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Short communication

Mapping potential conflicts between photovoltaic installations and biodiversity conservation

Fernando Ascensão *, Sergio Chozas, Helena Serrano, Cristina Branquinho

cE3c - Center for Ecology, Evolution and Environmental Changes & CHANGE - Global Change and Sustainability Institute, Universidade de Lisboa, Lisboa, Portugal

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A B S T R A C T

European countries are expanding utility-scale solar farms to reduce carbon emissions and increase energy independence. However, the expansion of these facilities raises concerns about competition for land for other uses, including biodiversity conservation. Thus, quantitative assessment of the friction between renewable energy development and conservation potential is an important step towards the sustainable development of the energy sector in this region. Here, grounded on land sparing/land sharing concepts, we discuss a prioritization framework based on solar potential and human footprint (used as a proxy for wilderness) to identify zones where the development of solar farms may cause a negative impact on biodiversity (sparing areas), and areas where they may have beneficial outcomes (sharing areas). We apply this framework to the Iberian Peninsula, where the land conflict may become particularly significant in the near future, given the high potential for photovoltaic production and expansion of photovoltaic installations, and the vast areas of well-preserved habitats still remaining. We detected around 18,000 km^2 of sparing areas, of which half are not in protected areas, and >41,000 km^2 of sharing areas. Much of these sharing areas are found near urban areas, which is where energy is most needed for supplying homes, transport, and machinery. Through strategic planning, the implementation of solar farms in land sharing areas has the potential to yield dual benefits, for both local biodiversity and food production, driving economic growth. By doing so, these initiatives can also safeguard important wilderness areas, which play a pivotal role in conserving biodiversity.

1. Introduction

Human society must take significant measures to reduce carbon emissions to limit the global average temperature increase to 1.5 °C above pre-industrial levels, in accordance with the Paris Agreement and the United Nations Framework Convention on Climate Change (2015). As part of the COP26 (2021) objectives, the entire European Union (EU) has already committed to achieving net-zero emissions targets. These commitments impose a greater reliance on renewable energy sources, leading to a proliferation of power generation facilities such as solar photovoltaic (PV) farms. According to the International Energy Agency (IEA), it is projected that the annual addition of global renewable electricity capacity will average approximately 305 GW between 2021 and 2026, signifying a substantial 58 % increase compared to the expansion of renewables during the period from 2015 to 2020 (IEA, 2021).

In the EU specifically, the European Commission has recently put forth a proposal to revise the Renewable Energy Directive (2018/2001/EU) with the aim of expediting the adoption of renewable energy sources and aiding in the achievement of the 2030 energy and climate objectives. This directive establishes a collective target for the proportion of renewable energy in the EU's overall energy consumption by 2030. The proposed revision, along with the introduction of the 'REPowerEU' plan in May 2022, suggests a further advancement of the target (up to 45 %) to accelerate the adoption of renewables. This includes the permitting processes required for the deployment of renewable energy facilities (EC, 2022). The urgency of this transition is heightened by the current geopolitical situation in Europe, marked by the Russian invasion of Ukraine and the ensuing energy crisis (IEA, 2022).

To meet this target, EU nations will undergo a substantial increase in their utilization of renewable energy sources, with a significant portion derived from PV farms. However, the expansion of PV farms raises concerns regarding competition for land with other essential purposes, such as agriculture and natural areas (Nordberg et al., 2021; van de Ven et al., 2021). In fact, the land requirements for PV farms exceed those of fossil fuel plants (e.g., Palmer-Wilson et al., 2019), and given the limited

* Corresponding author at: Faculdade de Ciências Universidade de Lisboa, Edifício C2, 5° Piso, Sala 2.5.46, 1749-016 Lisboa, Portugal.
E-mail address: fjascensao@fc.ul.pt (F. Ascensão).

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capacity and resources for renewable energy development, the selection of sites for PV farms may conflict with other important interests, namely food production and the conservation of biodiversity (Gove et al., 2016; Katkar et al., 2021).

