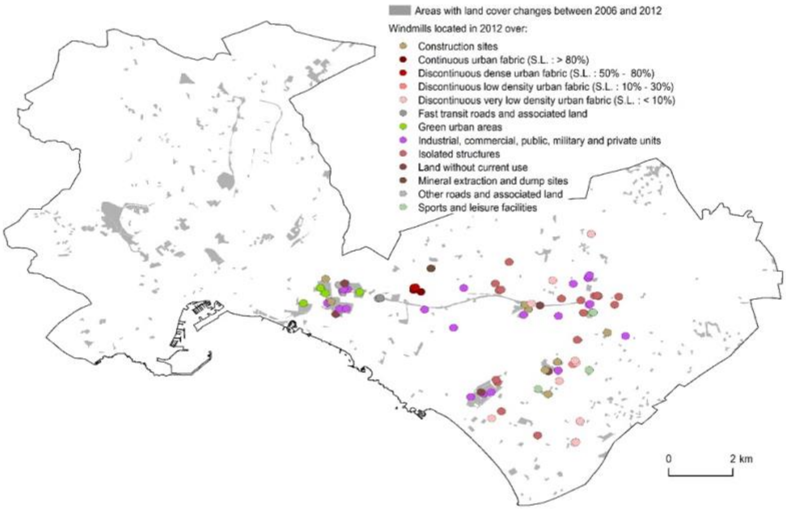

Figure 8 - Windmills affected (dot symbols) by Land Use changes during the period from 2006 to 2012 (*Urban Atlas* 2006-2012), and new Land Use classes over which they were located in 2012.

The orthophotographic sequence in Figure 10 shows certain details of interest that demonstrate the advance of urbanisation over areas that historically have been linked to peri-urban agricultural activity. They also reveal instances of urban sprawl in the advancing urbanisation. Thus, the eastern area in contact with the main urban center of Palma is an area where the artificialisation of the land is most evident (Figure 11). This area was entirely dedicated to irrigated agriculture in 1956 and retained that use in 1981. However, in 1997, various urban development operations aimed at increasing urban and developable land started to encroach on previously rural areas. The advance of urbanisation becomes evident in subsequent years: 2006, 2012 and 2018. It is noteworthy that the latest aerial images accurately depict new commercial, industrial, or residential areas where crop fields used to be located. Thus, the aerial images only corroborate the effectiveness of the *Urban Atlas* product in detecting land cover changes.

Imperviousness Changes (*HRL Imperviousness*)	**Number of Windmills, Imperviousness Changes 2006-2012**	**Number of Windmills, Imperviousness Changes 2015-2018**
0. Unchanged areas (IMD=0%)	835	683
1. New cover–Increased imperviousness density	4	19
10. Unchanged areas (IMD>0% at both reference dates)	216	350
11. Increased imperviousness density, IMD>0 at both reference date		3
	1,055	**1,055**

Table 6 - Imperviousness Change Classified (IMCC) layer classes 2006-2012 and 2015-2018, and respective number of windmills corresponding to each class.

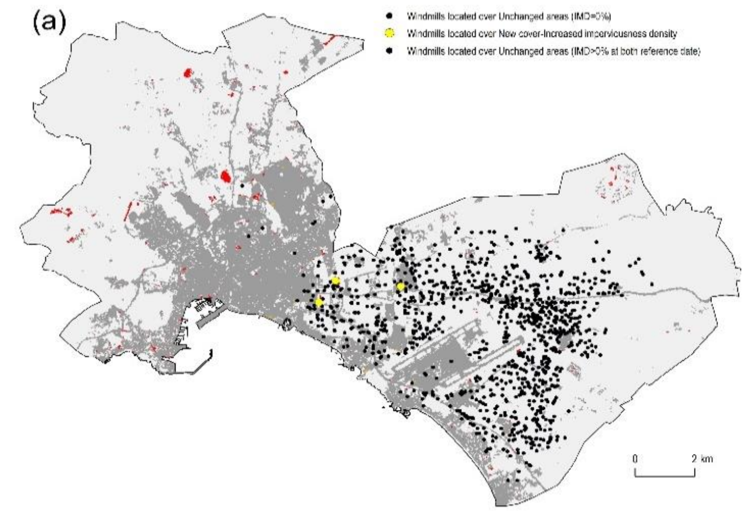

Figure 9a - Windmills affected and non-affected (dot symbols) by Land Use changes, from the Imperviousness Change Classified (IMCC) layer 2006-2012 period.

