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GIS mapping of agricultural plastic waste in southern Europe

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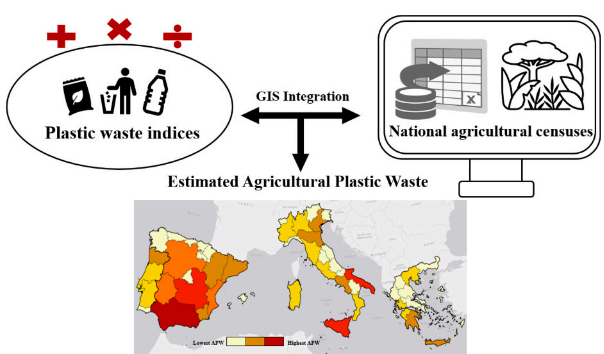
HIGHLIGHTS

- Agricultural plastic waste inadequately addressed by the research community.
- Estimation of agricultural waste quantities, mapping in Southern Europe.
- Methods include Geographic information system, waste indices, agricultural census.
- Spain with the highest agricultural plastic waste generation in Andalusia region.
- Foundation for effective management of agricultural plastic waste and hotspots.

GRAPHICAL ABSTRACT



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ABSTRACT

The escalating use of plastics in agriculture, driven by global population growth and increasing food demand, has concurrently led to a rise in Agricultural Plastic Waste (APW) production. Effective waste management is imperative, prompting this study to address the initial step of management, that is the quantification and localization of waste generated from different production systems in diverse regions. Focused on four Southern European countries (Italy, Spain, Greece, and Portugal) at the regional level, the study uses Geographic Information System (GIS), land use maps, indices tailored to each specific agricultural application and each crop type for plastic waste mapping. Furthermore, after the data was employed, it was validated by relevant stakeholders of the mentioned countries.

The study revealed Spain, particularly the Andalusia region, as the highest contributor to APW equal to 324,000 tons per year, while Portugal's Azores region had the lowest estimate equal to 428 tons per year.

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Significantly, this research stands out as one of the first to comprehensively consider various plastic applications and detailed crop cultivations within the production systems, representing a pioneering effort in addressing plastic waste management in Southern Europe. This can lead further on to the management of waste in this area and the transfer of the scientific proposition to other countries.

Abbreviations

APW	Agricultural plastic waste
MPs	Microplastics
GIS	Geographic information system
NUTS	Nomenclature of territorial units for statistics
EUROSTAT	Statistical office of the European Union
UAA	Utilized agricultural area
PWI	Plastic waste index
PA	Plastic application
CT	Crop type
ISTAT	Italian national institute of statistics
INE	Institute of national statistics

1. Introduction

Plastic is considered as a universal product mainly due to its high flexibility, durability, ease of manufacture and affordability (Lebreton and Andrady, 2019; Khan et al., 2023; Mohan and Lakshmanan, 2023). It is employed in a wide range of products including industrial, medical, electrical, and agricultural products (Sa'adu and Farsang, 2022; Liu and You, 2023). Recently, many stakeholders in diverse disciplines have faced a new challenge which is the continuous generation of plastic waste and its detrimental effects on the environment, especially considering the release and accumulation of microplastics (MPs) in the terrestrial and aquatic environments (Brandes et al., 2021; Ren et al., 2021; Lwanga et al., 2023). Although there is a great attention nowadays on plastic pollution in aquatic ecosystems, comparatively limited emphasis has been placed on its pervasive occurrence and widespread pressure posed to agricultural landscapes on a global scale (Khan et al., 2023).

Soil is considered one of the most important factors of an agricultural ecosystem and sustaining this factor is essential to support human development while preserving sustainability (Cillis et al., 2022; Liu and You, 2023). The surge in global population has precipitated a heightened demand for food, needing increased agricultural production (Hachem et al., 2023). Consequently, there has been a rise in the use of plastic products to facilitate year-round crop cultivation such as the implementation of greenhouse and low tunnel films for the creation of an adequate microclimate which can improve crop reliability. Plastic is also an essential commodity for transporting and storing fertilizers, agrochemicals, seeds, and crops (Blanco et al., 2018). Providing protection is also considered essential to provide high-quality end-products through various means such as plastic films and nets, agrochemical containers for pesticides, mulching films for weed control.

Unfortunately, this increase in plastic usage has resulted in escalated pollution in terrestrial ecosystems since most plastics have a short life duration between 6 and 60 months (Espí et al., 2006; Picuno et al., 2012; Vox et al., 2016). Therefore, higher amounts of agricultural plastic waste (APW) are generated each year (Schettini et al., 2014; Nanna et al., 2018; Isari et al., 2021) and this can lead to the release of MPs. Agricultural soils can act both as source and sink of these particles. According to literature, MPs have the propensity to accumulate in soils and interact with soil biota, including plant tissues. Very small particles, i.e. nanoplastics, were shown to undergo root uptake in laboratory experiments under hydroponic conditions, possibly representing an entrance point into the food chain. The same can happen for chemical additives which may leach out from plastic debris in the environment as a result of their progressing weathering. This can pose health risks to humans (Li et al., 2020; Mo et al., 2021). Additionally, MPs are implicated in adverse effects on plant growth, impacting soil properties, soil biota (Lwanga et al., 2016), and overall soil functionality by leaching both inorganic and organic compounds (Forster et al., 2022), as well as accumulating in groundwater by infiltrating through the rhizosphere (Lwanga et al., 2016; Kim et al., 2023).

APW is often mismanaged. It can be burned in open fields, abandoned near water courses, buried in the soil, or disposed of in landfills (Briassoulis et al., 2013; Sica et al., 2015). While legal measures have been instituted to prohibit uncontrolled burning, burial, and abandonment of waste, a distinct and comprehensive legal framework is lacking in Europe to establish an environmentally sustainable, economically viable, and socially accepted disposal system specifically tailored for APW (Zubris and Richards, 2005; Briassoulis et al., 2012).

Therefore, it is crucial to organize a plan for the correct management of APW, to allow stakeholders to efficiently reduce its amounts and prevent mismanagement, which are drastically increasing over time, and to mitigate its impact on different ecosystems. The scientific community could contribute to APW management by having a better understanding of the sources of the APW and tracing it back. This will allow to quantify and localize the hotspots of these potential pollutants especially in the terrestrial environment (Rillig, 2012; Piehl et al., 2018; Harms et al., 2021).

Geographic Information Systems (GIS) prove invaluable in this context, as they facilitate the organization, analysis, and visualization of georeferenced data within maps. This capability can for example enable the identification and localization of hotspots associated with a given studied parameter, elucidating its quantities and distribution across diverse geographic regions. Subsequently, this provides stakeholders with a foundational platform from which they can plan and implement interventions.

This study is the first part of a research aiming at realizing a GIS digital atlas of the APW for European countries. The primary objective of this study is to estimate the quantities of APW across diverse agricultural applications (greenhouse covering films, mulching films, low tunnels films, nets, irrigation pipes, agrochemical containers, bags for fertilizers, and support equipment for vineyards) and geographically represent its distribution at the NUTS 2 regional level (EUROSTAT, n.d.). The methodology was applied to the South Europe context (Italy, Spain, Greece and Portugal) covering regions characterized by similar cultivation practices, common for the Mediterranean climate. This involves the development and application of advanced indices tailored to each specific agricultural application, crop type, and for each country. The methodology integrates these indices with data retrieved by the national agricultural censuses of the countries in a GIS environment and includes a subsequent validation by local knowledge holders. The validation is performed to evaluate the accuracy of the estimate. This leads eventually to obtaining geo-referenced maps of APW. Finally, this study serves as a foundational framework with the potential to be extrapolated for similar assessments in other European countries and build the complete European APW atlas.

2. Materials and methods

The APW maps were obtained through the following steps:

- Development of Plastic Waste Indices (PWIs) to quantify APW (Section 2.1).

- Validation of the data with each of the countries under study (Section 2.2).
- Acquisition of utilized agricultural area (UAA) statistical data from each of the countries' agricultural census (Section 2.3).
- Identification of the main crops at regional country level (Section 2.4).
- Integration of the indices with the data from the agricultural censuses (Section 2.4).
- Acquisition of NUTS 2 level maps (Section 2.5).
- Manipulation of maps with the addition of APW quantities obtained for each region through QGIS (Section 2.5).

