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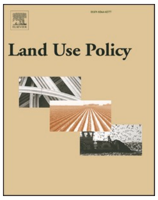

Addressing the challenge of photovoltaic growth: Integrating multiple objectives towards sustainable green energy development

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ABSTRACT

Photovoltaic production is growing globally thanks to climate change mitigation efforts. However, this growth is seldom planned which can lead to conflicts with other land uses, mostly agriculture and biodiversity conservation. There is, therefore, urgent need for adequate planning to minimise potential conflicts. We demonstrate how to identify priority areas for photovoltaic development to meet projected targets for 2050, as well as critical areas for the maintenance of different types of agriculture and biodiversity conservation, using Catalonia (NE Spain) as a case study. We tested three planning scenarios simulating alternative photovoltaic development models: setting targets at the whole regional scale or splitting those targets across counties distributing them equitably by county energy demand or area available for photovoltaic development. Photovoltaic targets could only be achieved when setting targets at the whole of Catalonia scale, although leading to heterogeneous distribution of development efforts and associated impacts on agriculture and biodiversity across counties. Setting targets for each county based on energy demand was far from achieving the regional photovoltaic development target, driven by the limited land available in some highly urbanised counties, where energy demand concentrates. On the other hand, setting targets based on area available within each led to the most equitable distribution of potential impacts of photovoltaic development, while also approaching the regional photovoltaic development target. Adequate planning of photovoltaic development will be key to ensure that photovoltaic development does not flourish at the expenses of other land uses, like maintenance of agricultural production or biodiversity.

1. Introduction

The urgent call to mitigate the impacts of climate change (IPCC, 2022) and halt ecosystem degradation and biodiversity loss (IPBES, 2019) are triggering environmental policies globally, with a focus on reducing greenhouse emissions, while promoting sustainable development and biodiversity conservation. Europe has developed and updated several of such policies in the last five years. For example, the European Green Deal (EC, 2019) has set ambitious emission reduction targets by 2030 (−55% compared to 1990 ś levels) across many sectors (industry, energy, transport and farming) with a vision of a fast transition towards climate neutrality by 2050 in line with the goals set by the Paris Agreement (UNFCCC, 2015). Some of the actions to achieve these goals include the promotion of both sustainable mobility and food production, a reduction in the use of natural resources by transitioning towards a circular economy, the development of a power sector based largely on renewable sources or the restoration of habitats with high climate change mitigation potential. The European Union (EU) Biodiversity Strategy for 2030 (EC, 2020) or the new Forest Strategy for 2030 (EC, 2021) constitute fundamental pillars of the European Green Deal, in recognition of the fact that biodiversity loss and climate change are tightly interlinked (Pörtner et al., 2021). Any effort directed at increasing nature protection and reversing ecosystem degradation will also play an important role in mitigating, and adapting to, climate change (nature-based solutions; Cohen-Shacham et al., 2016).

However, the rapid implementation of some of these actions, supported by financing mechanisms set by the European Commission to fight climate change (e.g., Next Generation funds) or reduce the EUś energy dependency on Russia (e.g., REPowerEU Plan; EC, 2022), is leading to potential conflicts and trade-offs between the objectives of the

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environmental policy itself. An example of these are the trade-offs between the development of large-scale solar energy generation, which is expected to experience a ~300% increase by 2050 (EC et al., 2021), and the biodiversity recovery goals (i.e., a trade-off between the generation of clean energy and nature conservation).

Solar energy has one of the greatest climate change mitigation potentials among all current sources of renewable energy and has fast become one of the cheapest technologies for electricity generation worldwide (Hernandez et al., 2014), with a 56% reduction in cost from 2015 to 2020 (IPCC, 2022). However, the development of solar projects at large scales (the so-called Utility-Scale Solar Energy) is associated with a wide array of environmental impacts throughout their lifecycle (e.g., pollution, erosion, land cover change), being land occupancy one of the most visible ones (Hernandez et al., 2014). These projects can take up significant amounts of land due to both the installation of the solar panels and the associated infrastructure (e.g., access roads, electrical requirements), potentially fragmenting, degrading, and modifying habitats of high conservation value in the process (Hernandez et al., 2014) or producing direct mortality (e.g., birds; Kosciuch et al., 2020). For example, Serrano et al. (2020) recently warned about the rapid and uncontrolled expansion of solar farms in Spain in low-cost marginal soils of high ecological value, such as extensive cereal farmlands, the main habitat of a community of species already threatened by the agricultural intensification of the last decades in Europe (Traba and Morales, 2019).

Solar energýs negative impacts on biodiversity are largely context-dependent (Lammerant et al., 2020). Therefore, planning at an adequate scale is key to minimizing them. Land use conversion to photovoltaic development may also clash with the goal of expanding the network of terrestrial protected areas to cover up to 30% of the continent's land area by 2030 set in the European Biodiversity Strategy for 2030 (EC, 2020) or the network of Green Infrastructure that connects natural and semi-natural habitats across the continent to deliver a wide range of ecosystem services (EC, 2013). In Mediterranean countries, unplanned expansion of photovoltaic projects also poses an important pressure on both traditional and intensive agriculture (Delfanti et al., 2016). It is, therefore, key to reducing the impact of future photovoltaic development on agricultural productivity, to ensure that local and regional production is not compromised and that sustainable development goals can be achieved (Delfanti et al., 2016).

Given the potential conflicts of this growth with other objectives, careful territorial planning is needed. For example, the REPowerEU Plan establishes that "Member States should identify suitable land and sea areas for renewable energy projects, while avoiding as much as possible environmentally valuable areas and prioritizing inter alia degraded land not usable for agriculture (EC, 2022)." There has been a growing interest in proposing different methodologies, from the use of decision support systems (Sacchelli et al., 2016) to sequential modelling to derive suitability indices (e.g., "compatibility index"; Stoms et al., 2013) or to the simple intersection of spatial layers representing constraints (environmental, social, legal and political, technical-economic) and opportunities (Guaita-Pradas et al., 2019). Conservation planning tools (Moilanen et al., 2009), originally developed to identify the most valuable areas for biodiversity conservation (i.e., designation of protected areas; Margules and Pressey, 2000), can also play an important role in addressing the new environmental challenges that the expansion of clean energy will bring in the coming years. These optimization tools are increasingly used in environmental impact assessments across different sectors (e.g., Morán-Ordóñez et al., 2018) since they allow addressing trade-offs and synergies between conflicting objectives in a quantitative and statistically robust way (Kukkala and Moilanen, 2013). However, their application to support the landscape-wide development of clean energies remains very limited (but see for example Egli et al., 2017), especially at the spatial scales at which relevant legislative development is taking place in terms of conditions for the practical implementation of clean energy (sub-national and local).