The effects of PV farms on ecosystem structure and functioning are likely to be context specific: if established in more natural and wilderness areas, the changes in land use and land cover resulting from their construction, maintenance, and operation can significantly impact local habitats and pose a threat to various organisms. These impacts may include vegetation removal, and the construction of access roads and power lines, which can adversely affect the overall structure and functioning of the ecosystem (see e.g., Hernandez et al., 2014; Kim et al., 2021; Zhang et al., 2023). However, in areas already heavily impacted by human activities, PV farms may have positive effects on biodiversity. For example, recent research encompassing a review of 185 studies revealed that interventions applied to PV farms can enhance pollinator biodiversity (Blaydes et al., 2021). Factors contributing to this enhancement include the presence of flowering plants, prolonged access to resources throughout the seasons, the introduction of sown vegetation, taller or more structurally diverse plant communities, organic farming practices, a semi-natural or heterogeneous landscape, and proximity and connectivity to semi-natural habitats (Blaydes et al., 2021).

Overall, striking a balance between reducing the carbon footprint and mitigating habitat loss for biodiversity is a pressing issue that necessitates careful planning. Habitat loss resulting from human activities remains one of the primary threats to biodiversity and ecosystem functioning (Pimm et al., 2014; Tilman et al., 2017). Consequently, the transition to renewable energy must not come at a high toll to biodiversity and should incorporate strategies for achieving sustainable energy pathways while prioritizing biodiversity conservation goals (Holland et al., 2019).

Building upon the concepts of land sharing (i.e., the integration of nature conservation into more anthropized areas) and land sparing (i.e., the separation between areas planned for human development and nature conservation) (Fischer et al., 2014), we present a mapping framework that can be utilized as an initial assessment tool to identify areas where the establishment of PV farms may pose a substantial impact on biodiversity and ecosystem services, as well as areas where PV farms may yield positive outcomes, at the landscape level. The goal is to identify regions where land sparing should take precedence, indicating areas where biodiversity may face a higher risk of impact from PV farms; and regions where land sharing should be prioritized, characterized by both a high solar potential and an already significant human footprint.

The framework combines information from readily assessable information, including of photovoltaic power potential and Human Footprint Index (Sanderson et al., 2002; Venter et al., 2016), allowing the application in any region of the globe. Here, we illustrate its applicability in the Iberian Peninsula, a region hosting a high photovoltaic power potential in a vast territory, while also possessing extensive tracts of well-preserved wilderness, evident through its comparably low human footprint in relation to other European nations (Supplementary material S1). This combination of a significant photovoltaic power potential and well-preserved natural areas makes the Iberian Peninsula a region where the conflict from PV farm development and biodiversity conservation may be particularly intense.

2. Methods

Our analysis consists in mapping and quantifying the level of co-occurrence between photovoltaic power potential and human footprint. Information on photovoltaic power potential was retrieved from the Global Solar Atlas (Global Solar Atlas, 2019), using the latest available information (2021). This atlas provides the evaluation of the practical photovoltaic potential i.e., the power achievable by a typical configuration of the photovoltaic system, considering the theoretical potential, the air temperature that affects the performance of the system, the configuration of the system, shading, and topographical and land-use constraints. Photovoltaic power output (PVOUT), defined as the specific yield, is used to illustrate this potential. PVOUT represents the amount of energy generated per unit of installed photovoltaic capacity in the long term and it is measured in kilowatt-hours per installed kilowatt-peak of the system capacity (kWh/kWp). This information is available for almost any site on Earth (land areas between 60°N to 45°S), with a 1km^2 resolution, in the online platform Global Solar Atlas (URL: globalsolaratlas.info, accessed 05-02-2023).

The human footprint was obtained from the Human Footprint Index (HFI), here used as a proxy of wilderness. The HFI represents the sum of the different ecological footprints of the human population across the surface of the earth, revealing through its variation the main pattern of human influence over nature. It is based on different information related to human activity, namely population density, built infrastructure (including roads, railways, factories, and other kinds of infrastructure), and night-time lights (Sanderson et al., 2002; Venter et al., 2016). The HFI is unitless, ranging from 0 (natural environments) to 50 (high-density built environments). HFI has been extensively used as a proxy for human disturbance and wilderness and widely used in large-scale ecological studies (Belote et al., 2020; Di Marco et al., 2018; Tucker et al., 2021, 2018; Watson et al., 2016; Williams et al., 2020). For example, it has been shown that HFI is a good predictor for biodiversity conservation, being significantly correlated to trends in species extinction risk, having higher predictive importance than environmental or life-history variables (Di Marco et al., 2018). Hence, we considered areas of lower human footprint in our study area to be associated with higher importance for conservation of biodiversity, ecosystems, and their processes and services (Williams et al., 2020). Recently, this metric was updated to include more accurate and recent information and is now available at a nominal resolution of 300 m (URL: wcshumanfootprint.org; accessed 05-02-2023).