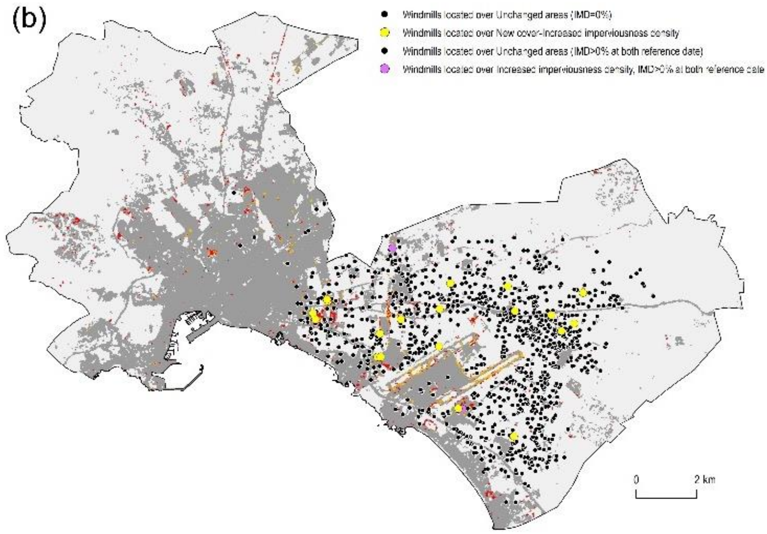

Figure 9b - Windmills affected and non-affected (dot symbols) by Land Use changes, from the Imperviousness Change Classified (IMCC) layer 2015-2018 period.

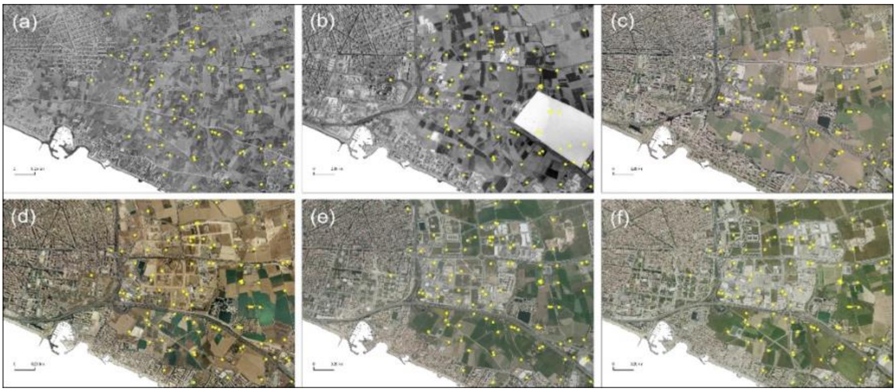

Figure 10 - Spatial-temporal evolution of urban sprawl east of the consolidated city, from historical orthoimages for the years (a) 1956, (b) 1981, (c) 1997, (d) 2006, (e) 2012 and (f) 2018, and its impact on windmills (yellow dots). Source: Own elaboration based on orthoimages from the National Aerial Orthophotography Plan and Historical PNOA.

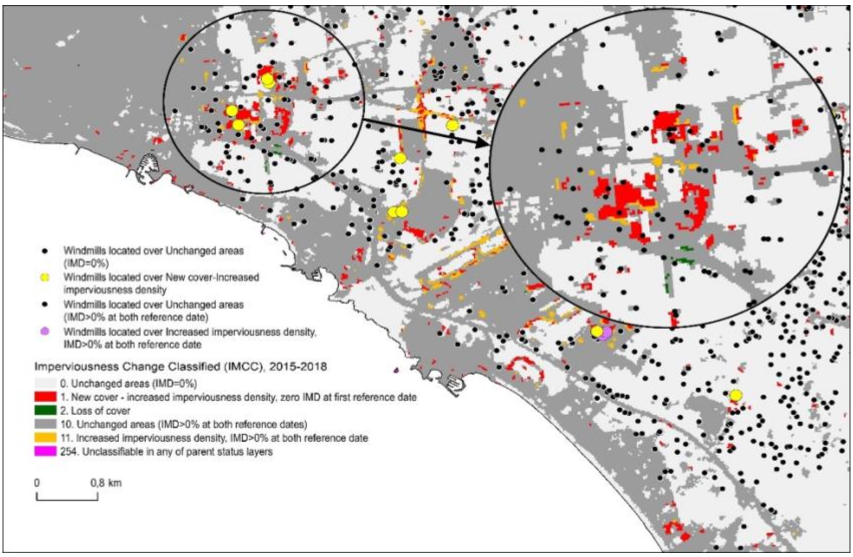

Figure 11 - Detail view of windmills affected and non-affected (dot symbols) by imperviousness density changes between 2015 and 2018, from the raster layer "Imperviousness Change Classified (IMCC), 2015-2018". Detail view of windmills in the eastern area of Palma, affected and unaffected (dot symbols) by imperviousness density changes between 2015 and 2018, from the 'Imperviousness Change Classified (IMCC), 2015-2018' raster layer.