In this study, we sought to demonstrate the use of spatial optimization tools to support a landscape-scale future photovoltaic development at the subnational scale, using Catalonia (NE of Spain; Fig. 1) as a case study. Catalonia covers approximately 32,000 km^2, 26% of which corresponds to agricultural land, and is currently experiencing an exponential increase in photovoltaic development, with more than 600 project proposals presented for approval in 2020 (Generalitat de Catalunya, 2021). This exponential growth, not adequately planned, has led to multiple socio-economic conflicts locally (e.g., because of inequitable bilateral negotiations between developers and landowners or because of social rejection of the visual impact of solar parks and the loss of productive land and associated cultural values).

Rapid and unplanned development of solar energy in non-urban areas may be leading to serious environmental impacts in the region due to the lack of in-depth assessment of cumulative and synergistic ecological impacts of small, fragmented projects (Serrano et al., 2020). For these reasons, and in response to the obligations acquired by the Green Deal (EC, 2019), the regional government of Catalonia has rapidly developed legislation to accelerate a sustainable deployment of renewable energies in the territory that also allows for the achievement of other territorial objectives, such as agricultural production, biodiversity conservation. This makes this region of an excellent model for study, given the recent legislative developments as a "blank" canvas on which to build an implementation in the territory in the coming decades and its relevant policy context, same legislation regarding energetic transition is under development across other regions in Europe and across the globe. Here, we address a multi-objective spatial prioritisation exercise, including photovoltaic production, agriculture and biodiversity conservation, with potential conflicts among all of them. We aimed to identify priority areas for the development of photovoltaic projects in Catalonia, to achieve a production target of 21,600 MW by 2050 as established in the regional plan for photovoltaic development on non-urban or industrial land (SOLARCAT; Generalitat de Catalunya, 2019a), while also maintaining agricultural land and preserving biodiversity. We also accounted for spatial constraints that limit the land suitability for each objective as well as for the opportunity costs. We test different planning scenarios by setting targets at the whole regional scale or splitting those targets across counties distributing them equitably by county energy demand or area available for photovoltaic development. These scenarios aim to simulate alternative ways of distributing the pressure of land demand for photovoltaic development across the region.

2. Methods

2.1. Spatial distribution of objectives and constraints

To identify priority areas for the development of photovoltaic projects and achieving the two-tiered objective described above, we mapped the distribution of features on which impacts needed to be minimized, such as different types of agricultural systems and biodiversity features (Table 1; Fig. 2). We also mapped different spatial constraints to the development of photovoltaic projects related to legal (e.g., prohibition of photovoltaic projects in protected areas or high-value agricultural land) or technical restrictions (e.g., unsuitable areas due to topographic constraints; Table 1). For subsequent analyses, the distribution of both features and spatial constraints were transferred into a network of 500 m resolution grid cells (planning units hereafter).

2.2. Agricultural systems

We measured the area covered by different types of agriculture (Appendix A) grouped by irrigated and dry-land crops. The grouping was done following the indications in the regional plan for photovoltaic development (Generalitat de Catalunta, 2019c), which sets goals of maximum area loss to photovoltaic development for these two broad agricultural classes. The distribution of each type of crop was sourced

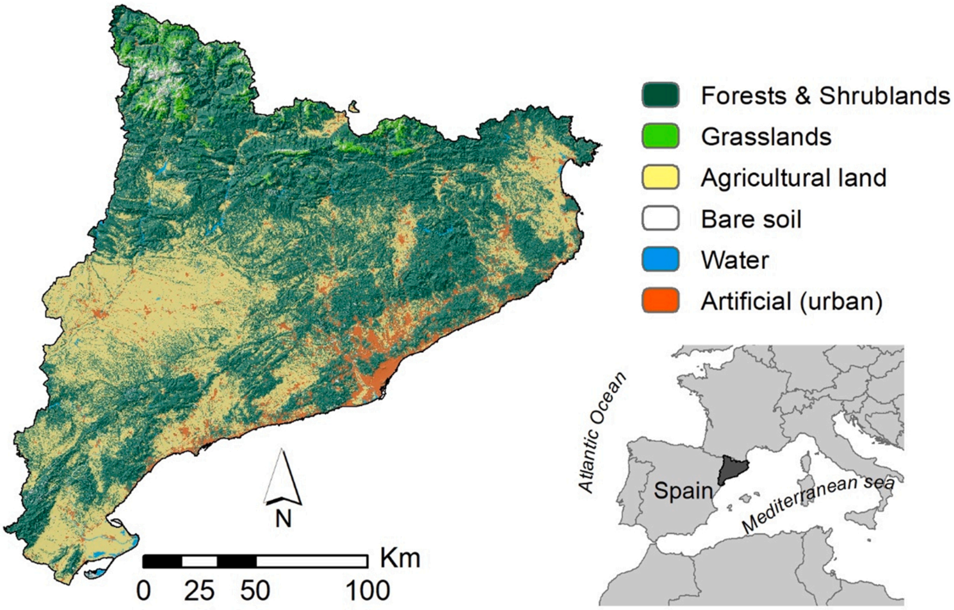

Fig. 1. Study area, with detail of the main land covers across the region. The inset map at the bottom right of the figure shows the location of Catalonia in the Iberian Peninsula and Europe.

Table 1
Representation targets pursued for the different features considered in this study. Targets for photovoltaic production and maximum agricultural land loss followed those set by regional policy (Generalitat de Catalunya, 2019a). Targets for biodiversity were set according to their coverage in the Habitats and Birds Directives and their conservation status. Targets for agriculture and biodiversity features represent the proportion that needs to be preserved from impacts derived from the development of photovoltaic projects.

Feature	Status	Target
Photovoltaic		43,200 ha
Agriculture (irrigation)		95%
Agriculture (dry-land)		90%
Species & habitats	Catalogue (EN)	100%
	Catalogue (VU)	75%
	Directives (only)	50%

from the Agricultural Geographic Information System of Catalonia (Generalitat de Catalunya, 2019b) which contains information on the distribution and use of all agricultural fields in Catalonia. We measured the area occupied by each type of agriculture in each of the 500 m cells.