2.1. PWIs definition and development

The PWI is a valuable tool to estimate the yearly average APW quantity generated per cultivated area (kg ha^{-1} yr^{-1}) for each different plastic application (PA) in each crop type (CT). It is essential to recognize that each type of plastic has its own unique lifespan, which can also vary between countries. Considering the vast array of commercially available plastic products, an average value for each country is typically used to represent the properties of these products, facilitating estimations and analyses.

For each European country, PWIs were evaluated for the main crops considering the most used agricultural plastic (AP) products in that country. The main crops include vegetables in open fields and in greenhouses, orchards, vineyards, olive groves, cereals, and silage crops. The following PAs generating waste were considered: films for crop protection; nets; low tunnel films; mulching films, solarization and direct covering films; bags for fertilizers and containers for pesticides and for other agrochemicals; silage bags; irrigation pipes; plastic supports for vineyards. More information about these applications can be found in the study conducted by Briassoulis et al. (2013).

2.1.1. Plastic applications in agriculture

Evaluation of PWIs is based on high occurrence and usage in agriculture of each PA in the analysed geographical area. PWIs can be later-on extended to more diversified and detailed applications since it is undoubtedly very crucial to try to cover as many applications as possible so that the estimation can be more accurate.

PAs considered in the study are the following:

- Covering films, which are plastic films used to cover a growing area useful to create a controlled environment by regulating the entering of solar radiation, heat, and humidity. This PA includes greenhouses covering films, high tunnel covering films, vineyards covering films and orchards covering films.
- Mulching films that are thin plastic sheets positioned over raised beds with the edges buried. Their aim is to cover the soil around plants acting as a protective layer. Benefits can be control of weed growth, conservation of soil moisture by reducing evaporation and others. It is used for berries production as well as horticultural crops.
- Nets used in agriculture are mesh-like structures that can be characterized by diverse colours, mesh sizes, yarn thickness and types of weaving. They include shading nets, anti-hail nets, nets for crop protection from insects and birds and harvesting nets (as olive collection nets).
- Films for low tunnels or what are defined as 1-m-high tunnels consisting in thin flexible sheets made of transparent plastic. These films are stretched over arc-shaped supports to form a low tunnel temporary structure. Low tunnel films are used to cover individual rows or beds of plants. The films provide protection from cold temperatures, frost, and pests while creating a warmer microclimate that promotes plant growth. It may be used for horticultural crops.
- Irrigation pipes constitute the main component of an irrigation system and are characterized by different diameters and lengths. The pipes considered can be used for the main water line as well as lateral lines. Pipes are used in greenhouses, for crops grown under mulching films, in open field cultivation, elevated or over the ground in orchards, olive groves and vineyards.
- Agrochemical containers that are mainly plastic containers filled with plant protection products and liquid fertilizers. They are secure vessels or packaging designed for the safe storage, transport, and application of the product contained inside. They include insecticide and fungicide containers.
- Bags for fertilizers and growing substrates are waterproof plastic bags. These bags can protect fertilizers/growing substrates under rough handling and storage conditions. The bags category also includes silage bags for storing and fermenting animal feed.
- Plastic supports, which are plastic tying items used to support plants (grapevines in this study), ensure stability and proper growth. These include strings, twines, anchors, clips, and ropes for vineyard fixation.

2.1.2. PWIs computation

It must be understood that producing inventories of AP uses and waste generation for large scales is a big challenge and necessarily requires to assume some level of approximation. Data on distribution and characteristics of specific materials used in different locations are mostly unavailable. The same applies for primary data on waste streams. In this context, PWIs are models conceived to enable sound approximation of masses of APW produced per unit of land cultivated with a given crop using a given production method during a given timespan. The computation of each single PWI was done based on each CT and each PA as well as considering the country under study, since factors can differ in terms of climatic conditions and cultivation techniques. The parameters considered include density and thickness of the plastic, its lifetime, and in some cases a correction factor.

For PAs like nets, which have holes throughout their surface, an additional factor called the areic mass is incorporated in the PWI calculation. This factor accounts for the density of the net's surface area.

On the other hand, when calculating the PWI for irrigation pipes, an average value of length and weight is considered for both large and small diameter pipes, in addition to their useful lifetimes. Moreover, estimating PWIs for PAs such as bags, containers, and plastic supports, involves utilizing consumption data from farmers and research on the proportion of UAA as well as literature reviews. These data-driven estimations help in understanding the scale of plastic waste generated by these specific applications.

The formulas used to estimate the PWI for each PA are shown hereafter. PWIs for films are calculated as:

$$\mathrm{PWI}_{films} = \frac{\rho \bullet \mathrm{T}}{\mathrm{years}} \bullet \mathrm{F}_{\mathrm{correction}} \bullet 10^4 \ \left(\mathrm{kg\ ha^{-1}\ yr^{-1}}\right) \quad (1)$$

where: ρ [kg m^{-3}] is the density of the plastic used in the covering, mulching and low tunnels films; T [m] is its thickness; years is the duration of its life; $F_{correction}$ is the dimensionless correction factor. The latter takes into account the increase in plastic material surface resulting from sidewalls and coverage slope in relation to the soil surface.

The PWI for nets is:

$$\mathrm{PWI}_{\mathrm{nets}} = \frac{AM}{years} \bullet \mathrm{F}_{\mathrm{correction}} \bullet 10^4 \ \left(\mathrm{kg\ ha^{-1}\ yr^{-1}}\right) \quad (2)$$

where AM [kg m^{-2}] is the areic mass of the net.

The PWI for irrigation pipes is obtained by:

$$\mathrm{PWI}_{Irrigation\ pipes} = \left(\frac{W_{LD}}{\mathrm{years}_{LD}}\right) + \left(\frac{W_{SD}}{\mathrm{years}_{SD}}\right) \ \left(\mathrm{kg\ ha^{-1}\ yr^{-1}}\right) \quad (3)$$

where: W_{LD} [kg ha^{-1}] and $years_{LD}$ are the weight and the duration of the large diameter irrigation pipe, respectively and W_{SD} [kg ha^{-1}] and $years_{SD}$ are the weight and the duration of the small diameter irrigation pipe, respectively. Distinguishing between small and large diameters irrigation pipes is crucial due to their different roles in agricultural water distribution and their different impact on agricultural plastic waste generated. Most of the pipes used are small diameter pipes in each row of crops, while large diameter pipes are only used to convey water from the wells or reservoirs to the small diameter pipes. The amount used for the combination will directly affect the agricultural plastic waste generated.

The PWI for the different support items is calculated as:

$$PWI_{supports} = \frac{W_{si} \bullet n}{years} \quad (kg\ ha^{-1}\ yr^{-1}) \tag{4}$$

where: W_{si} [kg] is the weight of each support item used in vineyards production system and n is the number of items used per hectare.

On the other hand, agrochemical containers and bags assigned PWIs were acquired by the data from literature, interactions with farmers as well as from databases in the countries under study (Briassoulis et al., 2013). Additionally, the sum of all the PWIs for each PA related to the specific CT gives the overall PWI per CT or Total APW per hectare.

The PWIs of the different countries distinguished per CT and PA are presented in Appendix A.

2.2. PWIs validation

For the study to be dependable and for the digital atlas to be accurate, PWIs needed to be calculated for each country only after information on which PWIs are based has been validated. The validation of the PWIs to be used for the maps of each country was conducted by entities from the countries under study. These institutions were universities, farmers' associations, and national research institutes, providing feedback on the parameters used in the PWIs calculation, to reflect local practices (e.g., thickness and density of the plastic material used for films, nets and irrigation pipes as well as the duration of use of each PA). Additionally, they validated the pairing of cultivation and production practices as they tend to be influenced by local conditions. Experience with agricultural PAs, questionnaires and interactions with farmers and associations as well as field surveys were essential for the validation process of the different APW estimations through the indices.

