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Solar plants, environmental degradation and local socioeconomic contexts: A case study in a Mediterranean country

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ABSTRACT

Photovoltaic plants developed on rural land are becoming a common infrastructure in the Mediterranean region and may contribute, at least indirectly, to various forms of environmental degradation including landscape deterioration, land take, soil degradation and loss in traditional cropland and biodiversity. Our study illustrates a procedure estimating (i) the extension of ground-mounted photovoltaic fields at the municipal scale in Italy and (ii) inferring the socioeconomic profile of the Italian municipalities experiencing different expansion rates of ground-mounted photovoltaic fields over the last years (2007-2014). The procedure was based on diachronic information derived from official data sources integrated into a geographical decision support system. Our results indicate that the surface area of ground-mounted photovoltaic fields into rural land grew continuously in Italy between 2007 and 2014 with positive and increasing growth rates observed during 2007-2011 and positive but slightly decreasing growth rates over 2012-2014, as a result of market saturation and policies containing the diffusion of solar plants on greenfields. We found important differences in the density of ground-mounted solar plants between northern and southern Italian municipalities. We identified accessible rural municipalities in southern Italy with intermediate population density and large availability of non-urban land as the most exposed to the diffusion of solar plants on greenfields in the last decade. Our approach is a promising tool to estimate changes in the use of land driven by the expansion of photovoltaic fields into rural land.

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1. Introduction

Since photovoltaic energy contributes to reduce pollutant emissions, the spread of solar energy plants has been widely supported as a response to global climate change (Bergesen et al., 2014) in regions with optimal conditions for photovoltaic fields due to a large and continuous solar irradiation along the year (Espinosa et al., 2014; Gunderson et al., 2015). Incorporating solar plants on existing grazing or agricultural land provides an additional income stream to land owners and promotes diversification of revenue for years when agricultural productivity is low or for crops that are relatively low value. Similar benefits have been demonstrated with wind developments on agricultural lands (Holmes and Papay, 2011). Based on these premises, ground-mounted photovoltaic fields are becoming a common infrastructure in the Mediterranean region and may contribute, at least indirectly, to various forms of environmental degradation including landscape deterioration, land take, soil degradation and loss in traditional cropland and biodiversity. While energy, economic and environmental impacts of photovoltaic plants have been generally seen as positive, the large scale use has a negative impact on rural landscapes (Carullo et al., 2013; Naspetti et al., 2016). Specific impacts on soils and rural communities (e.g. in terms of permanent or temporary soil sealing, total or partial soil shading, degradation of land, habitat fragmentation and loss of traditional agricultural practices) have been identified and require further investigation (Beylot et al., 2014; Hernandez et al., 2014a; Koldrack et al., 2014).

Solar power installations can be either temporary or permanent, and can be mounted at a variable distance from the ground, causing a variable impact on soils and on the overall land quality. Crops that are shade tolerant and low height may become suitable for production in an area with photovoltaic fields (Harinarayana and Sri Venkata Vasavi, 2014). At the same time, shade from solar infrastructure generally reduces crop productivity. Moreover, agricultural activities involving large machinery may have limited options for co-location with solar infrastructure (Beckman and Xiarchos, 2013). Soil shading by extensive photovoltaic fields can also reduce its infiltration capacity, altering the surface hydrological balance and determining, in some cases, an increased runoff possibly enhancing soil erosion processes. Previous studies have proposed strategies to reduce the environmental impact of photovoltaic fields (e.g. Graebig et al., 2010), indicating some possible solutions including a more complete integration into buildings and infrastructures - keeping ground-mounted installations to a minimum (Holmes and Papay, 2011). It has been also proposed to restrict the installation of ground-mounted systems on low-quality land, including brownfield sites or in the close vicinity of highways and railway lines (Beck et al., 2012). In both cases, spatially-detailed diachronic information on the expansion of solar plants into rural areas is required to support fine-tuned strategies aimed at reducing the environmental impacts of photovoltaic plants.

