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Prospective Scenarios for Addressing the Agricultural Plastic Waste Issue: Results of a Territorial Analysis

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Abstract: Agricultural activities have been positively affected by the use of plastic products, but this has resulted in the production of plastic waste and led to an increase in environmental pollution. To continue benefiting from the use of plastics but addressing at the same time the environmental issue, two strategies seem viable: the development of technologies for extending plastics lifespan and the gradual replacement of traditional non-biodegradable materials by biodegradable ones, at least for some products. This study focuses on a territorial analysis, performed using a Geographic Information System (GIS) in an agricultural area of the Apulia region (southern Italy). Areas of agricultural plastic waste production were identified through land-use maps. The application of plastic waste indices to different crop types and plastic products allowed quantifying and georeferencing actual plastic waste production. From this actual visualization, the other strategies were obtained by properly managing the indices. Two improved scenarios were obtained, the first consisted of extending the lifespan of some plastics, and the second entailed the introduction of some biodegradable alternatives. About 11,103 tons of agricultural plastic waste are yearly produced in the area and 7450 tons come from covering films. Lifespan extension would reduce the annual waste amount by about 25%, while more alternative products are needed to achieve significant results in the second scenario.

Keywords: sustainability; GIS; land use; plastic detection; waste management; biodegradable plastic; products lifespan

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1. Introduction

Plastic products are ubiquitous in our society, and it seems impossible to think of a world without plastics. This is because plastic has contributed to improving and facilitating many economically based activities, and agriculture is one of them. In 2021, global plastics production continued to grow, reaching more than 390 million tons, 90.2% of which are still produced from fossil-based feedstock. This is not considered acceptable anymore, especially in the optics of the circular and climate neutral plastics economy, in which plastics are produced, converted, used, and managed in a sustainable way, preventing their waste ending up in the environment [1,2]. The biggest plastics markets are those of packaging and construction. Agriculture, together with farming and gardening, accounts for 3.1% of the plastic demand. Nevertheless, these agricultural plastics are responsible for the pollution of the environment and especially of the soil [3–5]. In 2021, plastics used in this sector have been characterized by the highest percentage of recycled content, 25.4%, compared to all the other applications [1]. In 2020, 37% of the plastic waste produced by agriculture, farming, and gardening in the European Union was sent for recycling and 36% for energy recovery, and the remaining 26% ended up in landfills [6]. Further efforts are needed, and agriculture and related sectors can significantly contribute to a sustainable transition. The main challenges to achieve plastic circularity concern the production of high-performance products and the improvement of collection and sorting systems, as well as the increase in recycling efficiency.

Plastic products used in agriculture, especially in modern practices, help to improve productivity, as well as to reduce food losses and waste and to achieve higher food security [7]. The great success of plastics in agriculture is related to their peculiarities: the lightness and the good mechanical properties, the ease of installation, use and management, versatility of applications, and low cost. Among the most used agricultural plastics, there are mulching films, tunnel and greenhouse films and nets, irrigation pipes, bags and sacks for seeds and fertilizers, silage films, bottles for pesticides and fertilizers, coatings, non-woven protective textiles, fruits and plants protectors, strings and ropes, and other plastics used to store, transport, and sell agricultural products. Plastics are based on synthetic or semisynthetic polymers of organic molecules, designed to obtain a wide variety of products with different properties. Most plastics also contain additives added to the compound to provide the polymer with some specific properties required for the final product. A wide range of plastic polymers with proper additives and physical properties is used in agriculture [8,9]. It is a date of fact that there is a high variability between the different plastic products. Furthermore, the useful lifespan varies a lot depending on the application and the context of use. With some exceptions, most of the plastic products are single-use and reach their end of life in less than one year. This means that there is a relevant problem concerning the plastics' end of life, causing them to be one of the main sources of waste. This high quantity and the quality of agricultural plastic waste (APW) needs a proper management system that includes the collection, disposal, and possible recycling of plastic material. This system should consider the chemical composition of the APW and that it is often contaminated with chemicals or dirt of soil and organic matter [10]. APW represents a complex issue and a serious environmental problem. APW mismanagement and bad practices, such as abandonment, burying, or burning in fields and disposal in landfills, are inevitably and irreparably harming ecosystems [11–13].

The main point is continuing to benefit from the advantages that plastic products provide but at the same time stopping or minimizing the environmental damage. Correct management is the first imperative. Another actionable strategy is to try to limit the APW problem upstream by reducing the waste quantities. This can be considered a step forward in reducing the APW footprint in the environment, which has been escalating drastically during the years. This can be done by two complementary approaches: extending the plastics lifespan by developing appropriate technologies and practices, as well as replacing traditional plastics with nature-based sustainable solutions. In this second case, it could happen that the lifespan of the bio-based products is shorter or longer than that of traditional materials. If it is shorter, the quantity of waste would be higher, but it is not considered plastic waste at all. Consequently, these materials do not require disposal or any further complex procedure and can help to reduce the environmental impact.

The results of this study come from the above considerations. Since correct management should start from the classification and quantification of APW and from the knowledge of its flow in an agricultural area, the availability of a geo-referenced database is considered a very useful tool in this context [14,15]. Such tool allows the mapping and the continuous updating of APW information in relation to the territory, and it can be realized by using geographic information systems (GISs) [16–18]. A GIS is a computer program that allows one to assemble, store, modify and display data by their geographic location. It contains geographical objects with their attributes and allows making elaborations of the database by operating on the attribute table [19].