2.3. Biodiversity features

Appropriate planning of solar energy development, restricting the selection of locations that are important for EU-protected species and habitats, is the best mitigation measure for avoiding or minimizing impacts on biodiversity (Lammerant et al., 2020). We selected three biodiversity features:

EU priority and/or endangered bird species: We sourced the distribution of all bird species listed in Annex I of the Birds Directive (Directive 2009/147/EC) and the Catalan Catalogue of Endangered Species (Generalitat de Catalunya, 2019c) from the regional Atlas of breeding and wintering Birds (1 km^2 resolution derived from species distribution models; Estrada et al., 2004; Herrando et al., 2011). We treated separately (e.g., as individual features) the seasonal changes in species distributions across the study area during the breeding and wintering periods. The information on the distribution of species was available in three different quality classes, indicating the relative habitat suitability of each 1 km^2 cell for each species. We kept for our analyses all cells within classes 1 and 2, which corresponds to suitability classes above the average across the study area (Herrando et al., 2018) and treated them as presence-absence data. In this way, whenever a species had a habitat suitability score of 1 or 2 in a given cell, the species was assumed to be present. A total of 155 species occurred in both seasons, while only one of the species appeared during winter. In the former case, we treated each *species x season* as an individual pseudo-species to reflect seasonal changes in distribution in our analyses. Therefore, we finally included the presence-absence 311 species/pseudo-species in the prioritisation analyses.

Endangered vascular plants: We sourced distribution maps of 288 endangered vascular plant species available from the Catalogue of Endangered Plants of Catalonia (Generalitat de Catalunya, 2015). Eight of these species were also included in Annex II of the Habitats Directives (Council Directive 92/43/EC). This database contains information on the distribution range of each species gathered from literature and field data.

EU priority and/or endangered habitats: We also sourced the distribution of 88 habitats listed in Annex I of the Habitats Directive (Council Directive 92/43/EC) or classified as Endangered in the Catalogue of Habitats of Catalonia (Carreras and Ferre, 2012).

These three biodiversity features were selected to cover a wide range of species and habitats on which photovoltaic development may have a negative impact. Although other biodiversity features could also be impacted by photovoltaic projects, the information on their spatial distribution was not publicly available at the time these analyses were carried out. Further work would be needed to incorporate the distribution of these other features should the results of analyses like we demonstrate here to be used for decision-making. Moreover, here we follow a conservative approach and assume that all biodiversity features are equally sensitive to photovoltaic projects. However, future applications of the approach that we demonstrate here could benefit from also accounting for the sensitivity of each biodiversity feature to photovoltaic projects.

2.4. Spatial constraints

The development of photovoltaic projects is constrained by different factors that make some areas unsuitable or of difficult technical and economic feasibility. We considered two types of spatial constraints: 1)

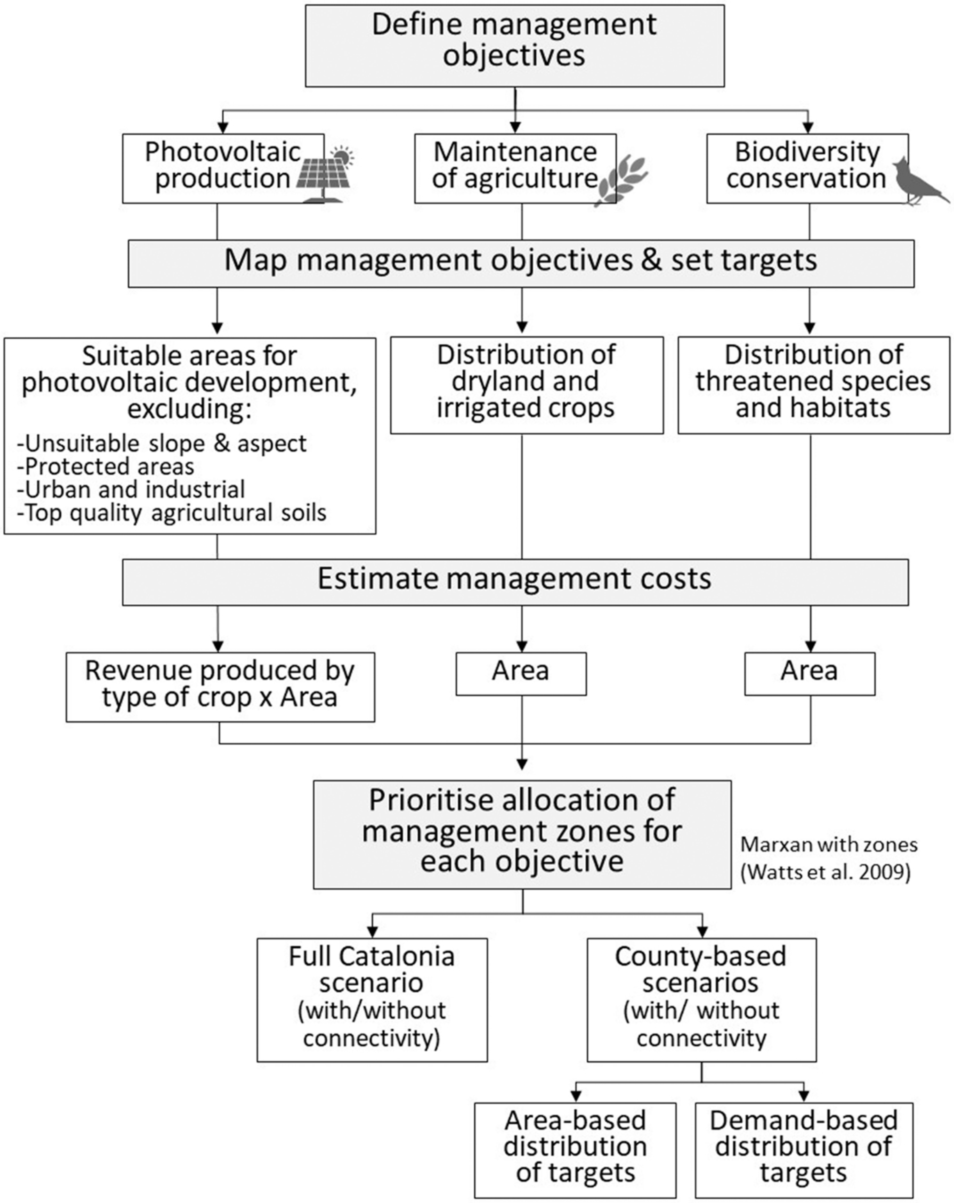

Fig. 2. Flow diagram of the analyses carried out in this study.

excluding factors, that made some cells unavailable for photovoltaic developments (slope and orientation, protected areas and unsuitable land cover) and 2) opportunity costs associated with current agricultural productivity (soil quality for agriculture).