However, local-scale information on the spatial distribution of ground-mounted photovoltaic fields and their possible impact on rural landscapes are generally scarce, fragmented or poorly comparable among regions or countries. Occupied surfaces are one of the critical variables regarding the environmental performances of large-scale ground-mounted photovoltaic installations. The occupied surface mainly determines the impact of large-scale installations on land quality (Costantini and Lorenzetti, 2013).

A rapid expansion in solar generation capacity has been recorded in Europe since 2005: solar-based electricity generation increased more than 10 times over the period 2005-2010 (Eurostat, 2012). According the recent report "Energy, transport and environment indicators" elaborated by Eurostat, the gross inland consumption deriving from solar photovoltaic source in the 28 European Union countries increased from 126 to 7939 thousand TOE (tonnes of oil equivalent) between 2005 and 2014. In 2012, Italy was the second country in the world for installed capacity of photovoltaic plants (INEA, 2013). Photovoltaic plants have developed recently in Italian rural areas, becoming highly attractive due to high earnings compared to traditional agriculture (Marcheggiani et al., 2013). An increased surface area of high-quality cropland was converted to solar power plants in the last decade (GSE, 2012). This phenomenon has progressively led to a significant reduction of the utilized agricultural area in some rural districts with traditional agro-forest environments, possibly determining loss in food production and the consequent alteration of the landscape value (Costantini and Lorenzetti, 2013; Kim et al., 2013; Tani et al., 2014).

A debate on the environmental impact of photovoltaic fields in terms of land occupation has progressively involved the public opinion in the very last years. Chiabrando et al. (2009) have tried to clarify the territorial impacts of the ground-mounted photovoltaic systems in Italy. Agricultural areas, destined to ground-mounted photovoltaic plants, have been estimated at 134 km^2, corresponding to 0.1% of Italian agricultural surface area (Squatrito et al., 2014). National institutions have recently placed some limits to the uncontrolled development of ground-mounted photovoltaic plants on rural land. National incentives granted to photovoltaic systems installed on agricultural land have been removed. The Italian Ministry of the Environment has proposed initiatives to manage and plan the installation of photovoltaic fields on rural land and to contain landscape and soil degradation, land take and loss of traditional cropland (INEA, 2013). A substantial reduction in the price for energy has been also observed in the last years; as a consequence, market has experienced a setback of new installations from over 1 GW in 2013 to about 385 MW in 2014, below the estimates of the beginning of 2014 (GSE, 2012).

Effective and reliable indicators based on the spatial distribution of solar plants are required to assess the environmental vulnerability of different local contexts to the expansion of ground-mounted photovoltaic fields (Schiffer, 2015). The present study proposes an indicator-based approach that assesses the expansion of photovoltaic plants installed on rural land in Italy, identifying at the same time the socioeconomic context of local communities experiencing various levels of photovoltaic plant density. Rural contexts were described considering topography, land-use and demography indicators. Our approach can be extended to other European countries, being possibly integrated in a comprehensive strategy harmonizing sustainable development and landscape conservation of traditional agricultural areas.

2. Methodology

2.1. Study area

The area investigated in this study extends the whole of Italy (301.330 km^2) and is administered by 20 regions and 8092 municipalities. Although the Italian coastline (including islands) extends nearly 7400 km, most of the continental land is hilly or mountainous. Topography, latitudinal range and proximity to the sea coast have had a strong influence on local climate, soil, vegetation and landscape (Salvati et al., 2011).

2.2. Data and variables

Elementary data of photovoltaic plants installed in Italy between January 2005 and December 2014 were derived from the Atlasole database provided by the Italian Energy Services Manager (GSE) by municipality and plant power. For each administrative region of Italy, the surface area of rural land occupied by photovoltaic fields was provided by GSE (2012). Plants were classified by installation support (e.g. ground, building or greenhouse roof, infrastructures). The total surface area of photovoltaic fields (m^2) was provided separately for each region, together with the number of plants and their total power (MW). The percentage of ground-mounted plants in the total number of installed photovoltaic plants was finally reported. On average, ground-mounted plants in Italy covered a surface area of 1.7 hectares per MW (GSE, 2012). Additional data referring to 2011 were derived from official statistics provided by ISTAT (Italian National Statistics Institute) including average elevation, total surface area and population density for each Italian municipality.

