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Review

Current Knowledge on Novel Semi-Arid Photovoltaic Ecosystems, Their Impacts on Biodiversity and Implications for the Sustainability of Renewable Energy Production

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Abstract: The transition from fossil fuels to renewable energy is fundamental to the mitigation of global climate change. Renewable power capacity is increasing globally, and solar photovoltaics will be the dominant renewable energy source by 2050. Photovoltaic parks (PVPs) require great expanses of land, usually in drylands, creating impacts that can compromise the sustainability of surrounding ecosystems and PVPs. But both novel ecosystems in PVPs and the effect of PVPs on ecosystems are rarely studied. This paper reviews the current knowledge on the impact of PVPs on arid and semi-arid ecosystems and describes the structure and functioning of these novel ecosystems, including changes in microclimatic conditions, soil properties, vegetation and fauna, and shows how these factors hinder the full recovery of ecosystems in PVPs. Ensuring that we do not sacrifice biodiversity for clean energy production restoration is necessary; hence, we address the limitations and challenges of restoring ecosystems within PVPs and suggest the use of modern ecological restoration techniques and the incorporation of grazing into rational planning. More research is needed to fully understand the long-term impacts and interactions of PVPs with the environment, the evolution of novel ecosystems in PVPs and the restoration techniques needed to achieve the long-term sustainability of these infrastructures.

Keywords: biodiversity; conservation; ecosystem services; environmental impacts; land-use change; novel ecosystems; photovoltaic landscape; renewable energy; solar park

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1. Introduction

In order to mitigate the effects of global climate change, transitioning from fossil fuels to renewable energy is fundamental. To achieve the target of limiting the global average temperature increase to 1.5 °C by 2030, as proposed by the Paris Agreement within the United Nations Framework Convention on Climate Change [1], the rapid, large-scale expansion of low- and zero-carbon renewable energy sources is already underway, promoted by local and national governments. In fact, the transition from carbon-intensive fossil fuels to renewable energy sources has been accelerated in the last decade on a global scale. Currently, renewable energy sources contribute ~1/4 of the world's growing electricity production, and the number of renewable energy facilities has tripled since 2003 [2,3]. Moreover, according to International Energy Agency (IEA) projections, global renewable energy capacity will increase by almost 2400 GW (almost 75%) between 2022 and 2027 [4]. Currently, solar photovoltaics generation accounts for almost 50% of the annual addition of renewable power generation to the energy market [5] and is predicted to become the dominant renewable energy source by 2050 [2,5].

This growth in infrastructure construction and renewable energy production has been faster than legislation and scientific research can adapt, so there are legal and knowledge gaps that are being filled as regulation and research on the effects of renewable energy on biodiversity, landscape and society advance. In this sense, it is important to highlight that many developing countries lack land-use planning policies, so the establishment of renewable energy plants is not regulated [6]. According to [7], 17.4% of the current (operational) large-scale renewable energy facilities (above 10 MW generation capacity) are located in areas with some level of environmental protection, most of them in Western Europe. Moreover, a large proportion of under-development energy facilities will impact important conservation areas in Europe, India, Southeast Asia and South America. Following the current trend, in 2028, the number of active renewable energy facilities within important conservation areas could increase by ~42% [7]. These data show that current legislation is not sufficient to keep these projects apart from areas of high natural value [7–9]. According to the observed growth trend, conflicts between conservation and renewable energy development will likely intensify in the near future [7].

Solar energy production requires a large land area compared to fossil fuel plants. For example, it needs almost four times more land area than a coal plant to produce the same amount of energy [9], which is detrimental to other productive activities and natural ecosystems. Therefore, solar energy production involves the conversion of large areas, which can have a large environmental impact at different scales. Due to the characteristics of the radiation necessary for the production and profitability of solar energy, the selection of sites for the installation of photovoltaic plants (PVPs hereinafter) is made according to technical and economic criteria (amount of insolation, topography, proximity to transmission corridors and to population centers; [10]), while factors related to the potential impacts on biodiversity and habitat loss are not usually included when evaluating the location of the projects [9,11]. Arid and semi-arid ecosystems, with abundant space and sunshine, are the most suitable for the siting of PVPs. These ecosystems are especially sensitive to disturbance because of the particular plant and animal communities they host. Therefore, the construction of PVPs has a significant environmental impact [12–14].