2.4.1. *Slope and orientation*

We identified areas across Catalonia where the installation and operation of solar panels are limited by terrain constraints, estimated through a combination of slope and orientation conditions. This was done following guidelines provided by one of the main companies promoting the installation of solar farms in Catalonia (Km 0. energy, *personal communication*; Appendix B). We excluded from the analyses all the 500 m cells that did not fulfil these criteria and assumed that there was no restriction to photovoltaic production due to terrain or solar radiation constraints in the remaining cells in Catalonia.

2.4.2. *Protected areas*

We measured the proportion of each 500 × 500 m cell covered by the Natura 2000 network and excluded all those with > 25% of its area covered by protected areas from the set of candidate cells for photovoltaic development. These protected areas included both, Special Protection Areas for Birds (SPAs) in accordance with the Birds Directive, and / or as Special Areas of Conservation (SACs) in accordance with the Habitats Directive. The information on the delimitation of protected areas was sourced from the Ministry of Climate Action, Food and Rural Agenda of the Generalitat de Catalunya (Appendix A).

2.4.3. *Unsuitable land cover*

While the regional legislation on deploying clean energies sets that 40% of the energy should be generated in urban areas, in these analyses we focused on identifying priority areas for the development of photovoltaic projects in the remaining 60% of non-urban areas (where conflicts with agricultural development and especially with biodiversity conservation are foreseen). For this reason, we excluded a priori all land cover classes across Catalonia that were considered unsuitable for the development of photovoltaic projects. We sourced land cover data from the 2018 Land cover map of Catalonia (Mapa de Cobertes del Sòl de Catalunya (MCSC) v1.0, Appendix A) and excluded from the analyses all cells with $>25\%$ of their surface covered by artificial surfaces (urban, industrial or transportation infrastructure), but also by forests, wetlands and beaches (Appendix C), where the deployment of photovoltaic power plants is unlikely to occur.

2.4.4. *Soil quality for agriculture*

The regional legislation has set maximum thresholds of loss of productive land due to the deployment of clean energies (especially solar energy), being this deployment banned in areas hosting the highest quality soils for agricultural production. Thus, we also excluded the latter from the analyses. Two different sources of data were used in this case: the maps of the agronomic quality of soils, only available for some areas in Catalonia, and the map of potential areas for photovoltaic development available for the remaining areas (Appendix A). The former has 8 soil quality classes ranging from areas of special aptitude for agriculture to areas with very limited capacity for agriculture (quality classes 1 and 8 respectively). The regional administration considers unsuitable for photovoltaic development the two highest classes, so we excluded from the analyses all cells with $>50\%$ occupied by these types of soils. Regarding the remaining areas, with no agronomic quality information, we used a map of 6 soil quality aptitudes for irrigation and dry-land agriculture, also developed by the regional administration (Appendix A) and excluded from the analyses all cells with $>50\%$ covered by soils of high aptitude for agriculture (both irrigation and dry-land crops).

After applying these filters, we retained for the analyses 31,127 cells out of the original 131,720 500 m cells available across the study area (Fig. 1). To minimise opportunity costs derived from photovoltaic development, even in areas considered suitable according to topographic, conservation and land use constraints, we accounted for the cost of rural land associated with different types of crops and pastures. We calculated the opportunity cost of each 500 m cell as a weighted sum of the cost of each different type of crop/ pasture (Appendix D) and the area they covered ($Opportunitycost = \sum_{i} \mathrm{a_i cost_i}$, being $\mathrm{a_i}$, the area of each of the different crop type/ pasture present in a given cell and $\mathrm{cost_i}$ of those different crops/ pasture).

2.5. *Prioritization of photovoltaic projects*

To identify priority areas to achieve the photovoltaic production target (established in the regional renewable energy plan) while minimising impacts on other sectors such as agricultural productivity and biodiversity conservation we used the spatial planning software Marxan with Zones (Watts et al., 2009). Given the potential impacts of photovoltaic projects on agriculture production and biodiversity conservation (Turney and Fthenakis, 2011; Northrup and Wittemyer, 2012) and between some agricultural practices and biodiversity (Sanz-Pérez et al., 2019) we defined three different zones, one for each group of objectives: photovoltaic production, agriculture, and biodiversity. Although we were mainly interested in identifying priority areas for photovoltaic production, the use of these three zones allowed us to set explicit maximum loss targets for the other features, rather than minimising the impact of photovoltaic development on these other features as traditionally done in spatial planning approaches by treating them as constraints (e.g., through opportunity costs; Mazor et al., 2014) rather than objectives. In this way, we ensured that the loss of land for agriculture and biodiversity conservation did not exceed a certain magnitude, in the former case established by policy (Generalitat de Catalunya, 2020). To specify how each zone should contribute to the achievement of targets for each feature, we used the *zonetarget* file in Marxan with Zones, which allows to allocate representation targets of each feature to each of the zones being spatially prioritized. We allocated targets of photovoltaic production, agriculture, and biodiversity loss exclusively in their respective zones. To further minimise the potential impacts of photovoltaic production on the other objectives, we used different cost measures for each zone. For the photovoltaic production zone, we used the opportunity cost explained above, so cells that would incur a high opportunity cost (measured in 10^3 euros) would preferentially be avoided for photovoltaic production. We used the inverse of the opportunity cost as the cost for allocating cells under the agriculture zone. In this way, those cells that had the highest economic agricultural productivity would preferentially be maintained for this use. Finally, for the biodiversity conservation zone, and lacking estimates of the cost associated with conservation across the study area, we applied an area cost (measured in ha); this sought to maximize the achievement of biodiversity targets set in the smallest possible area. Therefore, the basic mathematic problem we addressed in Marxan with Zones was to minimise the cost of achieving targets for all features under their respective zones:

$$minimize \sum_{i=1}^{m} \sum_{k=1}^{p} c_{ik} x_{ik} + b \sum_{i1=1}^{m} \sum_{i2=1}^{m} \sum_{k1=1}^{p} \sum_{k2=1}^{p} cv_{i1,i2,k1,k2} x_{i1,k1} x_{i2,k2}$$

$$subjectto \sum_{i=1}^{m} \sum_{k=1}^{p} a_{ij} x_{ik} \geq t_{jk} \forall j$$

Where, c_{ik} is the cost of cell i if allocated under zone k; x_{ik} is a control variable that determines whether cell i has been allocated under zone k (1) or not (0); $cv_{i1,i2,k1,k2}$ is the connectivity penalty for including only one of the pair of planning units i1, i2; $x_{i1,k1}$ and $x_{i2,k2}$are control variables that take values of 1 when the planning unt i1 or i2 are included in the solution or 0 otherwise; b is a weight applied to the connectivity penalty that can be used to aggregate planning units in space or determine the spatial structure of zones; a_{ij} is the contribution of cell i to the achievement of targets for feature j; t_{jk} is the representation target desired for each j feature under their respective zone k (see Watts et al., 2009 for more detail on the mathematic problem solved by Marxan with Zones).

2.6. *Target setting*

To set targets on both photovoltaic production and maximum loss of agricultural land we followed goals set by the regional policy. In the case of photovoltaic production, we translated the total production capacity expected to be achieved by 2050 in non-urban surfaces (in Mw), and as described in the regional plan for renewable energy production, into an area target, under the assumption that 2 ha are needed to produce 1 Mw (*sensu* Hernandez et al., 2014). As stated above, we discarded from the analyses all cells that did not fulfil slope and irradiation criteria, so we could assume this area-production relationship. This resulted in an overall area target for photovoltaic production of 43,200 ha for Catalonia. The maximum loss of agricultural land to photovoltaic production is set by regional policy not to exceed $>5\%$ of available irrigated land and $>10\%$ of dry-land agricultural areas per county (Generalitat de Catalunya, 2020). For this reason, we sought to retain at least 95% and 90% of irrigated and dry-land agricultural areas respectively. Targets for biodiversity were set according to policy coverage and the threatened status of the different features. Although we excluded protected areas from our analyses, we aimed to minimise the impact of photovoltaics on areas that are important for biodiversity management outside protected areas. With this aim, we classified species and habitats into three classes, according to whether they were already covered by the Habitats and Birds Directives, for which Natura 2000 sites have been specifically designated, or not and their threat status in the regional catalogues (Generalitat de Catalunya, 2015; 2019b). We set the highest targets for those species assessed as endangered or vulnerable in the regional catalogues, regardless they were included in the annexes of the Habitats and Birds Directives (Table 1). We also aimed to avoid the impacts of photovoltaic production on the distribution of habitats and species listed in the Directives, but since these are already the target of the Natura

2000 network, we set lower targets for them (Table 1).

2.7. Planning scenarios

In a context of unplanned development, intermediate population density areas with a large availability of non-urban land are often under higher photovoltaic development pressure (Delfanti et al., 2016), leading to imbalances in the impacts and benefits of the implementation of solar energy. To tackle this issue, we addressed the previous objectives under three alternative scenarios: setting photovoltaic development targets across the whole of Catalonia simultaneously (*full-Catalonia* scenario hereafter) or by counties individually (N = 42 counties; two alternative scenarios; Fig. 2). In the case of county-based scenarios, we split photovoltaic development targets equitably across counties according to two different criteria: energy demand (county target= Catalonia target x % of the Catalonian demand associated with each county; *county-demand* scenario hereafter), and area availability for photovoltaic development (county target= Catalonia target x % of the Catalonian land suitable for photovoltaic development in each county; *county-area* scenario hereafter). This way of splitting photovoltaic development targets across counties aimed to distribute production according to energy demand or area available for photovoltaic production, respectively, so regions with a high energy demand or more area available would be responsible for producing more than regions with lower demand or less area available (Appendix E). Targets for the remaining features (agriculture and biodiversity) were translated into regional targets applying the same targets reported in Table 1. Therefore, targets across all three evaluated features (photovoltaic development, agricultural production and biodiversity conservation) were equal at the whole of Catalonia level across scenarios, allowing cross-scenario comparisons. Finally, we evaluated the impact of aggregating photovoltaic projects in space (e.g., the impact of fostering larger photovoltaic projects against small-scale solar parks), by including a connectivity penalty for not achieving solutions spatially aggregated (see Watts et al., 2009). We built a connectivity matrix containing all pairwise combinations of each cell with its contiguous neighbours (*boundary* file in Marxan) and calibrated the *zoneboundary* file in Marxan with Zones following the recommendation in Watts et al. (2008), to seek spatial clumping of cells selected under each zone individually. So, we finally tested 6 different scenarios (3 target distributions -Catalonia, county-demand, county-area- x 2 connectivity scenarios -with and without boundary file-).

We ran Marxan with Zones 100 times, 10^7 iterations each, and retained the best solution over the 100 runs as the best solution for each scenario individually. We then compared the achievement of the different objectives under each scenario. For the photovoltaic development objective, we measured the proportion of the target achieved globally and for each county individually; for agriculture, we measured the proportion of the two types of agriculture that would be impacted by photovoltaic projects; and for biodiversity we measured the proportion of the distribution of biodiversity features (species and habitats) that could be impacted by photovoltaic projects. Potential impacts of photovoltaic projects on agriculture and biodiversity were measured as the proportion of the distribution of these features within suitable areas for photovoltaic uses that were finally selected for photovoltaic development under the three different scenarios. Therefore, a feature would be assessed as highly impacted if a large proportion of its distribution within areas suitable for photovoltaic development were finally selected for such an objective. Finally, we also measured for each scenario the number of individual photovoltaic projects, considering an individual project a group of contiguous cells selected or each isolated cell selected without neighbours for photovoltaic development. We also measured the average size of clumps of cells assigned to photovoltaic development under each scenario, using the *landscapemetrics* R package (Hesselbarth et al., 2019). We would expect solutions that considered connectivity constraints to be more spatially clumped, translating into fewer groups of a larger numbers of cells (e.g., larger photovoltaic projects).