In this paper, the methodology based on GIS was applied for quantifying and mapping the main sources of APW in the territory. It was investigated in an optimal collection area that includes four municipalities. Diverse crop types (CTs) were considered, and their related plastic applications (PAs) were evaluated. The application of the derived plastic waste indices (PWIs) allowed the mapping of the actual APW situation.

Two scenarios were hypothesized to decrease APW: longer lifespan (first scenario) and sustainable replacement of some plastic materials (second scenario). Moreover, the combination of the two scenarios (scenario comb.) was also considered. Based on this assumption, PWIs and APW were modified.

The obtained database can be a useful tool for policymakers and stakeholders for monitoring the real situation, promoting the development of proper management systems, and visualizing possible scenarios that can improve the state of APW and their effective handling through the adoption of more sustainable strategies.

2. Materials and Methods

The study area consists of 4 different municipalities in the province of Bari, located in the Apulia region, in the south of Italy. The mean coordinates of the area are latitude 40.962834° and longitude 17.207541° and the elevation ranging from 0 m asl to 408 m asl. The area is characterized by a mean annual precipitation ranging from 596 mm to 622 mm and by an annual solar irradiance equal to 5124 MJ m^{-2}. The municipalities are Mola di Bari, Conversano, Polignano a Mare, and Monopoli and cover an area of about 400 km^2. They are grouped together since they constitute a single optimal collection administrative area for waste management. In fact, Apulia's regional waste planning defines a single optimal territorial area, equal to the whole region and responsible for waste collection and disposal services, and several optimal collection areas, including a different number of municipalities, for the provision of sweeping, collection, and transportation services in order to maximize their efficiency. The study area is particularly suited to agriculture, and therefore, APW production is intense. The main crops grown inside this territory are olive trees, orchard trees such as almonds, and horticultural crops in open fields, as well as, in greenhouses, wine and table grapes and cereals. Furthermore, there are many nurseries growing horticultural crops and ornamental plants for commercial sale. Most of these nurseries are in the municipality of Monopoli. The land-use map (updated to 2022) of the study area, as well as its boundaries, are shown in Figure 1. For the elaborations of the land-use map, as well as the other maps, the free QGIS software [20] was used.

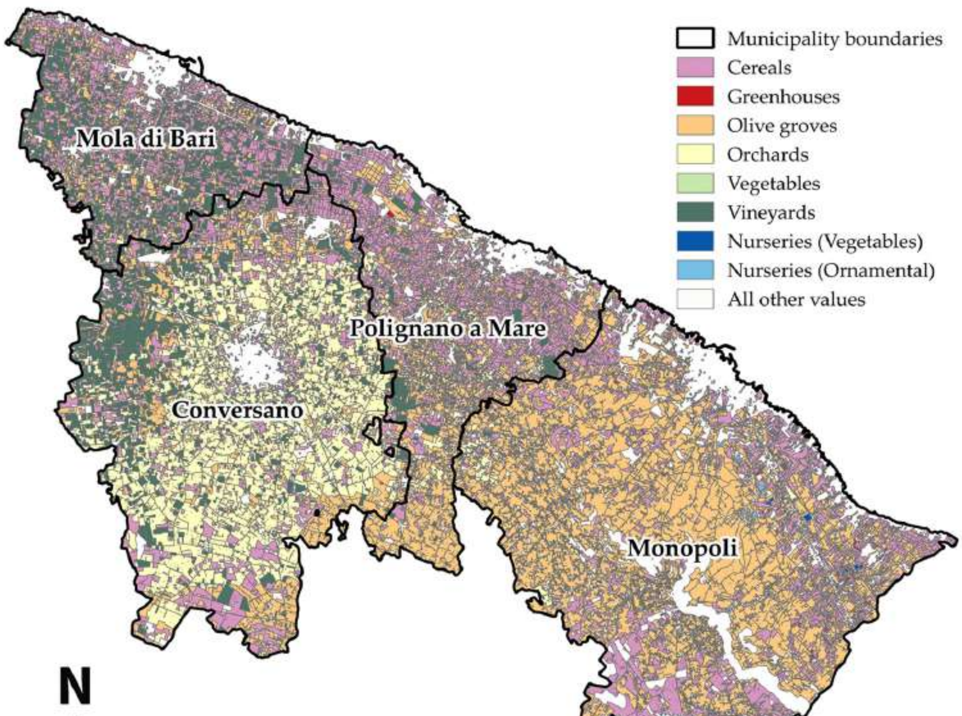

Figure 1. Land-use map of the study area taken by elaborations made using the QGIS software.