PWIs in this study were developed for four countries (Italy, Greece, Portugal and Spain).

From Italy, the University of Bari was the main contributor for the validation procedure. Italy was chosen as pilot for the initial deployment of the model and its validation.

In order to increase their reliability, the information obtained from the questionnaires, interviews and interactions with farmers and associations were cross-checked and verified with literature data; the 30-years database maintained at the University of Bari concerning the physical properties of AP materials; direct communications from companies involved in the production of AP materials. Companies involved were the following:

- o P.A.T.I. S.p.A., San Zenone degli Ezzelini, Treviso, Italy.
- o Arrigoni S.p.A., Uggiate Trevano, Como, Italy.
- o Retilplast Srl, Campagna, Salerno, Italy.
- o Polyeur, Benevento, Italy.

For the validation process of the PWIs in the other countries under study, the main contributions came from the Agricultural University of Athens, the University of Évora and the University of Almeria for Greece, Portugal and Spain, respectively.

2.3. National agricultural censuses

National agricultural censuses provide valuable statistics on various aspects of agriculture in different countries. Censuses are considered particularly important tools for acquiring the latest data available (mainly the UAA). In this study, data for 2021 in Italy, Greece, Portugal, and Spain were considered since this year is the latest with a complete dataset on the cultivated area (ha) for each CT. These data were used later for the estimation of the waste generated after integrating them with PWIs. Since the digital atlas is set considering the nomenclature of territorial units for statistics (NUTS) to the second level (EUROSTAT, n.d.), which consists of the administrative regions of each country, statistics were acquired on a regional level as well. Data from the different countries were extracted from each national agricultural census. Data were typically nonhomogeneous in terms of layout, units, area levels and more. Harmonization was required to produce a single format of the data for all the countries, enabling a well-formed establishment for the mapping of different agricultural PAs and their associated waste. This layout was also used for the association of the PWIs relative to each PA, each CT as well as each region.

Moreover, a reasonable explanation of the production systems was required by the involved entities to better understand the national agricultural census datasets. Harmonized data also contributed to having comparable and easily usable data that could be key for further studies and comparisons across the countries and regions in Europe. This established and harmonized agricultural data collection in Europe could be a useful tool to easily extract data and maintain the digital Atlas updated.

Italy's agricultural statistical data was acquired from the Italian National Institute of Statistics (ISTAT), which is a public research organization and the main producer of Italian official statistics in the service of citizens and policymakers. It operates in complete independence and continuous interaction with the academic and scientific communities. Twenty total regions were considered in the study.

Portugal's agricultural statistical data was acquired from the Portuguese National Institute of Statistics (INE) on the regional level and seven regions were the foundation for the generation of the APW maps.

Agricultural statistical data for Greece was acquired from the Hellenic Statistical Authority on the regional level with thirteen total regions considered for the elaboration of the APW maps.

While Spain's agricultural statistical data was acquired from the National Institute of Statistics (INE), with seventeen total regions under study.

2.4. Main crops identification and integration of PWIs with UAA

The main crops from national agricultural censuses (Hellenic Statistical Authority, 2021; INE Portugal, 2021; INE Spain, 2021; ISTAT, 2021) were grouped into categories of crops: vegetables in open field and in greenhouses, cereals, silage crops, orchards, vineyards, and olive groves.

For each crop, depending on what can be used as PA in the production process, a PWI was assigned for each PA. Knowing the cultivated area for the specific crop, each PA's index was multiplied by the UAA. This led to the APW quantity for each CT and each PA. Furthermore, to obtain the total APW for each crop, the sum of all the APW from each PA was performed.

2.5. Maps acquirement (NUTS 2 level) and APW merging

The NUTS 2 maps were acquired through the official statistical office of the European Union (EUROSTAT) on the regional level of each country in Europe (regional maps coinciding with the regions of the agricultural censuses).

These maps were later-on required to merge the PWIs estimated previously with their corresponding UAA in the regional map of each country. Then geo-referenced maps of APW based on each PA and CT were obtained as well as the map of the total APW after combining waste amounts of the different PAs. The operation of merging and manipulating the maps along with the data computed was performed using the open source QGIS software (QGIS, 2024) by associating fields inside each of the countries attribute table.

3. Results and discussions

3.1. Proportion of UAA

Crop production areas, derived from the national agricultural census of each country under study and aggregated according to the NUTS 2 classification, were overlaid with the overall land area of the corresponding regions. This analysis yielded the proportion of UAA as a percentage in the different regions of each country during the year 2021 (Fig. 1).

The highest observed percentage, equal to 80.3 %, was recorded for the island of Crete in Greece, followed by the Apulia region in Italy with a percentage of 71.8 % and the region of Extremadura in Spain (62.8 %). Although the region of Crete has the highest percentage of UAA, it is considered a small region compared for example to regions of Italy or Spain. Moreover, it has more than 70 % of its UAA as cultivated pastures and the rest are olive trees for oil production.

In contrast, the lowest percentage was recorded for the Madeira and the Azores regions in Portugal accounting for only 4.7 % and 6.4 %, respectively, of the total land designated for agricultural activities. The reason behind this low percentage is that these regions have most of their areas covered with natural forests (Massot, 2015).

The obtained different percentages emphasize the varying degrees of agricultural land utilization across the studied regions with correspondence to the nature of the land and the level of difficulty of exploiting.

A high UAA does not necessarily result in high level of APW generation. UAA is an important determinant of the potential of APW generation in a given region, but the use of agricultural plastic depends on the CT and on the production system adopted locally.

3.2. Total APW estimation

Upon the application of PWIs, maps were generated delineating estimated quantities as well as localization of APW generation. The aggregated data illustrating the total quantity of APW in each region in the year 2021 is represented in Fig. 2 (a), with a more detailed breakdown of each PA considered provided in Appendix B.

In Spain, Andalusia accounted for 324,000 tons of total APW, being the highest in the country as well as the highest between the 4 countries under study. This is due to the high amount of waste generated by nets for crop protection and olive collection as well as the "sea of plastic greenhouses" intended for horticultural production present in this region, particularly concentrated in the province of Almeria, and the prevalent use of Almería-type greenhouses (Valera et al., 2017; Sayadi-Gmada et al., 2019). The lowest estimated amount of total APW in Spain was assigned to the region of Cantabria with an amount of 3157 tons. In Italy, the highest amount of total APW was estimated for Sicily and was equal to 114,523 tons during the year 2021, followed by Apulia region (96,832 tons) with covering films for greenhouses and table grapes being the biggest contributors. The lowest amount estimated in Italy was of 439 tons in the Aosta valley region.

According to a study conducted by Briassoulis et al. (2013) in 2013 about mapping of APW generation and consolidation in Europe, Spain and Italy were the highest consumers of AP products, especially in their southern part, where films for protected cultivations such as greenhouse films, low tunnel films and mulching films were the most contributors to the APW generation. These results are consistent with the current study, since the biggest amount of waste was generated from Andalusia and Castile-La Mancha in South of Spain as well as in Sicily and Apulia in Southern Italy.

In Portugal, the North region had the highest amount of total APW with 35,530 tons of generated waste and with plastic nets for orchard protection being the biggest contributor. While the region of Azores had the lowest amount of total APW equal to 427 tons.

In Greece, the Peloponnese region had the highest estimated amount of total APW of 38,486 tons, with nets dedicated to orchard protection contributing the most to the total APW generated. These results are consistent with the study of Hiskakis et al. (2008), where the region of Peloponnese had the highest total APW between all the regions in Greece estimated at around 9330 tons of APW for the year 2004. On the other hand, the Southern Aegean region had the lowest amount of total APW estimated (3391 tons).