3. Results

The overall future photovoltaic production target of 43,200 ha could only be fully achieved under the *full-Catalonia* scenarios (both, with and without connectivity constraints), although closely followed by the *county-area* scenario (42,600 and 43,000 ha for the scenarios with and without connectivity respectively). The *county-demand* scenario showed the lowest photovoltaic target achievement: 69% and 78% of target achieved for the scenarios with and without connectivity respectively. Solutions under the *full-Catalonia* scenario did not achieve the county-level targets demanded under the other scenarios, with 40% and 60% of counties not achieving the demand and area targets respectively under the scenarios without connectivity constraints (40% and 50% for the scenarios with connectivity constraints). The county-based scenarios were more effective at achieving their respective targets, but with some counties still failing their targets. For example, 30% and 20% of counties did not achieve the demand-based and the area-based targets set under the *county-demand* and *county-area* scenarios respectively, with no connectivity constraints (20% for both scenarios with connectivity constraints). The area-based scenario was better at achieving demand-based targets (70% of counties achieved the demand-based targets under the *county-area* scenario) than the other way around (only 30% of counties achieved the area-based targets under the *county-demand* scenario).

Targets for maximum agriculture loss were achieved under all scenarios when checked at the whole Catalonian scale (*full-Catalonia* scenario), with the area potentially impacted below 5% and 10% for irrigated and dry-land agriculture respectively (Table 2). The lowest impact on agricultural land, both dry-land and irrigated, occurred under the *county-area* scenario, while the *county-demand* scenario posed the largest impacts on average across counties (Table 2; Fig. 3). Despite the Catalonian-wide achievement of agricultural targets across all scenarios, there were some counties that failed at achieving their individual targets (e.g., those hosting the largest urban areas across Catalonia: capital cities in Fig. 2). The only exception was the *county-area* scenario that achieved targets for irrigated agriculture across all counties (both, with and without connectivity) and only failed to achieve the targets for dry-land agriculture in one county (Table 2). Impact on agricultural land for the other two scenarios (*full-Catalonia* and *county-demand*) ranged between 2.1% and 3.1% and 3.5–5.9% for irrigated and dry-land agriculture respectively, which posed 4.5–5.8 and 1.6–2.7 times higher than the impact obtained under the *county-area* scenario for irrigated and dry-land agriculture respectively (Table 2).

The overall target for biodiversity could not be achieved for all

Table 2
Average impact across counties of future photovoltaic development in Catalonia on agriculture and biodiversity features under the three different scenarios tested in this study. Numbers for agriculture show the proportion of each type of agriculture in cells selected for photovoltaic development and the proportion of counties that did not achieve the target between parentheses. In the case of biodiversity features, the numbers show the average proportion of the distribution of species and habitats within areas suitable for photovoltaic development and the proportion of biodiversity features that did not achieve the targets between parentheses.

Scenario	Irrigated agriculture	Dry-land agriculture	Biodiversity
Full-Catalonia (no connectivity)	2.5 (0.19)	4.6 (0.17)	6.5 (0.10)
Full-Catalonia (connectivity)	2.1 (0.12)	3.5 (0.05)	6.4 (0.09)
County-demand (no connectivity)	2.9 (0.12)	5.8 (0.19)	6.6 (0.11)
County-demand (connectivity)	3.1 (0.12)	5.9 (0.19)	6.6 (0.11)
County-area (no connectivity)	0.5 (0)	2.4 (0.02)	4.5 (0.10)
County-area (connectivity)	0.4 (0)	2.2 (0.02)	4.5 (0.09)