As a result of the territorial analysis, maps considering the real-time scenario that characterizes the actual state of the APW in the four different municipalities were obtained. Moreover, two different scenarios were simulated to evaluate how it may affect the APW. The 1st scenario considered the extension of the life duration of some plastic materials used in several PAs and for which that extension is deemed really feasible. Life extension was proposed according to the maximum recorded useful life of the materials available on the market. These values are based on the surveys delivered to farmers, manufacturers, and stakeholders and on the database of plastic materials held at the University of Bari. Improvements in plastics lifespan can be obtained by using highly effective additives able to hamper polymer degradation due to solar radiation exposure. The 2nd scenario was oriented towards the replacement of some of the plastic materials, mostly with biodegradable materials, such as starch-based mulching films. They can be disposed of in the soil, where bacterial flora transforms them into biomass, methane, carbon dioxide, and water without plastic waste generation. Products already on the market were considered. The different changes in the PAs are addressed in the Table 1. Maps showing APW density as a result of the application of the actual and improved scenarios were produced. They are useful tools for identifying the areas on the land where the application of the different improved scenarios is more effective.

Table 1. Scenarios changes in respect to real-time scenario; 1st scenario based on the maximum useful life of the materials on the market; 2nd scenario based on the use of materials not generating plastic waste.

Plastic Application	Useful Life Extension 1st Scenario	Plastic Material Replacement 2nd Scenario
Plastic films	Addition of 1 year	-
Mulching films	-	Biodegradable mulching films
Irrigation pipe lines	Addition of 5 years	-
Olive collection nets	Addition of 10 years	-
Anti-hail nets for vineyards	Addition of 2 years	-
Orchard nets	Addition of 2 years	-
Greenhouses shading nets	Addition of 3 years	-
Vineyard hooks	Addition of 1 year	-
Vineyard pole ties	-	Biodegradable ties
Vineyard pole caps	-	Recyclable non-plastic pole caps
Vineyard cigar drippers	Addition of 1 year	-
Vineyard block cruises	Addition of 2 years	-
Plastic seeding trays for greenhouses and open-field crops	-	Biodegradable seeding trays

APW management is an issue that requires the involvement of different sectors to minimize its impact on the environment. In this study, a GIS database was created to georeference the APW in the area, characterizing the real-time scenario of APW distribution and the two improved scenarios, based on the following methodology:

1. Identifying the main crops through the support of the land-use map and the nurseries through their direct identification, thus creating the final land-use map on QGIS software (Figure 1);
2. Identifying the PAs for each CT, such as covering and mulching films, plastic nets (crop protection, olive collection . . .), irrigation pipes, plastic bags (fertilizers, peat storage . . .), pesticides containers, support system accessories (mainly for vineyards), and seed plastic trays [21];
3. Creating several PWIs based on the CT (vineyard, olive grove, orchard, greenhouse, vegetable, nursery ornamental/vegetable, cereals) and the characteristics of the ap-

plied plastics (density, dimensions, useful life, application techniques) for the real-time scenarios and for the improved scenarios;
4. Assigning the actual and modified PWIs to their relative CTs on the land-use map by means of the calculator of the attribute table in QGIS software;
5. Realization of total APW maps in the study area for different scenarios by using QGIS software;
6. Evaluating the quantities of the total APW based on the utilized agricultural area in the different scenarios by using the database extract from the attribute table.

For the calculation of the different PWIs, plastic properties such as the density of the plastic used and its thickness, as well as the lifespan of the material, were evaluated, based on the relationships from Blanco et al. [17] and Cillis et al. [18]. For instance, the PWI [kg ha^{-1} yr^{-1}] of the mulching films used in the study was obtained using the following equation:

$$PWI_{mulchingfilms} = \frac{\rho \cdot T}{years} \cdot F_{correction}, \quad (1)$$

where ρ [kg m^{-3}] is the density of the plastic used in the mulching films, T [m] is its thickness, *years* is the duration of its life, and $F_{correction}$ is the dimensionless correction factor used, based on the slope of the plastic material in relation to its coverage on the soil surface [18]. The sum of the PWIs for each PA related to the specific CT gives the overall PWI per CT.

Maps were obtained starting from the data available due to the existence of the territorial information system of the Apulia Region [22]. For the base map, materials used were: the Google satellite images [23], the municipality boundaries, the land-use map, and the regional technical map of the Apulia Region.

The maps created with QGIS software were placed in the WGS 84/UTM zone 33N reference system. Both the land-use map and the regional technical map consisted of several shapefiles which were merged to create only one which is clipped to the municipality boundaries of the area. The land-use map (updated to 2022) and the polygons (features or territorial units) of the technical map were used to extract information about the CTs distribution by using the categorizing tool in QGIS software. Google satellite images helped the identification of the nurseries both through the commercial addresses and by their shape. In this way, the area covered by each nursery was detected, and also its type (ornamental or vegetable), was identified.

Once the CTs were identified in the area and the final land-use map (Figure 1) was elaborated, the database was modified by adding new fields in the attribute table. The added data concern the area of each feature (S_i, ha) and the PWI for each CT (PWI_{CT}) and for the different scenarios. This allowed the calculation of the APW for each CT (APW_{CT}, kg yr^{-1}):

$$APW_{CT} = S_i \cdot PWI_{CT}, \quad (2)$$

Then, the overall amount of APW for the study area was calculated as the sum of the APW for each CT.