Overall, in the hierarchy of total APW generation comparing all the countries together, as mentioned before, the region of Andalusia in

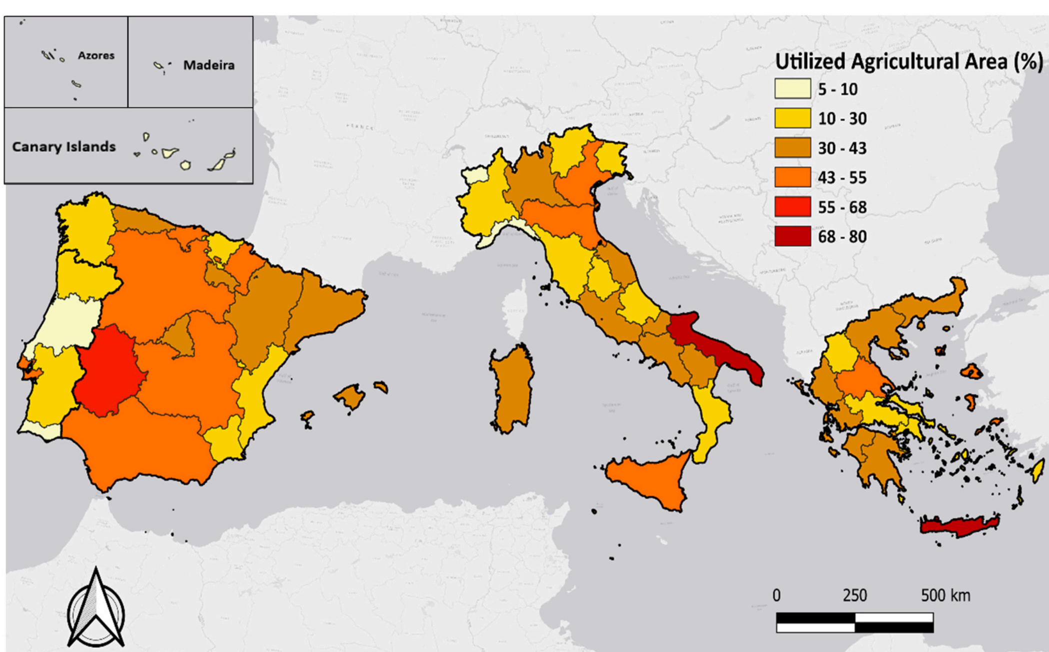

Fig. 1. Proportion of UAA in the regions of the four countries under study.

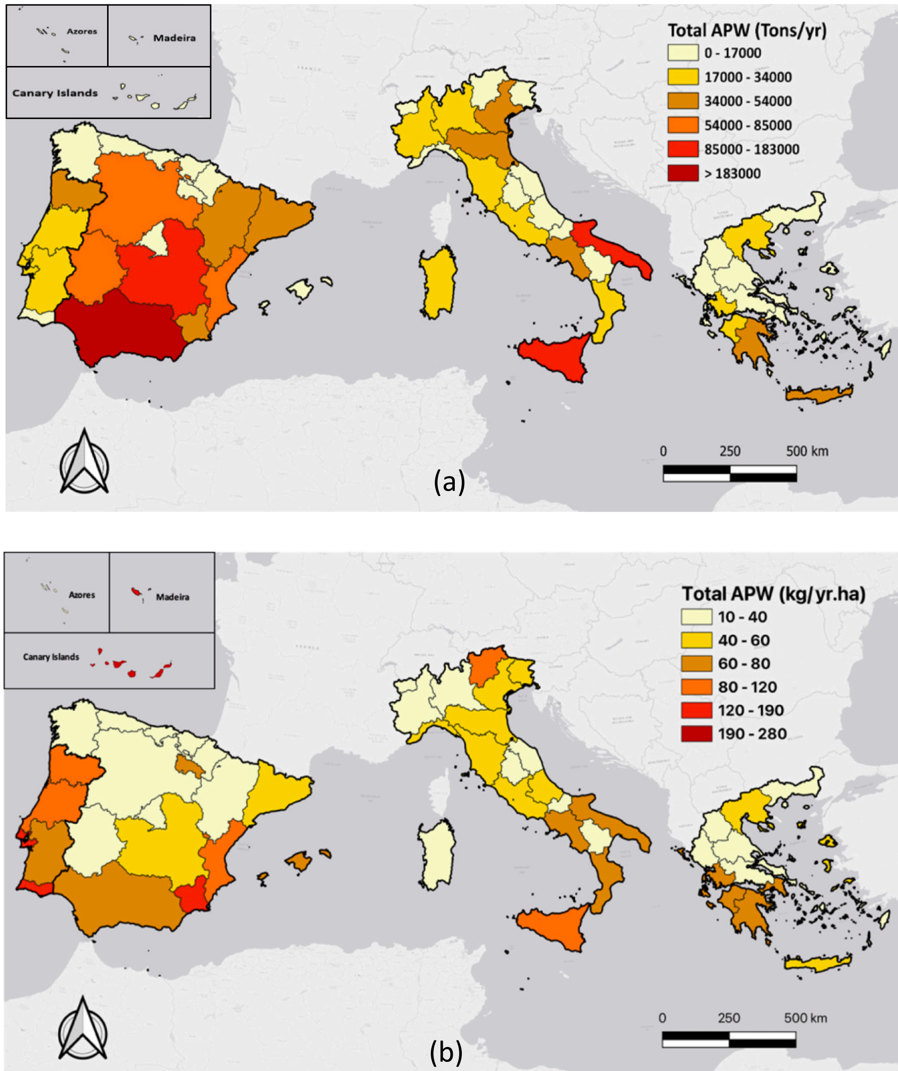

Fig. 2. (a) Total APW distribution and estimated quantities in each of the regions under study; (b) Total APW distribution and estimated quantities considering the utilized agricultural area.

Spain has the highest record of estimated total APW (324,000 tons), followed by the second-highest region which is Castile-La Mancha also in Spain, with an estimated quantity of around 183,000 tons. Conversely, regions displaying the lowest generation of APW between all the countries included the Azores and Madeira regions in Portugal which are mainly islands, as well as the Aosta Valley region in Italy characterized by its mountainous landscape, with estimated quantities of approximately 428 tons, 590 tons, and 439 tons of total APW, respectively. Furthermore, some regions (e.g., Marche, Umbria, Abruzzo, Basilicata, Central Greece, Asturias), presenting relatively medium UAA, have a low APW compared to the other regions that have lower UAA. This is because of the high percentage of cereals and silage crops grown in these regions and in turn of the low PWI associated with these crops.

Unlike Fig. 2 (a) that represents the total APW generated in each region, Fig. 2 (b) shows the total APW per UAA. This value can be high even in presence of a low total APW. A good example can be the Canary Islands, which had a total APW of 14,620 tons/yr, which is considered low, compared to other regions. However, it had the highest total APW per UAA equal to 279.4 kg yr^{-1} ha^{-1}.

3.3. *Covering films plastic waste*

Fig. 3 illustrates the plastic waste estimated from covering films across the four distinct countries. Notably, the data highlights a substantial disparity in waste production, with the region of Andalusia in Spain contributing a significant amount (41,190 tons) in comparison to other Southern European regions. Following Andalusia, the regions of Sicily (15,675 tons) and Apulia (15,503 tons) in Southern Italy exhibit the highest generation of this waste mainly because of the high amount of covering material for table grapes as well as for horticultural crops. Conversely, regions with the lowest estimated quantities of waste from covering films are Azores in Portugal (0 tons), attributed to the absence of greenhouses cultivation as stated in the agricultural census as well as the absence of vineyards coverings, and the Aosta Valley in Northern Italy (1.26 tons), owing to its mountainous topographical characteristics.