We categorized the PVOUT and HFI information into quartiles for mapping purposes. The overlap of PVOUT and HFI provides a bivariate map that allows detecting areas where high PVOUT coincide with low HFI, which may be regarded as “land sparing areas”; and areas where high PVOUT overlaps areas of high HFI, which could be considered as “land sharing areas”. We considered the land sparing areas as those being in the top quartile of PVOUT and in the first quartile of HFI, which we suggest should be kept free from solar PV farms and any other human activity; and land sharing areas as those overlapping the top quartiles of both PVOUT and HFI. These latter areas are where human activity is concentrated and therefore have higher energy demand, and therefore we suggest being prioritized for the installation of solar PV farms.

We quantified the installed solar PV capacity in both land sparing and land sharing areas, as well as the extent to which protected areas cover these respective zones. Information on the occurrence and characteristics of PV farms were obtained from Dunnett et al. (2020), which provides a global, open-access, and harmonized spatial dataset of solar facilities using OpenStreetMap data. Protected areas existing in Iberia were obtained from Witjes and Parente (2022), assembling protected nature area status in 2019 according to Natura 2000 and the International Union for Conservation of Nature (IUCN). We also quantified the amount of sharing areas per land cover type, in order to have a better perception of which type of land cover was being highlighted for potentially installing PV farms. We used the information from Corine Land Cover (CLC2018, version is v.2020_20u1; available at URL: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018). The CORINE Land Cover is the EU dedicated inventory of land cover, using 44 classes, and has a higher resolution than the one used in HFI (minimum mapping unit of 25 ha).

3. Results

The PVOUT in the Iberian Peninsula is higher in southern regions, having values over 4.6 kWh/kWp (Fig. 1A). The first and fourth quartiles of HFI for the Iberian Peninsula were $HFI_{q1} = 10.05$ and $HFI_{q4} = 19.00$, respectively (Fig. 1B). HFI_{q1} areas are spread across the Iberian Peninsula, most notably in the southern region of Portugal (Alentejo) and semi-arid regions, such as the areas of Monegros or Tabernas deserts. The landscape here is mostly plains, with few significant topographical features, which makes them potentially more attractive to install PV farms. Other HFI_{q1} areas are found in mountain regions, such as the Cantabrian mountains, Pyrenees, the Iberian System, Sierra Morena, and northern interior regions of Portugal (Serra da Estrela, Montesinho e Gerês). Unsurprisingly, HFI_{q4} areas are found in littoral and near major cities, most notably near Lisbon, Madrid, Barcelona, Valencia, or Seville.

Overlapping the areas with higher PVOUT ($PVOUT_{Q4}$) and low and high HFI (HFI_{q1} and HFI_{q4}, respectively), allowed obtaining a first assessment on where land sparing and land sharing areas should be prioritized, respectively (Fig. 1C). Land sparing areas i.e., those overlapping $PVOUT_{Q4}$ and HFI_{q1}, span over 18,497 km^2, representing 3 % of the area covered by $PVOUT_{Q4}$ (Fig. 1D). Conversely, 7 % of $PVOUT_{Q4}$ overlaps HFI_{q4} areas, representing over 41,000 km^2 (Fig. 1E).

Four solar PV farms (<0.3 % of the total and covering ca. 1 km^2) fall within sparing areas, while 391 sites (27 %; 110 km^2) fall within sharing areas (Fig. 2). This suggests that the bulk of solar PV farms are being installed in areas with a higher human footprint, where the energy demand is also higher. Noteworthy, 47 % of sparing areas are within protected areas (8704 km^2, Fig. 1D). However, across the Iberian Peninsula, we identified 152 solar PV sites (ca.10 %) to be inside protected areas, covering a total of 19 km^2, including 114 sites in Natura 2000 areas (11 km^2).