3. Results and Discussion

The values of the PWIs for the different CTs and the diverse PAs are shown in Table 2. After several investigations (using the QGIS database, visits to farms, and contacts with farmers of the area) and after all the calculations (concerning the PWIs for the different scenarios and the attribute tables in QGIS) were performed using the properties of the plastic material and the results of some field surveys from farmers, the APW in the area was characterized. It was found that bags for fertilizers and plastics used for the packing of agricultural products are utilized in all types of crops. It recorded the highest values for nurseries, both vegetables and ornamental, with 307 kg ha^{-1} y^{-1} and 154 kg ha^{-1} y^{-1}

of plastic waste, respectively, since the nurseries have a large amount of material arriving each year packed in plastic films and directly unfolded and thrown away.

Table 2. Plastic waste index for each plastic application and for each crop type.

Plastic Application	Plastic Waste Index [kg ha^{-1} y^{-1}]							
	Vegetables	Greenhouses	Vineyards	Olives	Orchards	Cereals	Nurseries (Vegetables)	Nurseries (Ornamental)
Films	-	564.97	613.80	-	764.15	-	564.97	564.97
Nets	-	133.33	159.03	43.20	192.16	-	-	-
Irrigation pipes	50.00	75.00	60.00	36.00	45.00	-	-	-
Mulching films	154.00	154.00	-	-	-	-	-	-
Bags	2.50	2.00	1.60	0.50	2.20	2.70	307.00	154.03
Containers	1.70	3.40	8.00	0.63	1.80	0.60	15.00	5.60
Seeding trays	181.35	146.25	-	-	-	-	-	-
Support accessories	-	-	17.05	-	-	-	-	-

Overall, plastic films used to cover greenhouses, vineyards, orchards, and nurseries had the highest contribution to APW, with PWI ranging from 565 kg ha^{-1} y^{-1} to 764 kg ha^{-1} y^{-1}, in addition to the plastic nets, mulching films, and seeding trays with values ranging from 43 kg ha^{-1} y^{-1} to 192 kg ha^{-1} y^{-1}.

The smallest contribution to APW was recorded from the bags used for fertilizers, the containers for pesticidal application, and irrigation pipes, with values ranging from 0.5 kg ha^{-1} y^{-1} (bags for olive collection) to 75 kg ha^{-1} y^{-1} (irrigation pipes for greenhouses).

In a study conducted by Blanco et al. [17] on mapping APW using GIS in Italy, the results were in accordance with the results of our study, wherein the highest contribution was recorded for plastic films (613 kg ha^{-1} y^{-1} to 764 kg ha^{-1} y^{-1}), followed by plastic nets (141 kg ha^{-1} y^{-1} to 192 kg ha$^{-1\ -1}$), irrigation pipes (50 kg ha^{-1} y^{-1} to 104 kg ha^{-1} y^{-1}), and finally fertilizers bags and agrochemical containers (0.5 kg ha^{-1} y^{-1} to 4 kg ha^{-1} y^{-1}).

Similar results were obtained by Cillis et al. [14], who considered only plastic films, mulching films, and irrigation pipes in mapping APW through the provinces of Italy on some protected and open-field crops. The highest values were assimilated to the plastic films, followed by the mulching films and the irrigation pipes, with corresponding values of 1500 kg ha^{-1} y^{-1}, 100 kg ha^{-1} y^{-1}, and 40 kg ha^{-1} y^{-1}, respectively.

The application of the PWIs for each CT of the area allowed the obtention of the overall APW yearly produced per surface unit (Figure 2) in the four municipalities. The municipality with the highest APW density was Conversano, where farms are mainly orchards and vineyards, characterized by higher PWIs. In this actual scenario the total amount of APW yearly produced in the area was equal to about 11,103 tons. Although olive groves cover most of the area (39.1%), the highest contribution to the APW does not come from them. The most impactful farms are orchards, contributing 60.6% to the annual APW, followed by vineyards (28.8%) and then olive groves (9.1%) (Figure 3).

The extension of the useful life (1st scenario) of some plastics (Table 1) allowed the obtention of the first improved scenario (Figure 4). In this 1st scenario, the highest reduction of the PWI was achieved for olive groves (25.4%), followed by orchards (25.2%) and vineyards (24.6%), which are the farms producing most of the APW. It had no impact on cereals and a negligible effect on vegetables (2.1%). The APW state was positively and significantly influenced by such strategy.

By pursuing the second strategy (2nd scenario), improvements were observed, but they were less significant than those made by the first strategy (Figure 5). The highest effect was achieved for vegetables, with a reduction of 46.6%, then for greenhouses (27.8%) and lastly for vineyards (0.6%).