3.4. *Agricultural plastic waste generated by mulching films*

Mulching films generated waste is demonstrated in Fig. 4. This type of waste is mainly concentrated in Spain especially in the regions of Andalusia (11,286 tons), Castile-La Mancha (10,232 tons), Murcia (7475 tons) and Extremadura (5726 tons) as well as in Apulia region

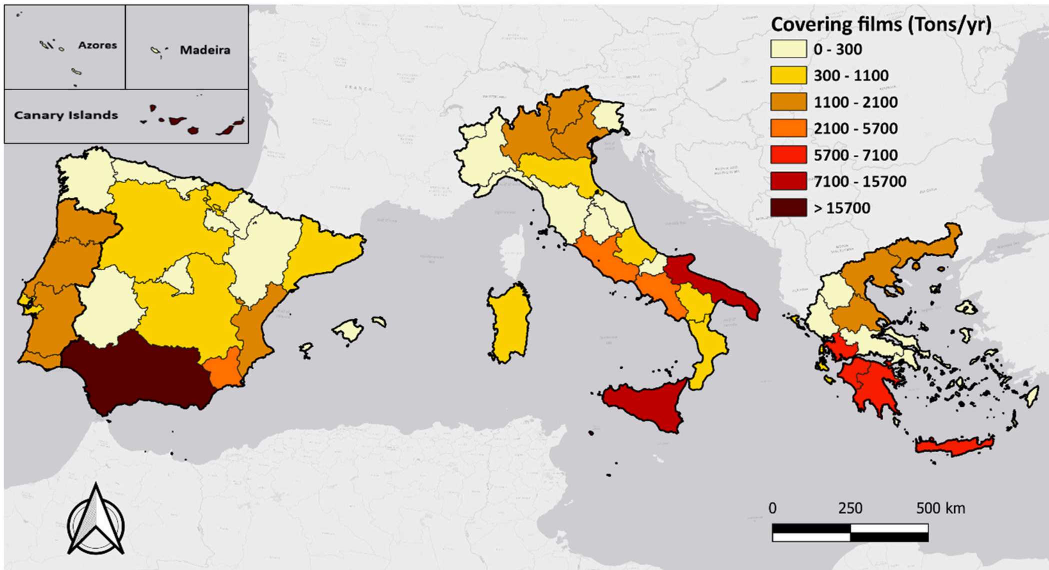

Fig. 3. Covering films waste distribution and estimated quantities in each of the regions under study.

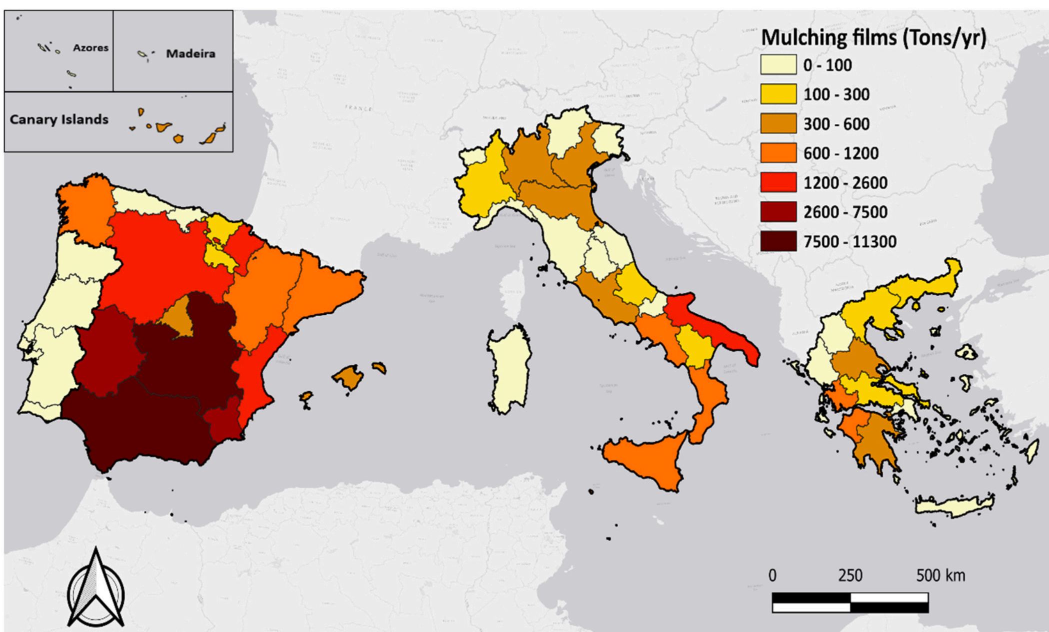

Fig. 4. Mulching films waste distribution and estimated quantities in each of the regions under study.

(1960 tons) in Southern Italy. Mulching films in Spain are usually used for vegetables in open field, as well as for strawberries and melons and these are the main crops that contribute the most to this type of plastic waste. Similarly, in Italy, some vegetables in open field as well as strawberries in greenhouses are mulched and this made Apulia the region with the highest rate of estimated plastic waste generated from mulching films.

3.5. Low tunnels plastic waste

Low tunnels considered in the study (Fig. 5) had the highest impact in the region of Andalusia in Spain with an estimated amount of plastic waste of 32,691 tons, considering that this type of PA is applied inside the greenhouses intended for vegetable crops, melons, and strawberries productions systems. Additionally, it is worth noting that, the region of Sicily in Italy had a relatively high amount of generated plastic waste (10,295 tons) from low tunnels intended to produce melons, watermelons, and strawberries in open field. Other regions with a high amount of plastic waste originated from this type of PA were Lombardy and Lazio in Italy, Murcia in Spain, and Western Greece with amounts of 3654 tons, 3045 tons, 3430 tons and 3095 tons, respectively. The main crops contributing to the waste generated in all these countries were melons, watermelons, and strawberries. In contrast, the lowest amount was recorded in the Aosta valley region in Italy (0.94 tons).

3.6. Irrigation pipes plastic waste

Irrigation systems and pipes can generate a large amount of waste (Fig. 6) depending on the types of irrigated crops and the UAA. It is directly correlated with the type of irrigated crops, but it can be different

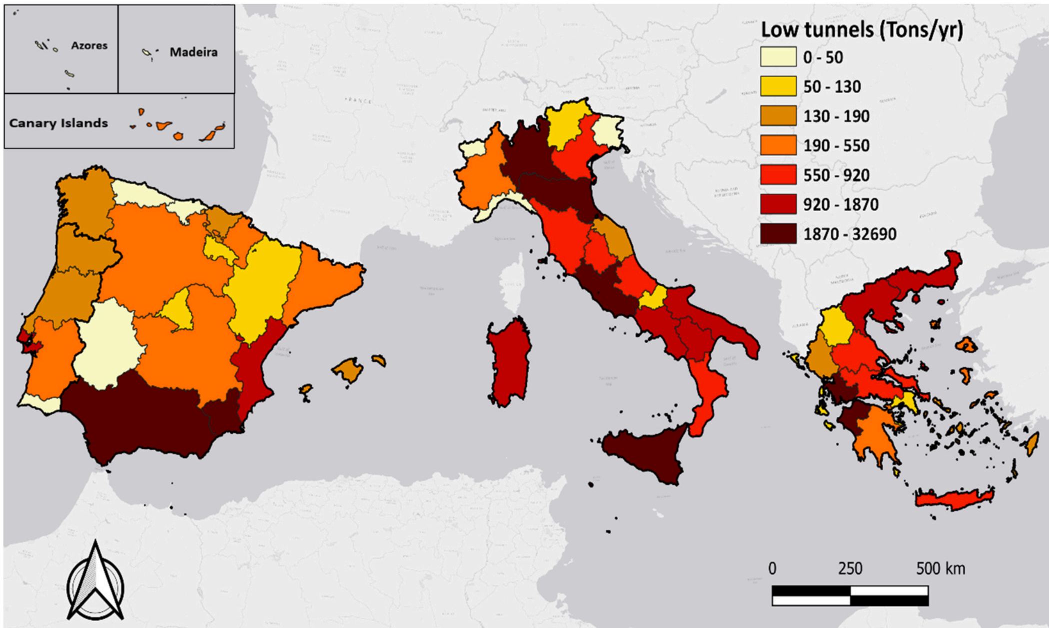

Fig. 5. Low tunnels waste distribution and estimated quantities in each of the regions under study.