Less than 10 % (ca. 3000 km^2) of sparing areas are currently artificial surfaces and urban fabric, while almost two thirds are arable land (36 %, ca. 14,760 km^2) or permanent crops (25 %, ca. 10,250 km^2) (Fig. 3). Within arable land, the dominant class is 'Non-irrigated arable land', covering almost 10,000 km^2 (Fig. 3).

4. Discussion

Burning fossil fuels for electricity is still a major source of greenhouse gas emissions globally, undermining our need to avoid global warming above 1.5 °C in line with the Paris Agreement. The decarbonization of our energy system is therefore the most important component to achieve that goal. To reduce our dependence on fossil fuel-based energy production, countries are expanding their facilities in renewable energy sources. The development of solar photovoltaics is crucial to achieve this goal and decarbonise the power sector in a cost-effective manner. This development will be particularly significant in the Iberian Peninsula, given its great potential of photovoltaic power production (Supplementary material S1). Furthermore, both Spain and Portugal have set ambitious renewable energy targets for the coming years to accelerate the green transition, which will further drive the development of PV farms in the region. This development is expected to be higher in southern Iberian regions, where the solar potential is higher (see Fig. 1A and Supplementary material S2).

While there is scarce information on the impacts of solar facilities on biodiversity, one can expect that the encroachment of PV farms into more pristine, wilder and thus with more potential biodiversity regions may cause significant negative impacts (Blaydes et al., 2021; Hernandez et al., 2014; Kim et al., 2021; Tinsley et al., 2023; Zhang et al., 2023), also due to the proliferation of transport and energy infrastructure that accompany PV farms that causes landscape fragmentation and loss of landscape connectivity. Conversely, the installation of solar PV facilities in areas already having a high human activity, including urbanized and intensively agricultural areas, may actually result in beneficial impacts for at least some biodiversity, including pollinators (Blaydes et al., 2021) and other taxa. For example, a recent report assembling the monitoring data from 37 operational solar sites surveyed across the UK revealed benefits for plants, invertebrates, birds, and mammals, including species of conservation concern (SEUK, 2023). Nevertheless, to our knowledge, there has been no large-scale attempt (but see Guaita-Pradas et al., 2019) to assess the spatial friction between the development of solar facilities and biodiversity conservation areas and zones where the installation of solar facilities may have a positive outcome for both socio-economic development and biodiversity. Here, we provided such an assessment for the Iberian Peninsula, a region with the best conditions in terms of photovoltaic potential at the European level (Perpiña Castillo et al., 2016) and with a rapid expansion of PV solar farms underway (Supplementary material S2).

According to our assessment, land sparing areas represent ca. 3 % of the top quartile of PVOUT, half of which (8704 km^2) is covered by protected areas, suggesting that infrastructure development therein can be legally contained or controlled. Nevertheless, a recent study at the global scale identified >2200 fully operational renewable energy installations (i.e., including onshore wind power, hydropower, and solar photovoltaics) within the boundaries of conservation areas (protected areas, key biodiversity areas, and wild areas), with another 922 facilities under development (Rehbein et al., 2020). Hence, the fact that a given area is legally protected may not suffice to avoid its conversion to renewable facilities. Moreover, the other half of sparing areas may become more exposed to the installation of utility-scale projects, given fewer legal constraints. This may be particularly relevant for areas with smooth terrain in southern Portugal and Spain, given their higher suitability for the installation of solar farms. For example, much of the distribution area of Iberian lynx (*Lynx pardinus*), little bustard (*Tetrax tetrax*), and great bustard (*Otis tarda*) coincides with these sparing areas (Silva et al., 2023). As such, the conservation of these iconic and threatened species could be compromised if solar farms and associated infrastructure spread across these regions. Furthermore, although the northern slopes of mountainous regions in sparing areas are unlikely to have solar farms, the southern slopes may have good conditions for the development of such facilities. The installation of PV panels is possible and effective even in steeper regions and mountains (Kahl et al., 2019), and therefore guaranteeing the safeguard of more hilly terrain in sparing areas should also be considered.