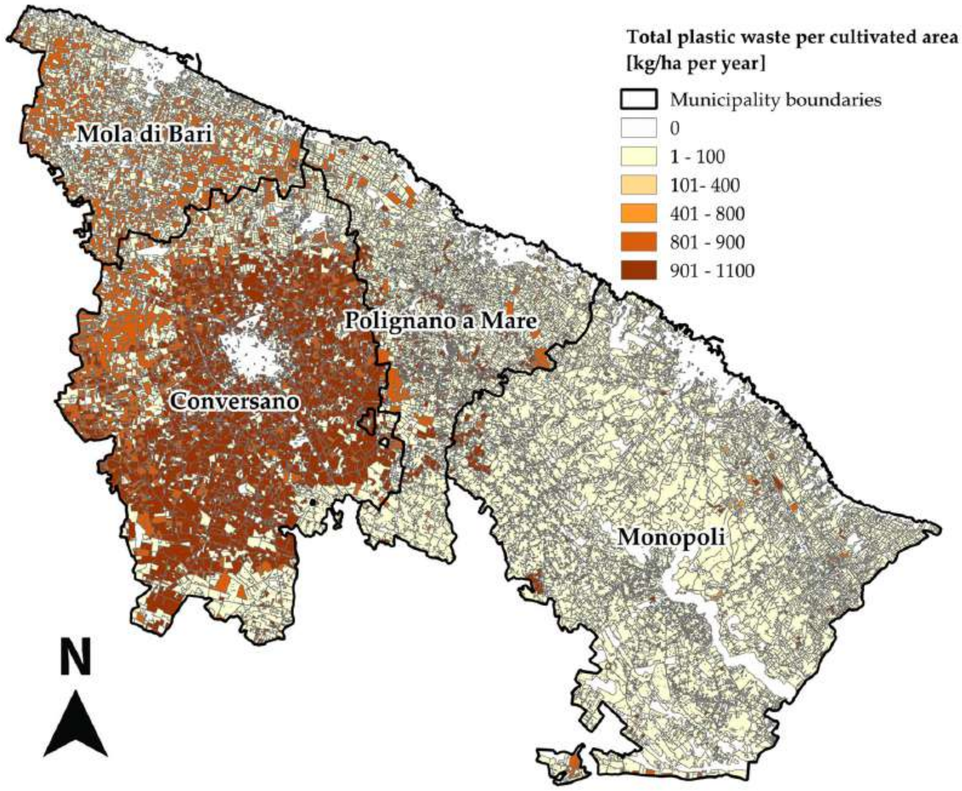

Figure 2. Distribution of the total APW in the four municipalities in the actual scenario.

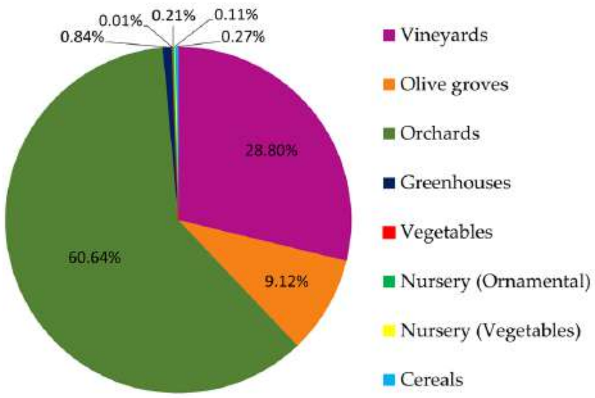

Figure 3. Distribution (%) of annual APW generated by the different crops in the four municipalities.

The combination of the two improved scenarios (scenario comb.) (Figure 6), due to the synergistic positive effects made by both strategies, produced the best situation, wherein the highest decrease in APW came from vegetables (48.7%), followed by greenhouses (42.5%).

Since covering films significantly contribute to the APW production, the attention was then specifically pointed on them. Therefore, the map of APW from covering films was realized (actual scenario) by applying the PWI related to this specific PA only to CTs that imply their use (Figure 7). It was found that about 7450 tons of APW are yearly generated from covering films in this area. By extending their useful life (1st scenario) (Figure 8), the situation visibly improved, and the highest density range became 501 to 600 kg ha^{-1} y^{-1}.

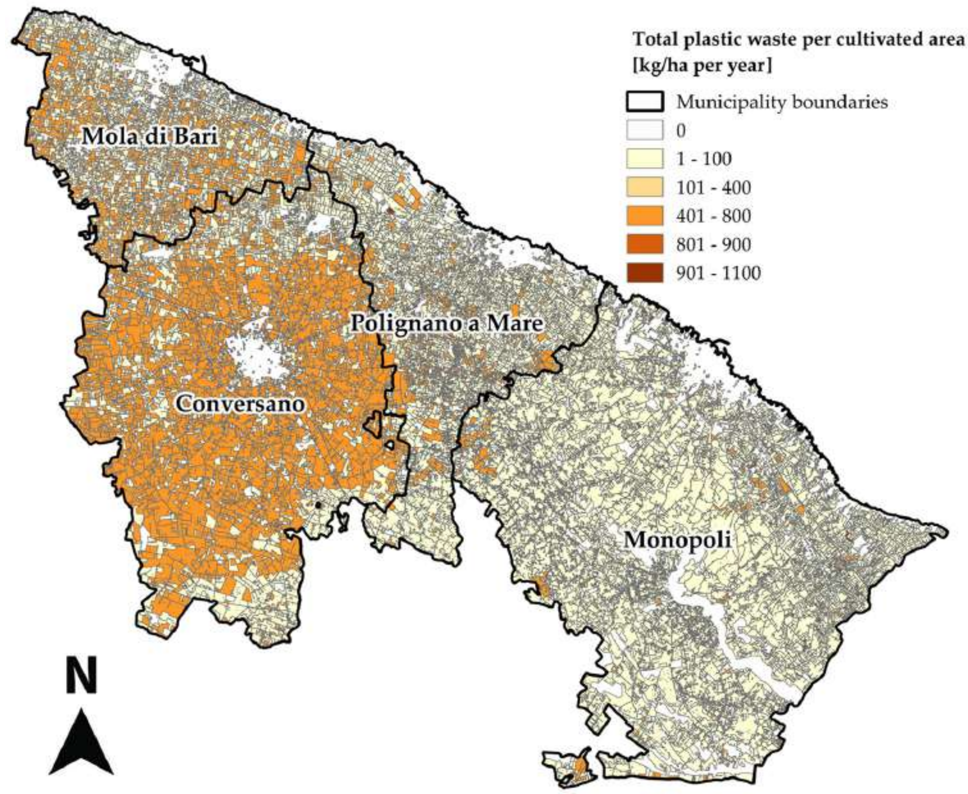

Figure 4. Distribution of the total APW in the four municipalities in the scenario of longer lifespans (1st scenario).