The construction of PVPs gives rise to new ecosystems, the functioning of which is still poorly understood. Hobbs et al. [15] explain how novel ecosystems can result in hybrid systems, retaining some original characteristics as well as novel elements, whereas larger changes will result in novel ecosystems that comprise different species, interactions and functions. The structure of PVP ecosystems is conditioned by the rows of solar panels, the new characteristics of the soils, the management of vegetation to protect solar panels, the fencing and the connectivity with the surrounding ecosystems, among others [16]. Understanding how ecological processes function in this context is a challenge, but this understanding is key to managing these ecosystems to maximize the biodiversity and ecosystem services they provide and, hence, their contribution to sustainable development [16]. But current knowledge on both the effects and functioning of PVP ecosystems is scarce and needs to be reviewed to reach conclusions.

Achieving sustainable development requires an equilibrium between economic growth, social inclusion and environmental protection [1,16], but, as stated before, in the case of solar energy, there is also a conflict between the United Nations Sustainable Development Goals (SDGs), particularly SDG 7, SDG 13 and SDG 15. In this sense, the coordinated spatial planning of renewable energy expansion and biodiversity conservation by governments and other decision-makers is essential to avoid compromising the success in reaching these objectives [12].

With the exponential growth in PV energy, there are more studies on the effects on specific species or taxonomic groups and some general literature reviews. However, to our knowledge, there are no reviews focused on the effects of PVPs on ecosystems in arid and semi-arid areas, which are the most affected by the concentration of PV projects and which present a particularly sensitive biodiversity adapted to the extreme conditions in which species live. Hence, the aim of this study is to review the state of knowledge about the effects of PVPs on the environment and biodiversity in arid and semi-arid ecosystems and try to give some insights on how to make solar energy production compatible with biodiversity conservation in order to achieve the sustainable deployment of PVPs. Section 2 explains the methodology used to review the literature. Section 3 addresses the main impacts associated with the different stages of construction of PVPs, from the manufacturing of the panels to the end of their useful life. Section 4 focuses on the general impacts of PVPs on the environment and arid ecosystems described in the literature. Section 5 describes the characteristics and functioning of novel photovoltaic ecosystems; in particular, changes in the soil, flora and fauna are addressed. Section 6 summarizes and contextualizes the results of the literature review, identifies limitations and knowledge gaps in the study of PVP impacts and proposes future steps for research in PVP novel ecosystems; it presents some proposals for PVP restoration in semi-arid ecosystems to minimize negative impacts. Finally, a critical comment on the review and the concluding remarks are presented in Sections 6 and 7.

2. Methods

A bibliographic search was conducted in December 2023 to identify research articles and review papers published in peer-reviewed journals, as well as scientific reports, and the gray literature. The search was performed using ISI Web of Science (WOS) and Google Scholar. The search period was restricted to publications from 2000 to 2023. Additionally, reference lists from the included studies and reviews were screened to identify further relevant literature. The search strategy targeted information contained in the title, abstract and keywords. The following terms were used in the search:

"photovoltaic energ*" OR "photovoltaic plant*" OR "photovoltaic facilit*" OR "photovoltaic power" OR "solar park*" OR "solar farm*" OR "solar plant*" AND "biodiversity" OR "vegetat*" OR "soil*" OR ""bird* OR "wildlife" OR "animal*" OR "ecosystem*" OR "habitat*" OR "*climate" OR "*arid*" OR "desert*" OR "restoration".

Following an initial screening of the articles based on the content of their abstracts, studies that were not related to the research topic or that did not focus on arid or semi-arid regions were excluded. The remaining articles were then reviewed in detail.