2.3. Data analysis

For each Italian municipality, the surface area of land occupied by ground-mounted photovoltaic plants was estimated for two points in time (2007 and 2014) by disaggregating the total surface area covered by ground-mounted photovoltaic fields at the regional scale. Since the surface area of land destined to photovoltaic fields in each Italian administrative region corresponds to the total surface area covered by photovoltaic fields in all municipalities of that region, the municipal surface area of ground-mounted photovoltaic fields (unknown) - depending on the number and power of installations in each municipality (known) - was estimated as proportional to the total number and power of installations recorded in each administrative region (known). The amount of the total surface area occupied by ground-mounted photovoltaic fields in each Italian municipality was estimated for 2007 and 2014 (Hernandez et al., 2014b). For each Italian municipality, five contextual indicators were calculated: (i) average elevation (m), (ii) population density for 2007 (inhabitants/km^2), (iii) percent change in population density between 2007 and 2014, (iv) total surface area administered by each municipality (km^2) and (v) a binary (0-1) variable distinguishing southern Italy municipalities (1) from central and northern Italy municipalities (0).

2.4. Statistical analysis

Non-parametric pair-wise correlations using the Spearman rank test (testing at $p < 0.05$ for significance) were carried out to identify linear and non-linear relationships between the selected variables (Salvati and Zitti, 2009). A Principal Component Analysis (PCA) was run on the dataset composed of 7 variables (the 5 variables illustrated in Section 2.3 *plus* the two variables assessing the percent area of ground-mounted photovoltaic fields in the total municipal surface area for 2007 and 2014). The analysis was carried out to identify the spatial relationship between the selected contextual variables and the percent area of ground-mounted photovoltaic fields. The PCA is a multivariate statistical technique widely used to summarize the latent factors influencing the relationship among variables within a data set. This technique allows reducing redundancy derived from high levels of serial autocorrelation in the observed data (Salvati, 2013). We based the PCA on the correlation matrix, and components with eigenvalue > 1 were considered in the following analysis (Salvati, 2014). A non-hierarchical clustering (using the *k*-means computation strategy) was run on the data matrix with the aim to classify Italian municipalities into homogeneous partitions. Following the parsimony criterion, the analysis was carried out for a set of solutions (cluster numbers) ranging from 2 to 10 (the highest number of cluster partitions considered appropriate to illustrate the characteristics of local contexts in the study area). The most efficient cluster partition was identified using pseudo F statistic and the Cubic Clustering Criterion as diagnostics (Salvati and Zitti, 2009). Based on cluster membership, each *k*-means group of municipalities was profiled using the average value of each contextual variable.

3. Results

3.1. Descriptive statistics

Table 1 reports selected indicators estimating land destined to ground-mounted photovoltaic fields in Italy by year, geographical division, elevation and class of population density. The percent area covered by photovoltaic fields in the total country area was estimated at 0.03% in 2007 and increased to 0.06% in 2014. After a major spread of ground-mounted photovoltaic fields in southern Italy up to 2007 (Fig. 1), the largest increase in the number of photovoltaic plants was observed in rural areas of central Italy over 2007-2014 (0.07%). In this region, the percent land area covered by photovoltaic fields in the total surface area was 0.09% in 2014. This figure is moderately higher in respect to what was observed in southern Italy (0.08%) and substantially higher than the value observed in northern Italy (0.02%).

Table 1
Estimated sealed land by photovoltaic plants in Italy by year, geographical division, elevation and population density class.