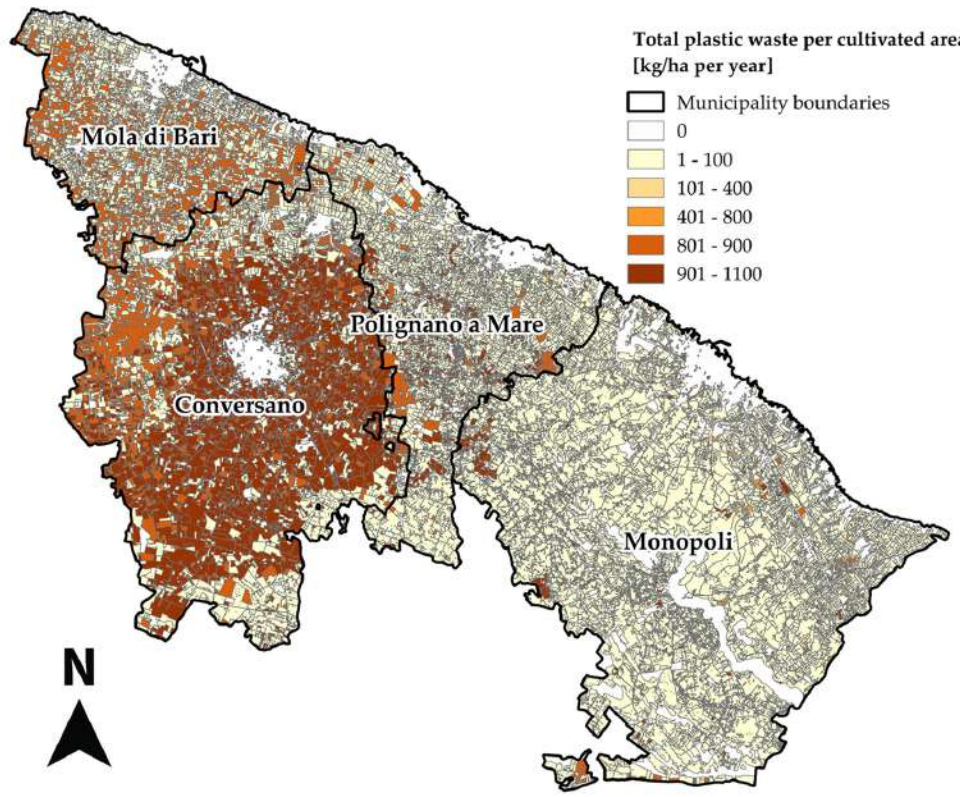

Figure 5. Distribution of the total APW in the four municipalities in the scenario of partial replacement of some of the plastics with bio-based materials (2nd scenario).