The DPSIR (Driver–Pressure–State–Impact–Response) framework [17] was adopted to improve the coherence and organization of the reviewed literature. This framework allows for a structured classification of the ecological dimension of photovoltaic development. Accordingly, the selected studies were categorized based on the following components: (i) underlying drivers (e.g., energy policy, economic incentives), (ii) pressures exerted on arid or semi-arid ecosystems, habitats and wildlife (e.g., land transformation, habitat fragmentation), (iii) changes in ecosystem state (e.g., species richness, soil quality), (iv) ecological and environmental impacts and (v) proposed or implemented responses (e.g., mitigation strategies, restoration measures).

3. Overview of the Pressures, State and Impacts Associated with the Different Stages of Solar Energy Production

The main research lines associated with the environmental impact of solar energy can be classified into three stages: the manufacturing of photovoltaic modules, infrastructure construction and lifetime and the post-use or decommissioning phase. However, the number of research papers discussing the effects of the initial and final stages of PVPs is negligible compared to those studying the lifetime stage [18] (see, however, Espinosa et al. [19]). This could lead to the erroneous assumption that the only impacts of solar energy on the environment occur during the operation of PVPs, which can alter the overall picture of the benefits and negative effects of PVPs on the environment [18]. Although the pressures and impacts of solar panel manufacturing and PVP dismantling on ecosystems remain poorly studied, in this section, we describe the main points detected in each of the stages in order to summarize the current research.

3.1. Module Manufacturing Phase

Research in photovoltaic module production focuses on developing more powerful and efficient panels to increase performance [20]. Module manufacturing has numerous pressures and impacts on the environment. During this process, large amounts of energy and a large volume of water are consumed [18]. In the manufacturing of photovoltaic panels, heavy metals and harmful and hazardous chemicals for humans and the environment are used [20,21]. Moreover, this is the stage that produces the largest carbon footprint [18,21]. Thus, the carbon footprint generated and the amount of water used at this stage is highly dependent on the materials and technology used and the country where the panels are produced [18].

3.2. PVP Construction and Operation Phase

From an environmental point of view, the operation phase (including the construction of the PVPs) is the most studied phase because of its direct effects on the landscape and biodiversity. These effects are discussed in more detail in Sections 4 and 5. In general, the main critical points are the choice of the construction site, the effects during construction and the effects of the panels themselves during the lifetime of the PVP. Solar energy requires large areas of land for solar panels (driver), which leads to habitat transformation and degradation (pressures). During the construction phase, changes in the physical structure of the soil occur due to the use of heavy machinery [22], causing potential increases in erosion [23,24] (state), and the establishment of vegetation becomes harder because of soil compaction (impacts).

In addition to solar panels, the construction of complementary infrastructure (roads, power lines, buildings, etc.) has effects on biodiversity. These pressures include the destruction and fragmentation of habitats (outside of those strictly considered by the PVP), an increased risk of being run over and collisions with power lines, increased human presence in remote areas (due to the availability of new roads) and an increased risk of dispersal of invasive species, among others [25]. There are numerous studies on the effects of linear infrastructures on biodiversity, so we will not dwell on them here [26–28]. However, it is striking that the secondary and support structures of all photovoltaic installations are not taken into account in studies on the effects of PVPs on biodiversity [21,25].

During the operation phase of PVPs, solar panels change microclimatic conditions (temperature, humidity and photosynthetically active radiation), which may result in changes in plant communities (see Section 5). Effects on vegetation growth and flowering and plant and animal species richness and abundance, among others, have also been detected (see Sections 5.3 and 5.4).

3.3. Decommissioning Phase

The dismantling phase of PVPs is a major challenge for the solar industry and the environment. Photovoltaic panels contain a large number of heavy metals, such as lead or cadmium, and many other harmful chemicals [18,21,29], so their improper storage or incorrect disposal can have negative consequences for the environment, polluting soil and water. However, due to the relatively short time of existence of this energy production system, there is still little experience with the dismantling of PVPs and the recycling of their components.

Currently, only Europe obliges solar panel manufacturers to collect and dump solar panel waste [5]. Outside Europe, a few countries have addressed the issue of photovoltaic waste regulation, but in most countries with PVP installations, there are no waste management and recycling regulations. Therefore, panels are usually disposed of at regular sites, where the modules can degrade and leach harmful chemicals into the soil [29].