On the other hand, our assessment identified over 41,000 km^2 of land sharing areas where high PVOUT coincides with high HFI, and in fact, the bulk (27 %) of PV farms occur therein (Fig. 2). According to the EU Market Outlook for Solar Power 2022–2026, Spain and Portugal have together an installed solar capacity of over 30 GW, aiming to add 46–80 GW by 2026, depending on the scenario considered (SolarPower Europe, 2022). Hence, assuming that utility-scale projects require ca. 0.02–0.03 km^2 per MW (2–3 ha per MW), an area of ca. 1520–2200 km^2 (ca. 5 % of Iberian land where high PVOUT coincides with high HFI) would suffice for accommodating photovoltaic farm facilities capable of generating the entirety of the energy required to meet the Iberian supply goals. This is <1 % of the Iberian Peninsula. It's important to highlight that rooftop photovoltaic systems are expected to make substantial contributions to this energy capacity. These systems will be distributed across a multitude of rooftops, characterized by their decentralized and smaller-scale nature, which will result in reduced costs, namely in distribution (Bódis et al., 2019).

A significant portion of the land designated as sharing areas may not be feasibly converted into utility-scale solar farms, namely urban areas, areas occupied by transportation infrastructure, and more productive agricultural land. However, the installation of utility-scale solar farms can be advantageous in areas formerly dedicated to intensive agriculture that, for some reason, are now unproductive, degraded, or desertified (Ferreira et al., 2022). Therein, we might expect some positive impacts on biodiversity, with solar farms functioning as set aside areas from agriculture where soil disturbance is reduced, and microclimatic conditions are ameliorated in the extreme climatic conditions of Mediterranean areas. Such agrivoltaic systems, combining agriculture and PV solar production, may inclusively provide an opportunity to ameliorate the competition for land use between food and energy production