4. Discussion and Conclusions

In order to test the analytical usefulness of Copernicus products and services for monitoring urban sprawl over a heritage hotspot formed by 1,055 windmills, this research has carried out different analyses whose results show the progress of urbanisation and its impact on these former agro-industrial infrastructures. This type of impact analysis is rarely applied by users of Copernicus products and services. This scarcity is perhaps due to the fact that cultural heritage is not one of the six main thematic areas addressed by Copernicus (Geospatial, Earth Observation and Environment, Meteorological, Statistical, Companies and company ownership, and Mobility). In any case, works such as that of Kristy (2008), studying the impact of urban sprawl on cultural heritage in Herat (Afghanistan) or Vaz et al. (2011), studying the impact of urban growth trends on the Pyramids complex in the metropolitan area of Cairo, are examples that show a very current problem, such as the threat of urban growth to heritage infrastructures located in peri-urban areas.

The purpose of this study has been to demonstrate the need for further research, by focusing on Mallorca, an island with a high concentration of windmills that played a crucial role in the island's recent history of irrigation. Like in similar cases (Smaczyński et al., 2022), their decline and abandonment is due to economic and technological changes, that made the use of windmills to extract water from the subsoil and irrigate crops unprofitable. However, the fact that a thousand old mill towers have survived in the municipality of Palma, some of which still have their wheels and blades and are still operational, suggests that abandonment did not always result in their physical removal from the landscape.

In my work, I used two products of the Copernicus Land Monitoring Service (CLMS) – the *Urban Atlas* and the *HRL Imperviousness* – to confirm the process of substitution of agricultural activity by tertiary sector activities on a coastal plain where most of the surviving windmills are located. The main areas affected by urban sprawl are the rural-urban sectors located east of the city of Palma, which Iquantified in our study. I performed the analysis using techniques and methods commonly used in Geographic Information Systems, by analysing vector data of Land Use changes and raster data of changes in soil imperviousness density from 2006-2012 and 2015-2018.

The results reveal changes in the surface areas where the inventoried windmills are located. These changes affected a small percentage (8%) of windmills. The main issue is that these changes are transforming agricultural or semi-natural land into urbanised land, which is resulting in the loss of the windmills' agricultural purpose and their eventual abandonment. In fact, urban cover is characterised by its tendency to be irreversible, making it difficult to restore agricultural land once it has been urbanised. Additionally, the percentage of sealed soil increases as a result of this process. As for the windmills' constructions, they end up being fixed within the new urban fabric, resulting in them being permanently decontextualised from their original agricultural setting.

This conclusion was reached through the use of data sets from the CLMS. While the *Urban Atlas* was useful in measuring urban sprawl in the study area, it was surpassed by the land registry (cadastral) data in terms of thematic richness, spatial resolution, and level of detail. In Spain, these data can be used to generate urban land use classifications with varying levels of complexity (Martín & Rodríguez, 2022). With scales between 1:1000 and 1:5000, they offer an excellent approximation to the thematic reality of each parcel. However, one of the advantages of both the *Urban Atlas* and the *HRL Imperviousness* is their relatively rich temporal resolution, which makes it possible to determine and map the changes in land use and sealed soil that occurred during different periods. These change maps can potentially be considered very useful when addressing specific cultural heritage needs, even if Copernicus was not specifically designed for such purposes (EC, 2018).

The use of Earth Observation data in cultural heritage is expected to increase as new validated data are published, allowing for the quantification of urban sprawl over different time periods and its impact on heritage sites. In addition, the lack of human resources for regular field inspections of numerous heritage buildings makes it advisable to use satellite images and their derivative products to identify priority areas for inspection. Although the results of our work do not reveal significant changes in the environment that affect a large number of windmills, it is crucial to assess whether these changes impact heritage constructions that are in better condition or have been restored. Furthermore, when preserving windmill heritage, it is just as important to protect the building itself as it is to protect its surroundings. This recommendation applies to any heritage building that was originally located in a rural area. To prevent their complete disappearance, the only solution is to protect them through laws and regulations that promote their conservation, even if they are no longer on their original agricultural land.

Government programs for restoring old windmills can be very effective in preserving their historical significance, but it is preferable for the mills to regain their original function of drawing water from the aquifer for irrigation in an agricultural area that is being revitalised. In the meantime, the benefits of remote sensing can be used for cultural heritage monitoring, according to the method we have adopted in the present work. The availability of full, free and open access Copernicus data is contributing to an increase in heritage applications.

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