Panel recycling is a relatively new field of research, and the current aim is to recover and recycle the most important parts for use in new panels or for other uses, reduce production costs and optimize the use of the metals they contain. There are three different solar module recycling processes: physical, chemical and thermal [29]. Two types of PV recycling technology are currently commercially available; new ones are being investigated but are still on a laboratory scale. Current systems for recycling modules have the disadvantage that they produce a lot of waste, gases and other toxic substances and consume large amounts of energy [21,29].

4. Main Pressures of PVPs on Arid and Semi-Arid Ecosystems

PVPs require large areas of land, which are transformed into vast expanses of solar panels and other infrastructure, modifying ecosystems and affecting their dynamics. The concern to conserve ecosystems and biodiversity in this new scenario of "photovoltaic landscapes" has encouraged technical and scientific studies to determine associated ecological impacts and the selection of optimal areas for the siting of PVPs in which a compromise between biodiversity conservation and electricity production is achieved [11,30]. In general, these works have shown that in order to conserve biodiversity, renewable energy projects should be developed on already disturbed or degraded lands or lands with low environmental value, with little reduction in energy production [11,30]. These degraded areas are often close to cities or towns, so a new element comes into play—social opinion toward the construction of large areas with solar panels [6,31,32]. Reducing visual impact and social rejection are some of the aspects taken into account in the selection of sites for PVPs, which causes them to be generally built in remote and out-of-sight locations, even if this means affecting areas of higher natural value [11,30]. In any case, some kind of territorial planning is necessary to make PVPs and biodiversity compatible [16].

One of the main negative impacts of PVPs on natural ecosystems is the loss and fragmentation of habitats. The construction of PVPs can lead to the clearing of vegetation and conversion of natural habitats, resulting in habitat loss for many species. Migratory species and species that require large home ranges or have specific habitat preferences may be particularly affected [12]. There are many examples of threatened and protected species affected by the construction of PVPs. One of the most famous is the impact of PVPs in California's Mojave Desert on desert tortoise populations [14,33]. PVP development poses a substantial risk to tortoise populations due to habitat destruction and fragmentation. Desert tortoises dig burrows that provide habitat for many animals (rodents, lizards, burrowing owls). Therefore, the loss of tortoises will affect all species that depend on tortoise burrows for shelter and breeding. This case exemplifies how the impact on an individual species can have a cascading effect on entire communities and ecosystems.

Habitat fragmentation can disrupt ecological processes and increase the risk of local population decline. Especially for species with low mobility, it can lead to the isolation of populations forced to live on small habitat islands, which has consequences for fitness and population viability and threatens gene flow. PVPs can also create barriers or disturbances that impede the movement and migration of wildlife [34] and seed dispersal. Moreover, PVPs can harm wildlife both directly (collisions, roadkill, etc.) and indirectly (loss of habitat, change in resource availability, increased stress from noise or human presence; [14]).

PVPs also cause soil compaction and erosion, as well as the blockage or alteration of drainage channels, mainly during the construction phase [24]. Depending on the technology used, siting areas may be completely cleared, which may affect plant colonization and establishment and wildlife habitat. During utility operation, vegetation is mown to control vegetative growth, affecting vegetation performance and the availability of habitat for wildlife [12,13,35]. Moreover, the creation of new shaded areas by solar panels may change the plant communities of arid areas, favoring shade-tolerant plants and harming heliophytes [12,36].

Another major threat of PVPs to the environment, which is generally overlooked, is the cumulative effect of different projects (which are assessed individually in environmental assessment studies) and their impact on ecosystems and the landscape-scale dynamics of wildlife populations [11,12,37]. Kim et al. [9] demonstrated that the cumulative area loss of natural and semi-natural habitats by medium-scale PVPs was comparable to the loss of habitats incurred upon constructing large PVPs. However, in many countries, legislation for the development of renewable energy is being relaxed and simplified in order to reach energy and climate goals (see, e.g., Revised Directive EU/2023/2413), which may threaten biodiversity conservation.