Variable	Class area (%)			Share in the total sealed area (%)		
	2007	2014	% change	2007	2014	% change
Geographical division						
North	0.007	0.024	0.017	9.0	15.4	6.4
Centre	0.019	0.091	0.073	12.3	28.8	16.5
South	0.056	0.083	0.027	78.7	55.8	-22.9
Elevation (m)						
< 100	0.065	0.120	0.055	29.4	26.1	-3.4
100 - 300	0.062	0.132	0.071	40.6	41.5	0.9
300 - 500	0.030	0.058	0.028	19.4	18.1	-1.3
500 - 800	0.012	0.030	0.018	8.1	9.6	1.4
> 800	0.002	0.010	0.008	2.4	4.7	2.4
Population density (inhabitants/km^2)						
< 100	0.010	0.024	0.014	20.3	22.7	2.4
100 - 300	0.063	0.107	0.043	57.9	46.5	-11.4
300 - 500	0.036	0.103	0.067	8.6	11.7	3.1
> 500	0.049	0.147	0.098	13.2	19.1	5.9

The concentration of photovoltaic fields in central and southern Italy mainly depends on the optimal environmental conditions found in those areas, namely the higher solar radiation compared with northern Italy. However, important changes in the geography of photovoltaic fields in Italy have been observed between 2007 and 2014. Southern Italy concentrated more than 78% of ground photovoltaic surface area in 2007 shifting to 56% in 2014; at that time, central and northern Italy concentrated respectively 15% and 29% of the total ground photovoltaic surface area in Italy.

3.2. Non-parametric correlation analysis

Photovoltaic fields were mainly located on flat or moderately steep rural land with elevation < 300 m. The 0-300 m elevation zone concentrated the largest increase in the surface area covered by ground-mounted photovoltaic fields between 2007 and 2014. The highest concentration of photovoltaic fields was observed in rural municipalities with intermediate population density (100 - 300 inhabitants/km^2). The surface area covered by ground-mounted photovoltaic fields in 2007 increased in southern Italy municipalities ($r_s = 0.21$, $p < 0.05$, $n = 8092$) and in municipalities administering large surface areas ($r_s = 0.17$, $p < 0.05$, $n = 8092$). In 2014, the surface area covered by ground-mounted photovoltaic fields increased with the size of municipalities ($r_s = 0.29$, $p < 0.05$, $n = 8092$) and decreased with elevation ($r_s = -0.15$, $p < 0.05$, $n = 8092$).

3.3. Principal component analysis

Table 2 illustrates the results of a Principal Component Analysis carried out on 7 contextual variables including the estimated area of ground-mounted photovoltaic fields for each Italian municipality in both 2007 and 2014. The PCA extracted three components explaining respectively 29%, 28% and 15% of the total data variance. Component 1 identified a gradient opposing densely populated areas (with growing population) to economically-marginal and mountainous districts. Component 1 was not correlated with the percentage of sealed land in both 2007 and 2014. Component 2 was associated negatively to elevation