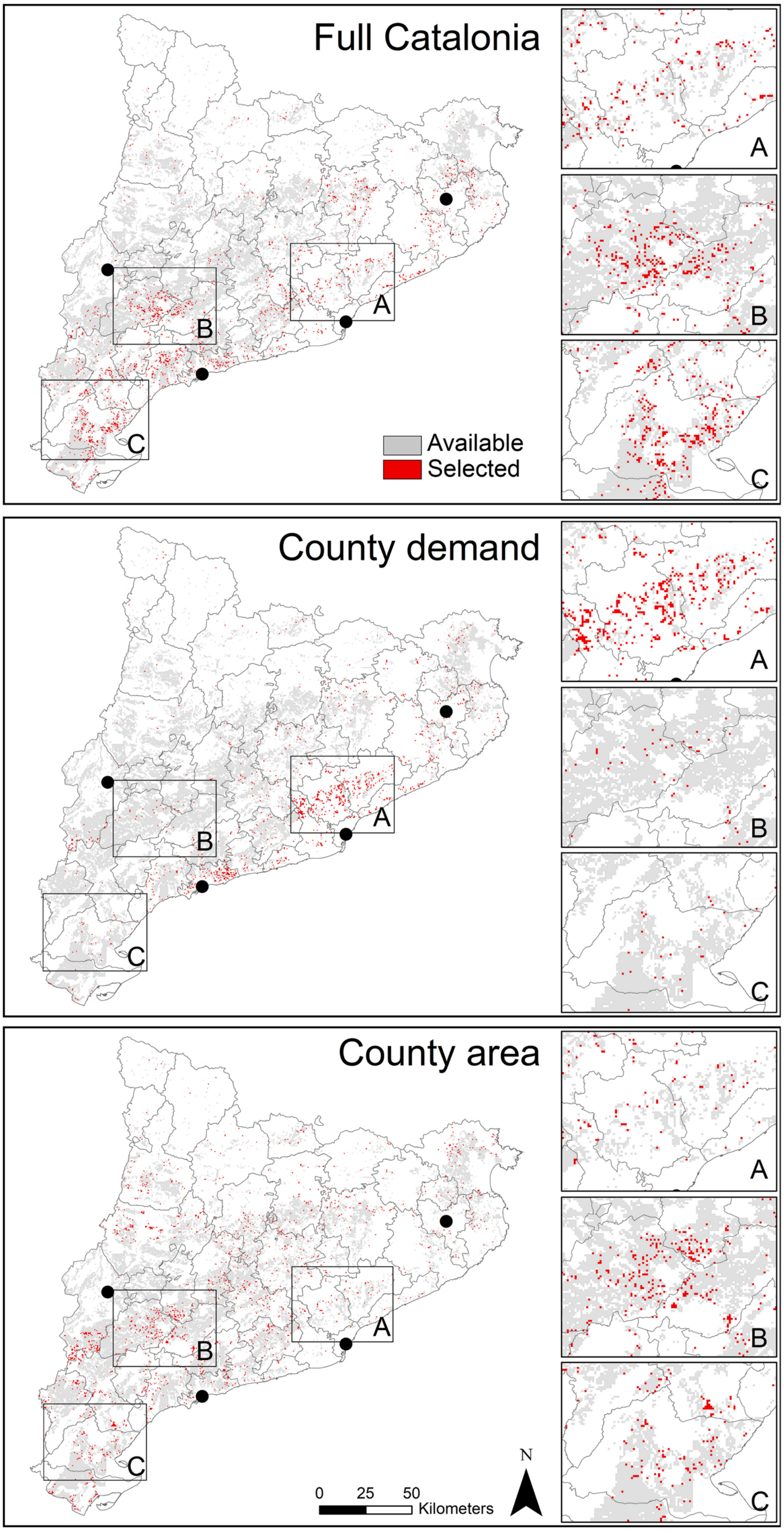

Fig. 3. Distribution of cells selected for photovoltaic projects (red) from the pool of all available cells (grey) under the three different scenarios tested in this study (*full-Catalonia*, *country-demand* and *county-area*). In white those areas that were not suitable for photovoltaic projects. Black dots show the location of the capital cities of the four provinces in Catalonia (Barcelona, Girona, Lleida and Tarragona), which concentrate most of the regiońs population and the energy demand. Given the focus of this study is on the prioritisation of photovoltaic projects, the distribution of the two remaining zones used in Marxan with Zones (those devoted to agricultural production and biodiversity conservation) are not represented here for clarity.

features neither in the *full-Catalonia* nor the county-based scenarios (Fig. 3; Table 2). The impact of photovoltaic development was, however, different across scenarios, being the lowest potential impact associated with the *county-area* scenario and the highest derived from the *county-demand* scenario across the different indicators that we measured (Table 2, Appendix F). The *county-area* scenario showed, however, potential impacts on a larger proportion of the distribution of biodiversity features that did not achieve their targets. For example, features that did not achieve their targets under the *county-area* scenario could not achieve them in 46% of the counties where they occur, compared to 28% under the *county-demand* scenario (Appendix F).

Pressure on area demand for photovoltaic development and derived potential impacts on agriculture and biodiversity were not equitably distributed across counties and differed across scenarios (Table 3; Appendix G-J). The area demand for photovoltaic development, as well as the potential impacts on biodiversity features were more evenly distributed across counties under the *county-area* scenario, while the potential impacts on both types of agriculture under the *full-Catalonia* scenario (Table 3). The *county-demand* scenario showed the largest differences in area demand and potential impacts on agriculture and biodiversity across counties under all scenarios (Table 3), more heavily concentrated in counties with the largest population density and energy demand. This later scenario, however, showed the highest spatial aggregation of cells selected for photovoltaic development (Table 4).

4. Discussion

Here, we have demonstrated how to prioritise the spatial allocation of land for photovoltaic development to achieve Catalonian regional production goals for 2050, while also attending to other objectives, such as maintaining agricultural land and areas important for species and habitats of conservation concern. With these analyses we aim to contribute to the need for better structured and planned growth of photovoltaic development, given the exponential growth of this source of energy is expected to continue in the near future (Bennun et al., 2021; EC, 2022). By testing different planning scenarios, we tried to simulate alternative ways of distributing the pressure of land demand for photovoltaic development across the region and to evaluate the potential impact of photovoltaic development on agricultural land and biodiversity. As we show, two of the scenarios, *full-Catalonia* and *county-demand*, tended to concentrate the selection of land for photovoltaic development in particular areas within Catalonia, which translated into a more asymmetric distribution of land demand and impacts on agriculture and biodiversity across the region (Appendix G-J). The *county-area* scenario showed the most homogeneous distribution of land demand for photovoltaic production across counties, which translated into a lower and more equitable distribution of potential impacts on agriculture and biodiversity. The overall production target for Catalonia could only be achieved, however, under the *full-Catalonia* scenario, although very closely followed by the *county-area* scenario (with only 1.4% of the objective not achieved). We found that if production needs to be concentrated close to areas where it is demanded, as regional policy states (Generalitat de Catalunya, 2021), there would be a large shortfall of more than 30% below expected production by 2050, at least under current plans that establish that 60% of production needs to be developed on non-urban areas and set limits to loss of agricultural land (Generalitat de Catalunya, 2019a). Given the differences across planning scenarios that we show here, that depict alternative management models, further debate on the most appropriate way of guiding future photovoltaic development is needed. We advocate for adequate planning that accounts for multiple objectives, and a flexible model when deciding where to develop photovoltaic projects that embrace differences and opportunities across the territory. Spatial scenario development alternatives based on the use of optimization approaches like the one presented here can provide stakeholders and project developers with a transparent framework within which to operate, tackling the current unplanned scenario (e.g., Generalitat de Catalunya, 2021) prone to conflicts and impacts. The approach that we demonstrate here could also be used to plan the growth of any other source of clean energy, like wind, facing similar problems.

Catalonia, like the rest of the EU, has committed to decarbonizing its economy and covering 100% of the energy demand through renewable sources by 2050 (EC, 2019; Generalitat de Catalunya, 2021) and accelerating the change to reduce the dependence on the energy sector from Russia (EC, 2022). There will be, therefore, strong support for the development of photovoltaic, among other renewable sources of energy, which is expected to experience a 120-fold increase in Catalonia, growing from 300 MW installed in 2019–36,000 MW by 2050. Beyond the unquestionable benefits, in terms of reducing greenhouse gas emissions and mitigating climate change impacts, photovoltaic development will have socio-economic and ecological impacts due to high land demand, most notably on food production and biodiversity conservation (Turney and Fthenakis, 2011; Northrup and Wittemyer, 2012; Dunnett et al., 2022). Careful planning and site selection for photovoltaic projects will, therefore, be essential to ensure that the expansion of photovoltaic, and other renewables, are not done at the expense of agricultural and ecological losses (Bennun et al., 2021). Our analyses show that adequate planning can help identify priority areas for future photovoltaic development, where impacts on agriculture and biodiversity can be considered simultaneously. For example, all scenarios resulted in a potential impact on agricultural land below the regional targets of 5% and 10% of dry and irrigated agriculture respectively. The *county-area* based scenario showed the lowest average impact on agricultural land and biodiversity, favoured by the most equitable distribution of land demand for photovoltaic development across all counties. When setting land demand targets for the whole of Catalonia or driven by spatial differences in energy demand priority areas for photovoltaic development were less homogeneously distributed across counties, mainly focusing on either areas with low opportunity cost (*full-Catalonia* scenario) or counties with the highest energy demand, regardless land availably and opportunity cost (*county-demand* scenario). The *county-area* based scenario resulted in a better balance between the area available and selected, minimising especially the impact on biodiversity features across all counties simultaneously. Future applications of the planning approach we present here could also benefit from integrated analyses for multiple sources of renewable energy, so the potential impacts of different types of projects could be simultaneously considered and minimised. These types of analyses are critical to evaluate the suitability of different development strategies and address the need to ensure just distribution of the various impacts of installations among the

Table 3
Coefficient of variation of target achievement of different objectives across counties (cv=[(SD/Average)* 100]) as a measure of equity in the distribution of pressure derived from areas selected for photovoltaic projects. Shaded grey areas show the most equitable scenario (e.g., lower cv value) for each objective.