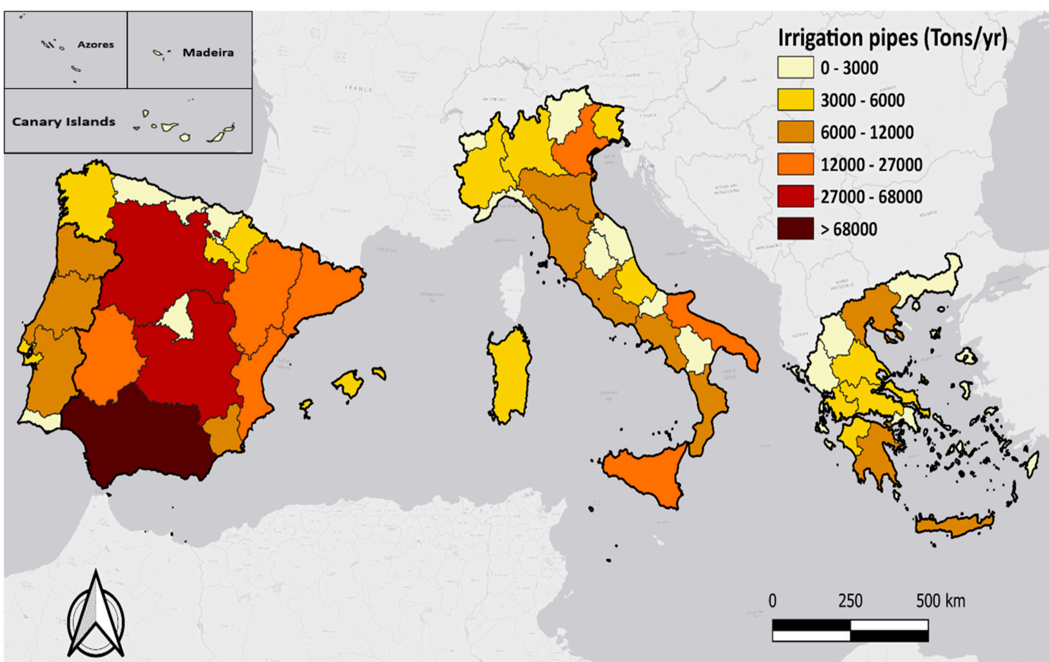

Fig. 6. Irrigation pipes waste distribution and estimated quantities in each of the regions under study.

in the case of UAA. In some cases, such as the one in Spain, where the UAA of Andalusia and Castile and León regions are 4,410,020 ha and 4,715,138 ha, respectively, Andalusia had the highest estimated amount of waste generated from irrigation pipes (98,146 tons), while Castile and León region had a lower amount of 67,671 tons. This is because in Andalusia, most of the irrigated crops (greenhouses crops, vegetables in open field) are more intensified while crops such as pastures and forage crops, which are non-irrigated crops (or crops with conventional irrigation systems) are more dominant in Castile and León regions. As previously mentioned, by taking the overall data elaborated, the highest amount of waste coming from irrigation pipes is mainly in Andalusia region in Spain while the lowest amount was recorded in the Aosta valley in Northern Italy (around 49 tons).

3.7. Nets plastic waste

Plastic waste generated by the usage of nets for plant protection, olive collection and other applications is illustrated in Fig. 7. This PA, like the others, has a wide array of disposed waste ranging from around 100 tons for Aosta valley and Cantabria regions in Northern Italy and Northern Spain, respectively, to around 116,640 tons of disposed nets waste in Andalusia in Southern Spain. This high amount is mainly due to the nets for crop protection in fruit orchards, shading nets for greenhouses and nets for olive collection.

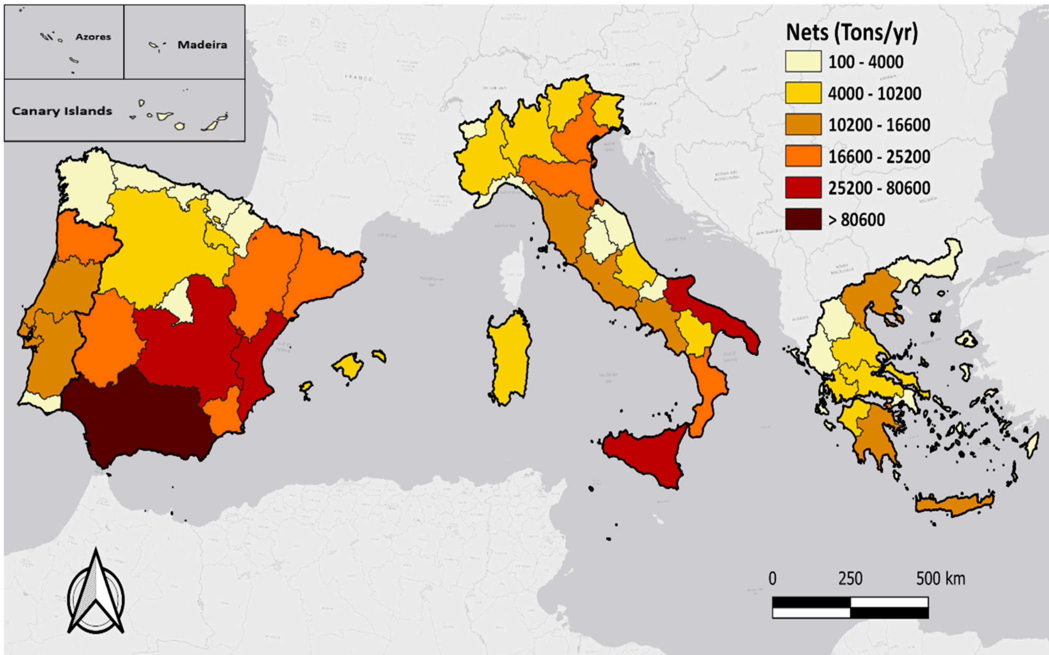

Fig. 7. Nets waste distribution and estimated quantities in each of the regions under study.