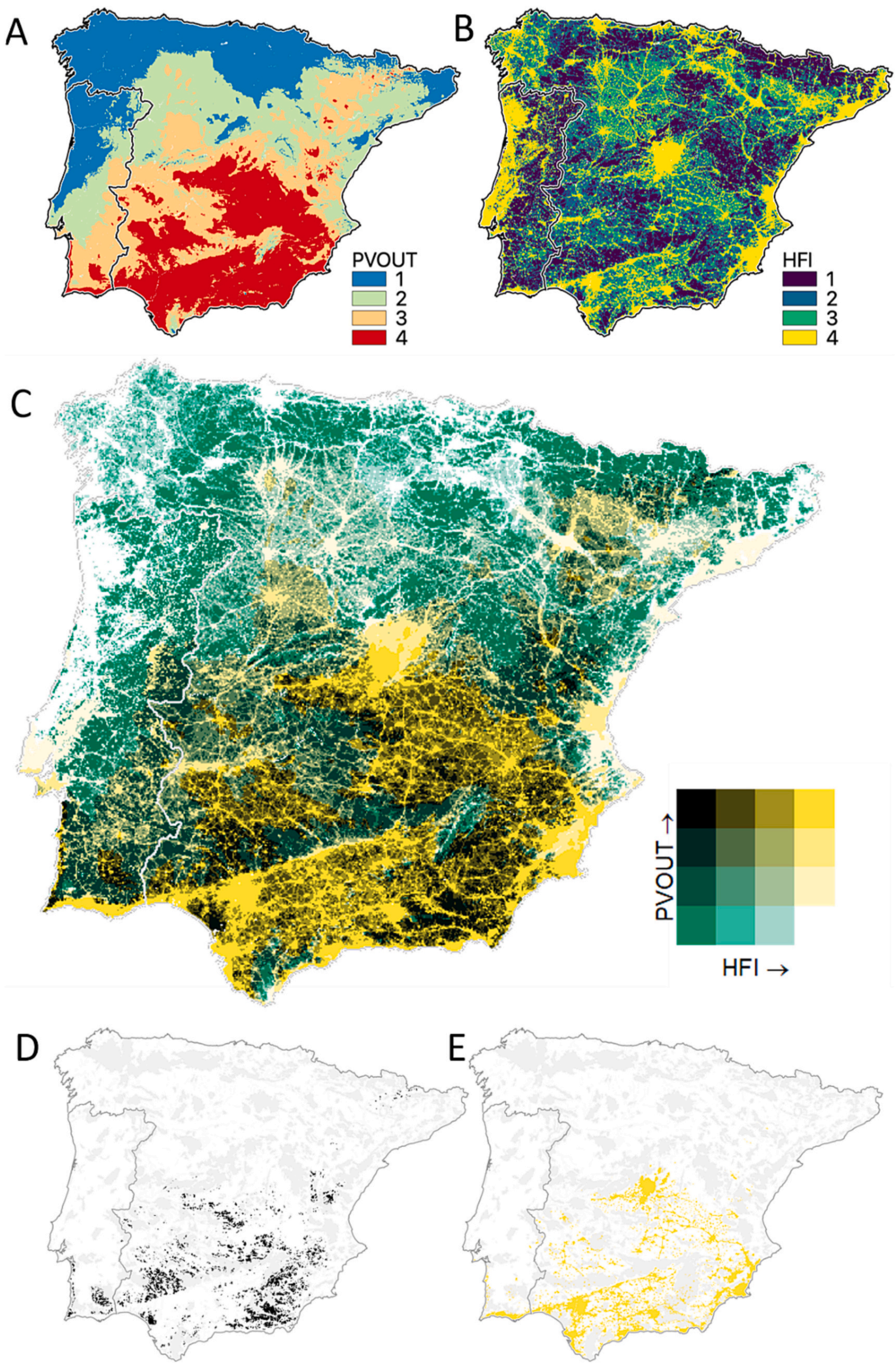

Fig. 1. Information on Photovoltaic Power Output (A) and Human Footprint Index (B) transformed into quartiles (e.g., 1 stand for first quartile). The overlap of these layers results in the bivariate map (C), reflecting the distribution of both layers across the territory. From the bivariate map, we obtain the potential land sparing (D) and land sharing (E). Grey areas in the bottom images stand for protected areas (including Natura 2000 and IUCN areas).

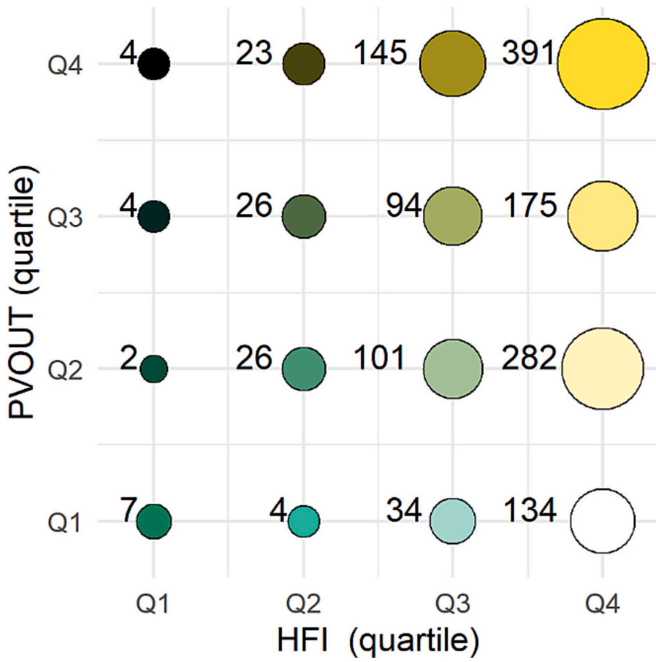

Fig. 2. Number of PV farms operating in the different areas, considering the quartiles of Human Footprint Index (HFI) and Photovoltaic Power Output (PVOUT). The size of the dot is proportional to the number of facilities (numbers to the left of each dot). The colours correspond to the legend of the bivariate map in Fig. 1. PV farms locations were retrieved from the harmonized global dataset of solar farm locations (Dunnett et al., 2020).