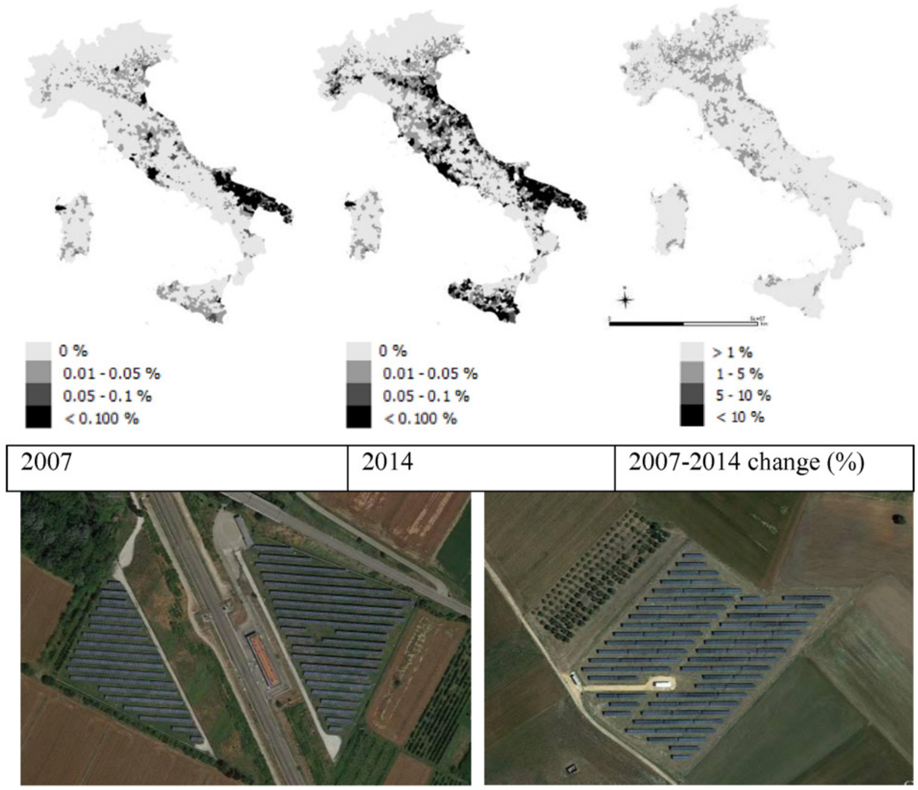

Fig. 1. (upper panel) Spatial distribution of sealed land by photovoltaic plants in Italy by year and (lower panel) two aerial views of photovoltaic fields in a flat area (northern Italy, left) and in a steep area (central Italy, right), courtesy of Google Earth.

and positively to population density and the percent area of land covered by photovoltaic fields in both 2007 and 2014. Component 3 illustrated the latitude gradient from northern Italy to southern Italy and was not correlated with the percent area of land covered by photovoltaic plants. Fig. 2 reports a PCA biplot discriminating municipalities with the highest estimated surface area of ground-mounted photovoltaic fields (ordered along the 'Sea' variable axis). These municipalities are concentrated primarily in southern Italy and in flat areas of central and northern Italy.

3.4. Cluster analysis

Non-hierarchical clustering (Table 3) identified four homogeneous groups of municipalities with distinct socioeconomic characteristics. Clusters were ordered according to the percent surface area of photovoltaic fields in the municipal surface area (2007). In 2007, the highest percent class area was observed in municipalities belonging to cluster 4 and concentrated in moderately steep areas of southern and central Italy with relatively low population density (148 inhabitants/km^2 on average) (Fig. 3). However, the largest expansion of ground-mounted photovoltaic fields was observed in dense municipalities (465 inhabitants/km^2 on average) administering flat areas of both central and northern Italy (cluster 3).

Table 2
Principal Component loadings (bold indicates significant correlations at $p < 0.05$).

Variable	PC 1	PC 2	PC 3
Sealed land (%, 2007)	0.42	**0.82**	-0.04
Sealed land (%, 2014)	0.42	**0.84**	-0.12
Municipal size	**0.64**	0.05	-0.36
Population density (2007)	**-0.69**	**0.47**	0.28
Population growth (2007-2014)	**-0.66**	0.33	-0.30
Elevation	**0.49**	**-0.47**	-0.06
South, dummy	0.38	0.11	**0.84**
Explained variance (%)	*29.4*	*27.7*	*14.5*

4. Discussion

Solar energy plants have risen exponentially and globally (Booth, 2014; Hernandez et al., 2014a, 2014b; Jäger-Waldau et al., 2011). Photovoltaic technology has had a significant success in the energy market (Gunderson et al., 2015; Suri et al., 2007). According to Dupraz et al. (2011), integrating new sources of renewable energy with crop production is a feasible solution provided that a high rate of soil sealing is prevented. However, legislation often failed to assess the negative impact of photovoltaic fields altering soil, landscape and cropping systems (Kapetanakis et al., 2014; Marcheggiani et al., 2013; Vasseur and Kemp,