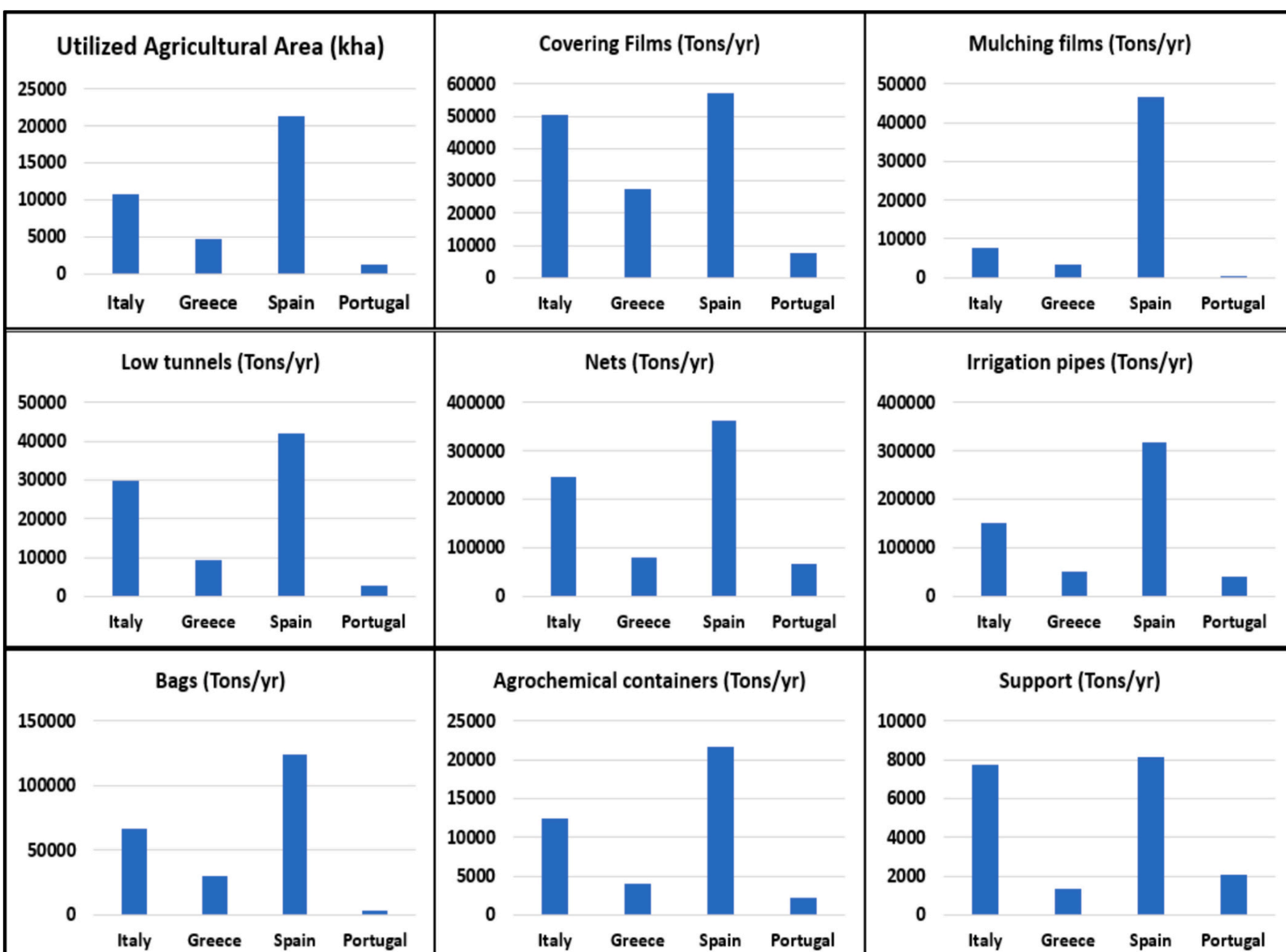

Fig. 8. Comparison of different countries regarding the UAA and estimated quantities of APW from the different PAs.

3.8. APW and UAA comparison between countries under study

Fig. 8 illustrates various histograms representing the UAA and the corresponding waste generated by different PAs in each of the studied countries. The primary purpose is to facilitate a comprehensive comparison among the countries.

Regarding the national agricultural census data, Spain exhibited the largest UAA (21,289,094 ha) and Italy had a UAA of 10,782,481 ha. Comparatively, according to EUROSTAT database, statistical data of the year 2020 revealed that Spain had around 24 million hectares of UAA, almost double to that of Italy which is around 12 million hectares (EUROSTAT, 2023). This indicates the accuracy of the data elaborated in this study from the national agricultural census of each country which is illustrated in Fig. 8. Additionally, the presence of some differences between the values of the agricultural census considered in this study and those of EUROSTAT is mainly because the latter considers livestock production as part of the UAA. The EUROSTAT database also indicated the minimal UAA in both Greece and Portugal, in line with this study's elaborated data, which were around 3 million hectares and 4 million hectares, respectively (EUROSTAT, 2023).

To this extent, considering the data from the national agricultural census, Portugal recorded the lowest UAA at 1,247,779 ha, constituting approximately 13.5 % of Portugal's total area. This trend is consistent across the histograms in Fig. 8, revealing a correlation between the waste generated by various PAs and the UAA when considering the entire country.

The analysis further indicated that Italy and Spain had the highest APW generation, through all the applications (572,000 and 982,000 tons, respectively), while Greece and Portugal exhibited the lowest levels (207,000 and 125,000 tons, respectively). This discrepancy can be attributed not only to the highest UAA in Italy and Spain, but also to the substantial intensity of agricultural production in Italy and Spain, where these two countries notably contributed the most among the Southern European countries included in the study.

4. Conclusions

Agricultural plastic waste represents a significant environmental challenge that has so far been inadequately and insufficiently addressed by the research community, particularly regarding its impact on terrestrial ecosystems. One of its primary implications is the contamination of soils with micro and nano plastics and the resulting chain of negative consequences. This study aimed to initiate the planning for the management of agricultural plastic waste in a well-defined geographic area by quantifying and localizing the generated waste from agricultural applications across four Southern European countries (Italy, Spain, Greece, and Portugal) at a regional level of detail, corresponding to NUTS 2 classification.

The proposed methodology implies the collection of statistical data, literature review and direct interactions with farmers allowing the definition of specific plastic waste indices. These indices are a function of the adopted agricultural techniques and plastic products used and are specific for the crop type and for the region. Their implementation is essential to quantify the plastic waste from each plastic application and for each crop in each country. The integration of such data with the functionality of a GIS allows the creation of a georeferenced database, the production of maps easily updatable over time and ultimately, the creation of a digital atlas of the agricultural plastic waste.

The investigation proposed in this study following this specific methodology revealed that Spain had the highest quantity of overall generated agricultural plastic waste, followed by Italy, Greece, and Portugal, respectively. Within each country, regions with the highest and lowest concentrations also emerged. Results were provided per plastic application and per crop as well. Overall, it was found that the highest quantities of plastic waste came from nets, irrigation pipes and bags, followed by covering films and then the other plastics. The observed variations in waste generation among countries and regions were associated with the utilized agricultural area, exhibiting a proportional relationship dependent on the type of crops grown and the production systems employed. Additionally, the study validated the data through collaboration with relevant entities in each country.

The followed approach and the obtained results highlight the power of the developed tool. This can be valuable for policymakers and stakeholders to quantify the amount of agricultural plastic waste in defined areas, identifying the most impactful applications and the areas with more intense waste production. This can help to assess possible intervention strategies, design specific infrastructures, and analyse possible development scenarios for rural areas. Waste mapping can be useful for localizing waste collection centres at different levels, considering the variation of quantity and localization due to the seasonality of the agricultural production.

Finally, this study intends to provide a first answer to the pressing need for further research into the quantification and localization of agricultural plastic waste due to its escalating annual accumulation and the current research gap in this domain. This and further endeavours will enhance the comprehension of the dynamics involved in the production of this waste, ultimately contributing to its effective and efficient management.

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CRediT authorship contribution statement

Ali Hachem: Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Fabiana Convertino:** Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Teresa Batista:** Writing – review & editing, Validation, Data curation. **Fátima Baptista:** Writing – review & editing, Validation, Data curation. **Demetres Briassoulis:** Writing – review & editing, Validation, Data curation. **Diego Luis Valera Martínez:** Writing – review & editing, Data curation. **María Ángeles Moreno Teruel:** Writing – review & editing, Validation, Data curation. **Luca Nizzetto:** Writing – review & editing, Funding acquisition. **Nikoleta-Georgia Papardaki:** Validation, Data curation. **Giuseppe Ruggiero:** Writing – review & editing. **Giuliano Vox:** Writing – review & editing, Supervision, Conceptualization. **Evelia Schettini:** Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Plastic waste index (kg/ha/yr)	Covering films		Mulching films		Low tunnel films		Nets		Irrigation pipes		Agrochemical containers		Bags		Support	
Italy	Vineyards	613.8	Greenhouses	154.0	Vegetables in open field	936.0	Vineyards (anti-hail nets)	159.0	Vineyards	60.0	Wine grapes	6.0	Vineyards	1.6	Table grapes	24.5
	Orchards	764.2	Vegetables in open field	154.0			Olive groves (nets for olive collection)	43.2	Olive groves	36.0	Table grapes	10.0	Olive groves	0.5	Wine grapes	9.7
	Greenhouses	565.0					Orchards (nets for crop protection)	192.2	Orchards	45.0	Olive groves	0.6	Orchards	2.2		
							Greenhouses (shading nets)	133.3	Vegetables	50.0	Orchards	1.8	Vegetables	2.5		
									Greenhouses	75.0	Vegetables	1.7	Cereals	2.7		
											Cereals	0.6	Greenhouses	2.0		
											Greenhouses	3.4	Silage	12.0		
Spain	Vineyards	613.8	Greenhouses	200.5	Vegetables in open field	334.8	Vineyards (anti-hail nets)	99.4	Vineyards	60.0	Wine grapes	6.0	Vineyards	1.6	Table grapes	24.5
	Orchards	764.2	Vegetables in open field	200.5	Greenhouses (Double roof)	697.5	Olive groves (nets for olive collection)	43.2	Olive groves	36.0	Table grapes	10.0	Olive groves	0.5	Wine grapes	9.7
	Greenhouses	878.9					Orchards (nets for crop protection)	120.1	Orchards	45.0	Olive groves	0.6	Orchards	2.2		
							Greenhouses (shading nets)	87.2	Vegetables	50.0	Orchards	1.8	Vegetables	2.5		
							Greenhouses (vents-anti-insect nets)	8.3	Greenhouses	75.0	Vegetables	1.7	Cereals	2.7		
							Greenhouses (nets for crop protection)	82.8			Cereals	0.6	Greenhouses	2.0		
											Greenhouses	3.4	Silage	12.0		
Greece	Vineyards	613.8	Greenhouses	154.0	Vegetables in open field	936.0	Vineyards (anti-hail nets)	159.0	Vineyards	60.0	Wine grapes	6.0	Vineyards	1.6	Table grapes	24.5
	Orchards	764.2	Vegetables in open field	154.0			Olive groves (nets for olive collection)	43.2	Olive groves	36.0	Table grapes	10.0	Olive groves	0.5	Wine grapes	9.7
	Greenhouses	565.0					Orchards (nets for crop protection)	192.2	Orchards	45.0	Olive groves	0.6	Orchards	2.2		
							Greenhouses (shading nets)	133.3	Vegetables	50.0	Orchards	1.8	Vegetables	2.5		
									Greenhouses	75.0	Vegetables	1.7	Cereals	2.7		
											Cereals	0.6	Greenhouses	2.0		
											Greenhouses	3.4	Silage	12.0		
Portugal	Vineyards	613.8	Greenhouses	154.0	Vegetables in open field	936.0	Vineyards (anti-hail nets)	159.0	Vineyards	60.0	Wine grapes	6.0	Vineyards	1.6	Table grapes	24.5
	Orchards	764.2	Vegetables in open field	154.0			Olive groves (nets for olive collection)	43.2	Olive groves	36.0	Table grapes	10.0	Olive groves	0.5	Wine grapes	9.7
	Greenhouses	878.9					Orchards (nets for crop protection)	192.2	Orchards	45.0	Olive groves	0.6	Orchards	2.2		
							Greenhouses (shading nets)	240.0	Vegetables	50.0	Orchards	1.8	Vegetables	2.5		
									Greenhouses	75.0	Vegetables	1.7	Cereals	2.7		
											Cereals	0.6	Greenhouses	2.0		
											Greenhouses	3.4	Silage	12.0		