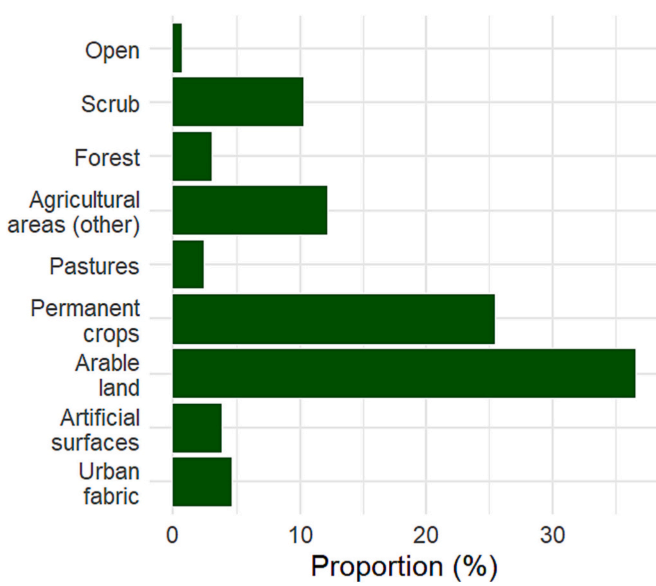

Fig. 3. Proportion of area occupied by 'shared areas', per land cover class. Classes of Corine Land Cover were aggregated according to the Table S3.1 in Supplementary material S3.

(Dupraz et al., 2011; Tölgyesi et al., 2023; Valle et al., 2017). Particularly for plants, insects, and other small animals, PV farms in shared areas can provide foraging and reproductive resources, increasing landscape heterogeneity and connectivity, and microclimatic variation that is beneficial to many species, especially in more arid environments (Blaydes et al., 2021).

As such, PV farms may contribute to ecological improvement in more degraded environments (Nordberg and Schwarzkopf, 2023; Tölgyesi et al., 2023). However, the proper management of those areas is critical to ensuring the benefits on soils, vegetation, and the rest of the trophic chain, including the avoidance of chemical inputs, namely herbicides and fertilizers, and the inclusion of small discontinuities in grasslands, such as hedgerows and shrub patches, which may notably improve habitat quality (Chozas et al., 2022). Similarly, we emphasize the necessity of conducting localized assessments within focal land sharing areas, as these locations might harbour significant biodiversity despite experiencing a greater human footprint. Notably, certain bird species exhibit strong adaptations to pseudo-steppe environments, such as the above mentioned little and great bustards, along with the Montagu's Harrier (*Circus pygargus*). According to our assessment, this habitat is predominant in land sharing areas, and the potential effects of photovoltaic solar installations on these species have not yet been studied.

Finally, we identify some limitations in our framework that should be considered in future research. First, we assumed that solar infrastructure development in lower human footprint areas is more detrimental than in high human footprint areas. We used the Human Footprint Index (HFI) as a proxy of potential wilderness, assuming that a low HFI is associated to potentially higher biodiversity and conservation values due to the lack of human presence. As such, we considered that the development of PV solar facilities in areas with low HFI would potentially result in considerable conflict with biodiversity conservation priorities (land sparing). On the other hand, areas with higher HFI are associated with high human activity, i.e., areas where energy is more required. Hence, the overlap between high PVOUT and HFI is likely to identify areas where solar farms may have a win-win result, both for socio-economic development and biodiversity (land sharing). However, there is a general lack of knowledge on solar PV effects on biodiversity (Lafitte et al., 2022), precluding the differentiation of the impacts across species. We further caution against using these maps to guide local conservation action. For that scale of analysis, other field-based measures of biodiversity are needed. This framework may serve as a preliminary assessment at the landscape scale, for planning and guiding further research through more focused efforts at the local scale, and according to the target habitats and species.

Overall, we propose a simple conceptual and methodological framework for producing a first assessment at the landscape scale of the potential conflicts and opportunities of utility-scale solar infrastructure for biodiversity. A clear benefit of implementing this framework is the possibility of producing assessments for infrastructure impact at a very large scale (from regional up to global scale), even in less studied areas. This framework can be used at the global scale since there is the same information across the globe. Consequently, this framework can be very useful for both researchers and wildlife managers, especially relevant in developing countries and remote areas where biodiversity will be potentially highly affected by future infrastructure development. Ensuring beneficial management of rapidly growing solar farms contributes to their wider environmental sustainability, with positive implications for both biodiversity conservation and the energy sector in general.

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CRediT authorship contribution statement

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Declaration of competing interest

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Data availability

All data used is available within the respective reference.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110331.

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