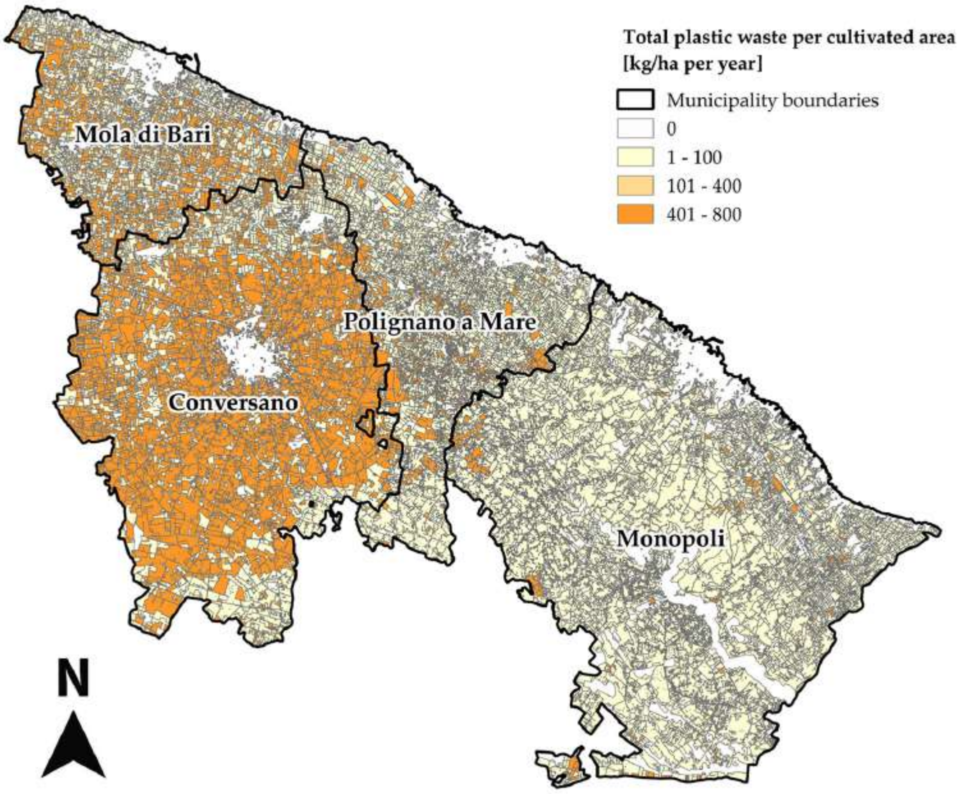

Figure 6. Distribution of the total APW in the four municipalities in the case of combination of the two improved scenarios (scenario comb).

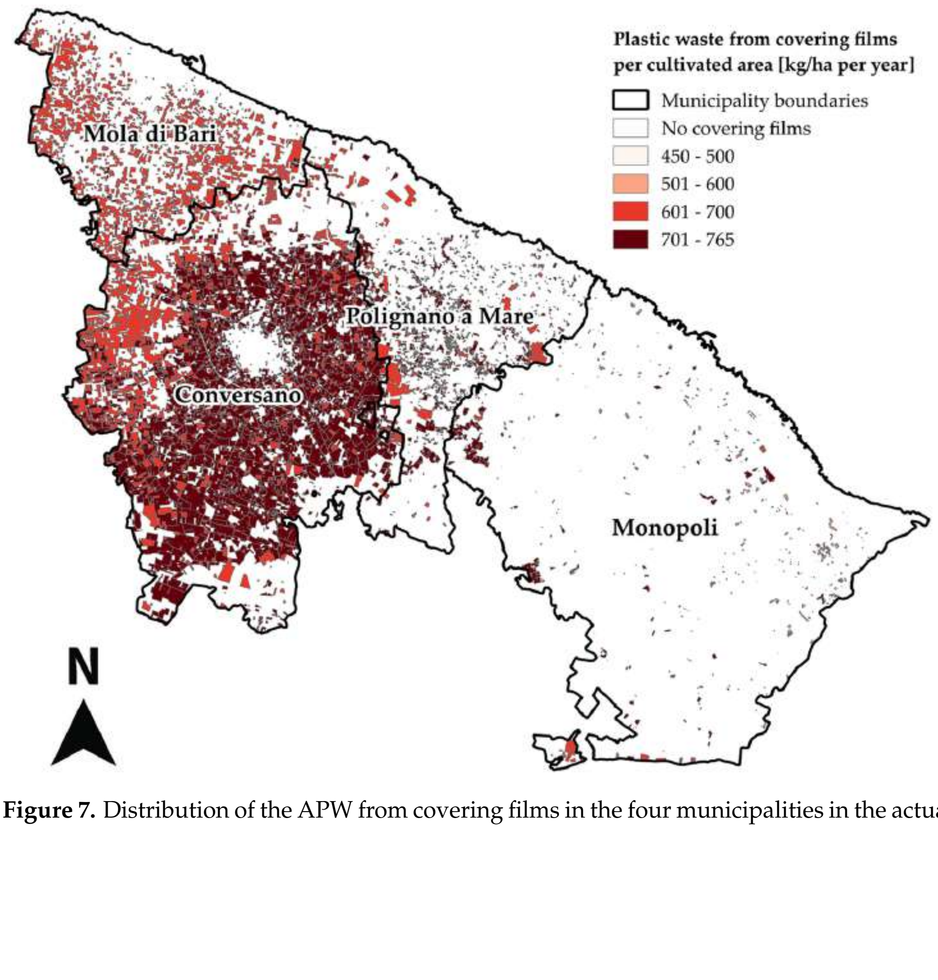

Figure 7. Distribution of the APW from covering films in the four municipalities in the actual scenario.