Appendix B

Region	UAA (ha)	Covering films (Tons/yr)	Mulching films (Tons/yr)	Low tunnels (Tons/yr)	Nets (Tons/yr)	Irrigation pipes (Tons/yr)	Bags (Tons/yr)	Containers (Tons/yr)	Support (Tons/yr)	Total (Tons/yr)
Abruzzo (IT)	306,647	474	276	807	7836	4950	1699	400	332	16,773
Alentejo (PT)	440,228	2111	18	513	15,785	12,034	996	521	338	32,316
Algarve (PT)	37,716	1314	2	49	3984	1486	83	61	16	6995
Andalusia (ES)	4,410,020	41,191	11,287	32,691	116,640	98,146	19,977	3797	192	323,921
Aosta Valley (IT)	21,453	1	0	1	120	49	248	16	4	439
Apulia (IT)	1,392,815	15,503	1961	1865	41,335	26,859	6113	1717	1479	96,831
Aragon (ES)	1,785,724	170	885	82	20,548	21,023	9787	1653	307	54,455
Asturias (ES)	319,814	83	70	45	619	761	3666	210	1	5454
Attica (GR)	63,502	158	122	57	2497	1653	300	87	74	4948
Azores (PT)	15,090	0	1	32	145	72	166	11	0	427
Balearic Islands (ES)	153,360	230	471	140	4933	3464	671	181	27	10,117
Basilicata (IT)	348,820	700	243	1220	4438	2215	2151	254	32	11,254
Basque Country (ES)	171,679	369	188	185	1931	1591	1350	198	139	5952
Calabria (IT)	427,304	621	783	923	18,099	10,729	1594	403	95	33,247
Campania (IT)	518,999	5693	764	1840	15,846	10,369	2891	616	251	38,270
Canary Islands (ES)	52,323	5736	538	2833	3307	1748	303	102	53	14,620
Cantabria (ES)	226,083	27	18	13	70	228	2658	141	1	3157
Castile and León (ES)	4,715,138	404	2568	280	8685	39,733	28,987	3959	609	85,226
Castile-La Mancha (ES)	3,442,799	694	10,232	347	80,640	67,671	14,199	5035	4059	182,878
Catalonia (ES)	1,041,512	661	1164	334	23,966	16,515	5463	1179	577	49,859
Central Greece (GR)	412,847	100	330	897	4254	4092	2795	303	49	12,819
Central Macedonia (GR)	741,425	1741	266	1417	15,641	7327	2934	628	100	30,054
Central Portugal (PT)	263,523	1823	7	187	16,228	7912	866	482	473	27,979
Community of Madrid (ES)	245,859	122	536	79	1732	2003	1704	199	57	6432
Crete (GR)	672,836	7134	126	783	13,165	9164	5284	548	257	36,461
East Macedonia and Thrace (GR)	430,790	1813	190	1193	2694	2299	2170	333	97	10,789
Emilia-Romagna (IT)	970,234	569	540	2184	18,282	10,483	6486	1041	514	40,098
Epirus (GR)	289,837	235	61	183	2871	1497	2876	191	4	7917
Extremadura (ES)	2,614,805	83	5727	36	25,178	21,723	23,008	2199	766	78,721
Friuli-Venezia Giulia (IT)	171,762	17	9	8	4998	3871	801	306	279	10,291
Galicia (ES)	587,928	308	773	190	2094	5164	5886	515	112	15,044
Ionian Islands (GR)	75,591	909	101	71	1964	1473	439	71	52	5080
Lazio (IT)	593,821	5334	413	3045	11,739	7969	4408	806	222	33,935
Liguria (IT)	38,628	25	34	6	1069	821	227	35	17	2235
Lisbon metropolitan area (PT)	146,734	1068	60	1711	11,397	6179	199	366	473	21,453
Lombardy (IT)	953,729	1160	381	3654	4932	5086	7391	783	232	23,618
Madeira (PT)	4287	64	1	39	344	119	11	7	4	589
Marche (IT)	355,176	31	68	168	3234	2617	2006	329	154	8607
Molise (IT)	172,058	39	31	122	1670	1267	1115	143	54	4440
Navarre (ES)	459,795	339	2277	238	2952	3987	2963	434	177	13,366
North Aegean (GR)	165,215	85	30	201	2929	2254	1186	119	25	6830
Northern Portugal (PT)	339,201	1192	6	186	19,419	12,146	1031	760	790	35,529
Peloponnese (GR)	477,594	7033	554	546	16,588	10,353	2609	480	322	38,486
Piedmont (IT)	678,975	136	252	238	10,196	5786	3704	720	420	21,450
Region of Murcia (ES)	310,686	4903	7475	3430	22,984	11,861	757	555	194	52,159
Rioja (ES)	197,129	138	309	53	6072	3852	1166	384	431	12,406
Sardinia (IT)	827,210	684	137	1229	6883	4373	8492	677	272	22,746
Sicily (IT)	1,310,266	15,676	1190	10,295	50,956	25,388	7482	1908	1628	114,523
Southern Aegean (GR)	134,961	126	46	161	931	663	1347	95	20	3391
Thessaly (GR)	635,099	1304	616	742	4466	3806	3923	486	87	15,430

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(*continued*)

Region	UAA (ha)	Covering films (Tons/yr)	Mulching films (Tons/yr)	Low tunnels (Tons/yr)	Nets (Tons/yr)	Irrigation pipes (Tons/yr)	Bags (Tons/yr)	Containers (Tons/yr)	Support (Tons/yr)	Total (Tons/yr)
Trentino-South Tyrol (IT)	146,950	1352	4	84	8323	2470	1276	216	155	13,879
Tuscany (IT)	541,986	180	95	773	13,303	8004	3235	672	556	26,818
Umbria (IT)	247,074	10	63	567	3255	2926	1542	243	121	8726
Valencian Community (ES)	554,440	1599	2076	930	41,573	19,090	1972	955	469	68,663
Veneto (IT)	758,575	2096	395	811	18,991	15,801	3430	1197	927	43,647
West Macedonia (GR)	277,345	87	37	127	1601	1617	1751	213	23	5455
Western Greece (GR)	419,692	6681	875	3095	9325	6012	2595	395	229	29,207

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