Scenario	*Full-Catalonia*		*County-demand*		*County-area*	
	No connectivity	Connectivity	No connectivity	Connectivity	No connectivity	Connectivity
Photovoltaic	107.0	103.0	127.8	116.4	82.8	81.1
Irrigated agriculture	114.4	130.7	358.6	331.1	131.8	174.4
Dry-land agriculture	94.7	95.5	218.6	213.8	99.5	108.5
Biodiversity	69.3	71.1	117.3	118.1	66.5	61.8

Table 4
Summary of spatial structure of 500 × 500 m cells selected for photovoltaic projects under different scenarios. Shaded grey areas highlight the scenario with the most spatially aggregated solution (e.g., lower number of patches, with larger areas and more spatially clumped).

Scenario	Full-Catalonia		County (energy demand)		County (area available)	
	No connectivity	Connectivity	No connectivity	Connectivity	No connectivity	Connectivity
N patches	1080	919	735.0	680	1144	988
Average area (ha)	40.0	47.0	40.5	49.4	37.2	43.5
Clumpiness	0.119	0.216	0.143	0.229	0.113	0.195

local population, as demanded by the EU (EC, 2022).

However, despite the benefits of adequate planning, potential impacts on agricultural land and biodiversity could not be completely avoided and depending on the planning scenario tested, their spatial distribution was more or less equitably distributed across Catalonia. There was a mismatch between the distribution of suitable land for photovoltaic production (after all the criteria we accounted for), and the areas where the energy demand is concentrated, an issue also described in other regions (e.g., Santangeli et al., 2016). This opens the discussion about what the future development model of this emerging activity within the overall management and planning of the territory should be; currently, this goes in the direction of concentrating energy production close to the areas where it is demanded, so the counties that demand more should also produce more (Generalitat de Catalunya, 2021). Despite the benefits of such a model (each county is responsible for what it demands), our results show that this model may not only fail at achieving the global photovoltaic production goal (30% less than needed by 2050) but also entails large potential impacts on agricultural land and biodiversity at the county level. The scarce suitable land available for photovoltaic production in some highly urbanised counties is a strong constraint in meeting their large energy demands, since it would require devoting all suitable agricultural land to photovoltaic production, at least under current legal specifications (60/40% rule for installations in non-urban/urban areas; Generalitat de Catalunya, 2019a). We demonstrate that an alternative scenario, where photovoltaic development is more equitably distributed across the territory could help minimise these local impacts. However, a more flexible planning scenario (not tested here), where the distribution rule of installations under different land cover classes could be adapted to local/ regional land availability would help further minimise the impacts of photovoltaic development. For example, installations integrated into the existing built environment, such as rooftop surfaces or degraded land, would help reduce the demand for land and potential impacts on agriculture and biodiversity locally (Dale et al., 2011; Hernandez et al., 2014), especially in highly urbanized counties, in line with a regional policy aimed at fostering small-scale production as a priority and complementary alternative to large projects (Generalitat de Catalunya, 2021). Another alternative to try to minimise conflicts between objectives could be the co-location of photovoltaic installations and other agricultural and grazing activities could be another option in areas where conflicts are difficult to avoid. Agrivoltaics (defined as the combination of solar energy production and agriculture on the same land) have been suggested as an alternative model in places where development may be perceived as a threat to agricultural interests (Pascaris et al., 2021). However, given the expected impact of different photovoltaic development strategies (e.g., the concentration of production in some counties or more equal distribution) on other objectives and despite improvements in technology and increase in efficiency that could help reduce the demand of land for photovoltaic development (Righini and Enrichi, 2020), it will be critical to analyse and agree on the model that best suits the characteristics and needs of each planning area.

Addressing socio-economic aspects is critical to adequate planning and enhancing the social acceptance of development plans. The social dimension of developing energy projects can ultimately condition the fate of photovoltaic projects (Sovacool and Ratan, 2012; Carlisle et al., 2016). To address this, the needs and perspectives of citizens and societal stakeholders should be considered at all stages of renewable energy development, from policy to spatial planning, and project development (EC, 2022). Here, we did not only consider explicit objectives for the maintenance of different types of agriculture but also used food production economic productivity as a spatial constraint in our prioritisation analyses. On top of securing no net losses over 5% and 10% of irrigated and dry-land agriculture respectively, we aimed at minimising the allocation of photovoltaic projects on the most productive land, by minimising opportunity cost. This could help ensure the maintenance of soils of higher agronomic potential and the continuation of the most profitable agricultural activities, reducing potential social conflicts between renewable energy development and other land uses. However, further involvement of stakeholders, productive sectors, conservationists, and landowners in these types of strategic planning would be key to ensure that the prioritisation of land for future photovoltaic development accounts for all the legitimate objectives that aim to coexist in the territory. Agreed priorities that arise from these planning and consensus exercises could be highly valuable also for the private sector that could more efficiently focus investment on those areas that have already been identified as of high potential, minimum impact, and low conflict. Moreover, public participation in photovoltaic project development and management can help reduce potential conflicts and opposition. Innovative forms of place-based participation are needed that would help citizens to debate the properties and trade-offs of energy systems in constructive ways downstream without damaging or breaking trust (Moore and Hackett, 2016). Whenever impacts of photovoltaic development cannot be fully avoided or equitably distributed through adequate planning, it will be necessary to implement compensation mechanisms to counterbalance socioeconomic losses (e.g., economic compensation from energy deficit areas to areas that help fill their production gap) or biodiversity impacts (e.g., offsetting or biodiversity banks).

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2023.106592.

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