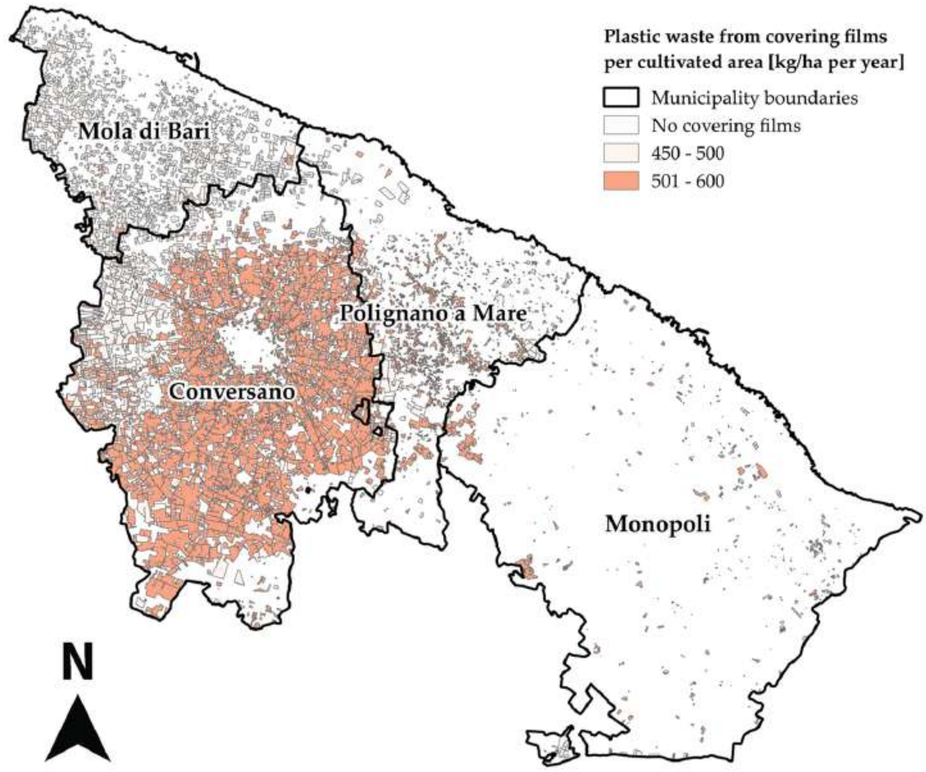

Figure 8. Distribution of the APW from covering films in the four municipalities in the scenario of longer lifespans (1st scenario).

The results of the application of the different scenarios are summarized in Figure 9. The total amount of APW decreased by 24.9% from 11,103 tons to 8343 tons per year (Figure 9a) through the lifespan extension (1st scenario). The annual quantity of APW slightly decreased by only 0.4% from 11,103 tons to 11,056 tons in the sustainable partial replacement scenario (2nd scenario) (Figure 9a). The application of the 1st scenario allowed achieving significantly better results than the 2nd one. This difference can be explained by the fact that the extension of lifespan was applied to a higher number of plastics and moreover to those PAs that contribute the most to the total amount of APW. In fact, their quantity is higher, and their weight as well. The latter is the main component in PWIs definition. On the other hand, the sustainable nature-based replacement scenario instead was considered for a lower number of plastics with lower impact (except for the mulching films) on the overall APW, since their used quantity is lower, as is their weight. Overall, when the two improved scenarios were combined (scenario comb.), the APW was lowered (by 25.3%) to a value of about 8296 tons per year (Figure 9a).

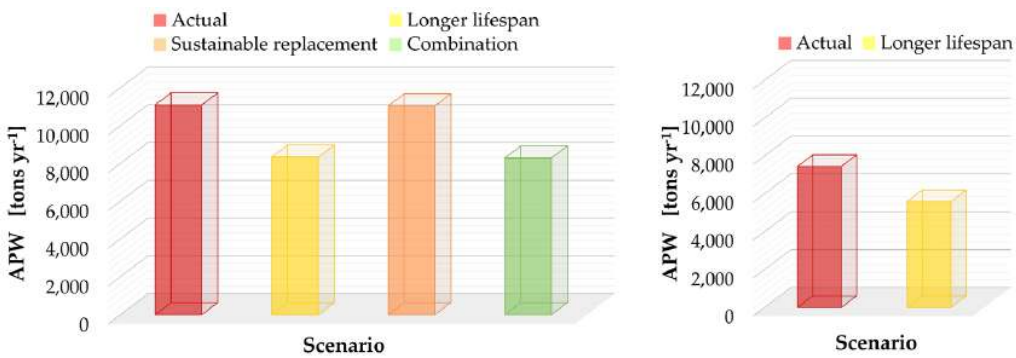

Figure 9. Yearly amount of APW in the different scenarios from overall plastics (**a**) and from covering films only (**b**).

Concerning the covering films, the extension of life (1st scenario) improved the situation and the amount of APW was decreased to about 25%, standing at some 5590 tons per year (Figure 9b).

4. Conclusions

The frequent use of plastics characterizes modern intensive and semi-intensive agricultural practices. As a result, high amounts of plastic wastes are generated, causing environmental pollution and damage to ecosystems. The mismanagement of agricultural plastic waste is a critical issue that needs to be addressed. Two approaches seem to be helpful in reducing the problem of agricultural plastic waste: extending the lifespan of plastics and replacing traditional plastic products with nature-based sustainable solutions. This study focuses on the territorial analysis of the agricultural plastic waste in an agricultural area of the Apulia Region (Italy). Through the evaluation of the crops and the related plastic applications, plastic waste indices were obtained. Once land uses in the area were defined, maps of agricultural plastic waste were created by applying the indices using a GIS. The maps reflect the actual situation and the best-case scenarios obtained through useful life extension and sustainable replacement strategies. The results showed the huge amount of waste generated annually by the agricultural sector. It was found that covering films give the highest contribution to the production of plastic waste, followed by nets, mulching films, and seeding trays. Orchards are the most impactful form of cultivation, followed by vineyards and olive groves. However, the application of the improved scenarios suggested that the current situation could be significantly improved, especially when incorporating several strategies together. It was found that the extension of the lifespan of some plastics could reduce the annual amount of agricultural plastic waste by 24.9%, that a slight reduction of 0.4% could be reached through sustainable replacement, and finally that combining the two strategies could achieve a decrease in APW by 25.3%. These findings suggest that more scientific efforts are needed to develop better-performing materials and more sustainable bio-based alternatives to plastics.

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Conflicts of Interest: The authors declare no conflict of interest.

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