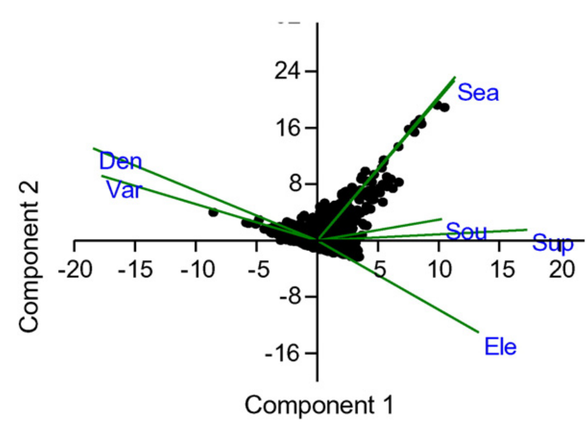

Fig. 2. Principal Component Analysis biplot (Sea = percent sealed land in 2007 and 2014, Den = population density (2007), Var = population growth rate (2007-2014), Ele = elevation, Sup = municipal surface area, Sou = binary variable indicating southern Italy municipalities).

Table 3
Distribution of contextual variables in the Italian municipalities by *k*-means clusters.

Variable	Cluster #				Italy
	1	2	3	4	
# municipalities	2263	898	3670	1261	8092
Surface area (%)	36.3	6.5	38.0	19.2	100
Sealed land (2007, %)	0.005	0.010	0.028	0.083	0.029
Sealed land (2014, %)	0.016	0.042	0.085	0.106	0.061
Change in sealed land (%)	0.012	0.032	0.056	0.022	0.032
Share of sealed land (2007, %)	5.8	2.3	36.8	55.1	100
Share of sealed land (2014, %)	9.8	4.5	52.6	33.2	100
Population density (inhabitants/km^2)	55	431	465	148	297
Population growth (%)	-0.5	2.7	0.7	-0.7	0.4
Elevation (m)	857	310	389	625	548
South Italy municipalities (%)	0.1	6.9	12.8	99.6	22.1

2011). Since the development of photovoltaic systems has led to a considerable loss of farmland (Stephens and Angel, 2012), effective management strategies and appropriate policies are required to preserve southern European rural land from environmental degradation possibly caused by the unplanned installation of ground-mounted photovoltaic fields or other temporary or permanent structures, such as greenhouses (Marrou et al., 2013; Nonhebel, 2005; Tsantopoulos et al., 2014). Information on topography, land-use, demography and, more generally, a set of socioeconomic indicators profiling the local context, should be considered in the decision-making process to minimize the environmental impact of photovoltaic plants in terms of landscape and soil degradation, land take and loss in traditional agricultural practices (Guerrero-Lemus et al., 2015; Holtmeyer et al., 2013; Murphy et al., 2015; Talavera et al., 2014).

The approach proposed in this study estimates the amount of rural land covered by photovoltaic fields at a disaggregated spatial scale in Italy. According to Fabiani and Tartaglia (2013), the evolution of photovoltaic systems in Italy started with the great race of energy giants, stimulated by substantial gains guaranteed by photovoltaic fields. Large agricultural land were purchased at a low cost to develop solar power plants. Between 2007 and 2014, photovoltaic fields have spread mostly in central and northern Italy, possibly due to the progressive saturation

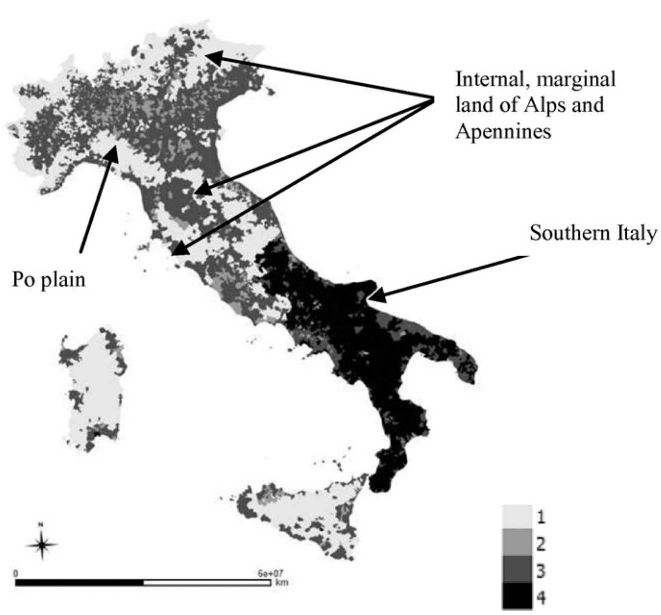

Fig. 3. Classification of Italian municipalities into homogeneous *k*-means clusters.