5. Characteristics and Functioning of Novel Semi-Arid Photovoltaic Ecosystems

5.1. Microclimatic Characteristics

During the PVP operation phase, solar panels modify microclimatic conditions; air temperature and photosynthetically active radiation (PAR) are lower under PV panels than in control plots without panels, while air humidity shows the opposite pattern [38–41]. This increase in air humidity is attributed to the shading effect produced by the panels (lower net radiation and air temperature; [38]). Fixed-mount solar panels create a shaded area where these microclimatic conditions are maintained throughout the day, while solar tracking panels create temporally varying shading conditions [39].

Solar panels also influence air circulation, wind speed and turbulence under the panels [40,42,43]. These alterations in air circulation are dependent on the structure of the installations (width of corridors, height of trackers, etc.) and the climate in which they are located.

In general, the microclimate is characterized by lower incident radiation, a lower maximum temperature and lower daily thermal amplitude under the panels than plots adjacent to the panels [37,40]. The panels appear to soften the arid microclimate, dampening the temperature extremes and relative air humidity immediately below them [36,39,41] (Figure 1).

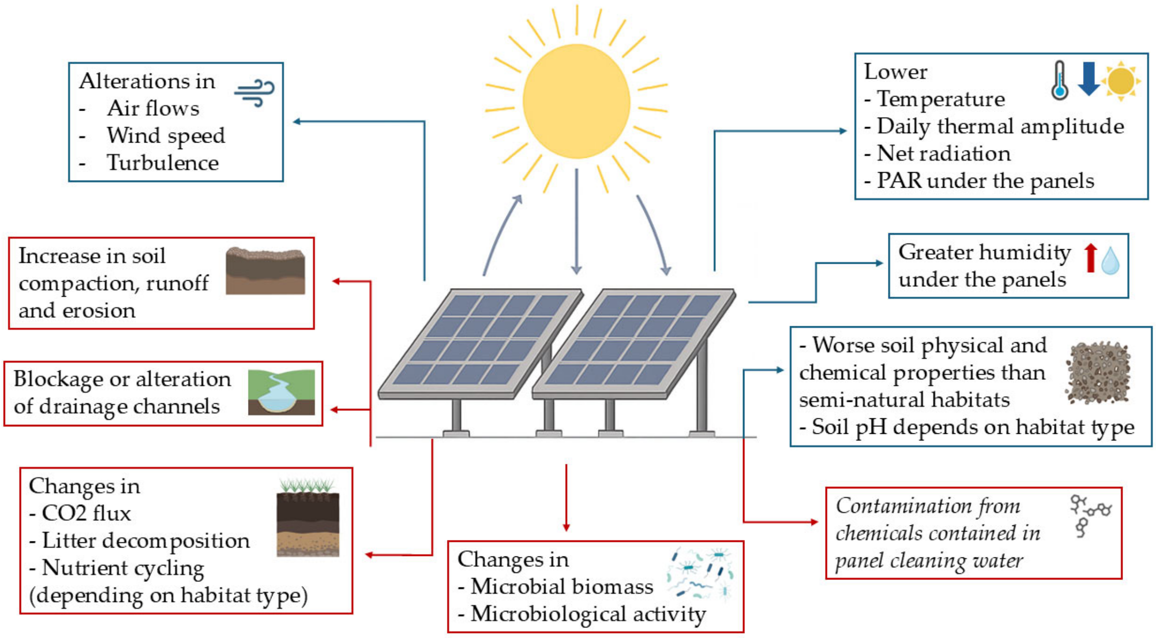

Figure 1. Graphical summary of the main impacts of PVPs on microclimate and soil. Red arrows and boxes indicate negative effects. Blue arrows and boxes indicate effects that are either neutral, undefined, or variable, depending on the context. *Italics* indicate potential impacts identified by the literature but not proven to date.

As indicated in the following sections, these particular microclimatic conditions have a significant influence on soil activity, vegetation and wildlife.