of the photovoltaic market in southern Italy. The expansion of photovoltaic fields into rural land is particularly evident in flat and moderately steep areas, with negative environmental impacts since these areas are also exposed to a higher human pressure in respect with economically-marginal and mountainous areas (Salvati and Zitti, 2009).

Our study indicates a progressive shift in the spatial distribution of ground-mounted photovoltaic fields in Italy from less populated (and partly abandoned) rural areas characterized by economic marginality to more populated and accessible rural areas surrounding metropolitan regions. Multivariate analysis identified rural municipalities in southern Italy with intermediate population density, high transport accessibility, large availability of cropland and flat land as the most vulnerable areas to the expansion of ground-mounted photovoltaic fields.

To reduce the environmental impact of solar plants, it has been proposed to restrict the installation of ground-mounted systems on low-quality land, including brownfield sites or in the close vicinity of highways and railway lines (Beck et al., 2012). Impacts on traditional agriculture and natural habitats could be minimized by utilizing already degraded, contaminated, or marginal lands that might not sustain viable wildlife populations or be considered for agriculture production (Weinzettel et al., 2013). By contrast, the results of our study indicate that the recent expansion of solar systems in Italy was mainly concentrated on both traditional and intensive agricultural districts in flat and hilly areas with optimal or sub-optimal conditions for cropping. The spreading of ground photovoltaic fields over accessible, medium-density rural areas, is the result of heterogeneous (and possibly poorly effective) planning measures regulating the spatial development of rural areas traditionally devoted to intensive agriculture (Ceccarelli et al., 2014).

The recent evolution of national and regional regulations in Italy is in line with the articulated territorial and socioeconomic local contexts described above. The boom of ground-mounted photovoltaic systems forced institutions, such as the Italian Ministry of Agriculture, to implement rules to contain the expansion of photovoltaic plants into greenfields (4th Energy Bill) which limited installations to 10% of the farm utilized agricultural area, prescribing also a minimum distance for installations falling on the same property. The most recent 5th Energy Bill definitely prohibited photovoltaic plant installations on greenfields. Effective planning actions have been also undertaken by some regional authorities in Italy. In 2011, Apulia (southern Italy) regional authority prepared guidelines for the sustainable management of photovoltaic fields within a spatial planning directive addressing sustainable development of rural land. Guidelines have indicated a thorough reduction of photovoltaic fields on fertile rural land allowing new installations of plants on roofs and other built structures. Sardinia regional authority approved a landscape management plan that provides regulatory measures to the expansion of photovoltaic plants over rural areas devoted to agriculture. In the last two years of study, the lowest expansion of ground-mounted photovoltaic fields in the country was observed in the regions which have adopted strict regulations and a more effective spatial planning (GSE, 2012).

5. Conclusions

Considering the huge expansion of solar power installations in Mediterranean countries and the different regulations applied at the national and regional scale, our evidences highlight that the unplanned expansion of ground-mounted photovoltaic fields can determine an increased environmental pressure on both traditional and intensive cropping systems. Significant limitations to ground-mounted installations on greenfields seem to be the only measure to contain land take and loss of fertile land in areas experiencing a too rapid expansion of solar power. Investigation is also required to identify strategies for the combined land use of low-input agriculture and solar power as a measure for the sustainable development of derelict and partly abandoned rural land with the final objective to reduce the environmental impact of solar power on natural landscapes in the Mediterranean region.

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