5.2. Soil

In general, soil physical properties under the panels vary little with respect to control plots outside the panels [42–45] but, in some cases, are worse than those in semi-natural habitats (pinewood and shrubland; [22]). Chemical properties under the panels are similar to those of abandoned vineyards but show significant differences from those of semi-natural habitats [36,46]. Moreover, soil pH variation in PVPs depends on habitat type [37,44]. According to Zhang et al. [37], in farmland ecosystems, soil pH increases under the panels, whereas in grassland ecosystems, soil pH measured under the panels is lower than that in control plots.

Soil respiration measured through CO_2 fluxes under solar panels has been little studied to date, and existing studies show that changes in CO_2 efflux depend on habitat type [22,37]. A reduction in CO_2 effluxes under solar panels, as reported by [22] in a Mediterranean region, indicates lower litter decomposition and nutrient cycling, suggesting that these ecosystem functions may be affected under solar panels.

Changes in microclimatic conditions produced by solar panels induce changes in the composition of soil microorganisms. Thus, there is a reduction in microbiological activity and microbial biomass under the solar panels [22,46]. Bacterial and fungal communities show distinct responses to PVPs, and these responses seem to be affected by the construction time, climate and other as yet unidentified factors, which is reflected in the fact that different studies have obtained opposing results. Li et al. [44] detected a significant change in the beta diversity of bacterial communities, but not in their alpha diversity, and an increase in the alpha diversity of the fungal community under the panels. In contrast, Liu et al. [45], in a study conducted on PVPs of different ages since their construction, detected reduced prokaryotic alpha diversity under the panels, but no effects on fungal diversity. Surprisingly, this lower diversity is correlated with soil moisture under the panels. These results suggest that some soil prokaryotic taxa that survive in dry and arid ecosystems may not adapt to the moist conditions created by the panels, while fungal communities appear more resilient to such environmental shifts [47].

However, in other cases, PVPs can produce a number of negative impacts on soil, on which, to our knowledge, research is still limited, although they are recognized as important factors in numerous research papers and reports [22–24,37,42,44]. These include increased runoff and erosion, the alteration of sediment transport, drainage channels and hydrological processes in and around PV installations [23,24,42] and the contamination of soil and vegetation from chemicals contained in panel cleaning water.

During the construction phase of the PVP facility, soil tillage, clearing and partial topsoil removal can lead to increased erosion and reduced soil aggregate stability, resulting in the degradation of soil physical quality compared to semi-natural and natural habitats (pinewood and scrubland; [22]). On the other hand, there is no consensus on the effects that the construction of PVPs has on soil carbon content, soil chemical properties, soil temperature or soil water content [22,36,44]. Figure 1 summarizes the main impacts of solar panels on soil.

Finally, two conclusions made by numerous authors are the following: (i) the time elapsed since the construction of PVPs is too short for changes in microclimatic conditions to influence soil physical and chemical properties; and (ii) long-term monitoring, including during different seasons, is required to evaluate the response of soil properties and microorganisms to PVPs [22,43,46]. Furthermore, land use prior to the installation of PVPs will determine the evolution of soil properties. In the case of PVPs located on former agricultural land, their effects on the soil will be conditioned by the management of the crops. If soil conservation practices were carried out, soil conditions are likely to worsen, while if intensive agriculture was applied, they may improve in the PVP.

5.3. Vegetation

Knowledge of the effects of PVPs on vegetation growth and physiological parameters is mainly thanks to studies that have been carried out with crops grown under panels in agrivoltaic systems. Some of these results can be extrapolated to natural vegetation, but there is still a lot of research work to be done. The main effects of PVPs on vegetation are related to the generation of shade and the alteration of the microclimate under the panels (Figure 2). The presence of solar panels reduces direct solar radiation on the ground and vegetation (Section 5.1). These factors have an impact on plant physiology and phenology, as evapotranspiration is reduced, growth is slowed and flowering and fruit ripening are delayed [10,35,48]. However, production is similar or higher in agrivoltaic systems than in traditional farming systems [49]. On the other hand, plants growing under panels are characterized by larger and thinner leaves adapted to shaded conditions [48]. Moreover, the panels reduce the risk of frost and damage by heavy rain and hail events by acting as a protective roof [50].

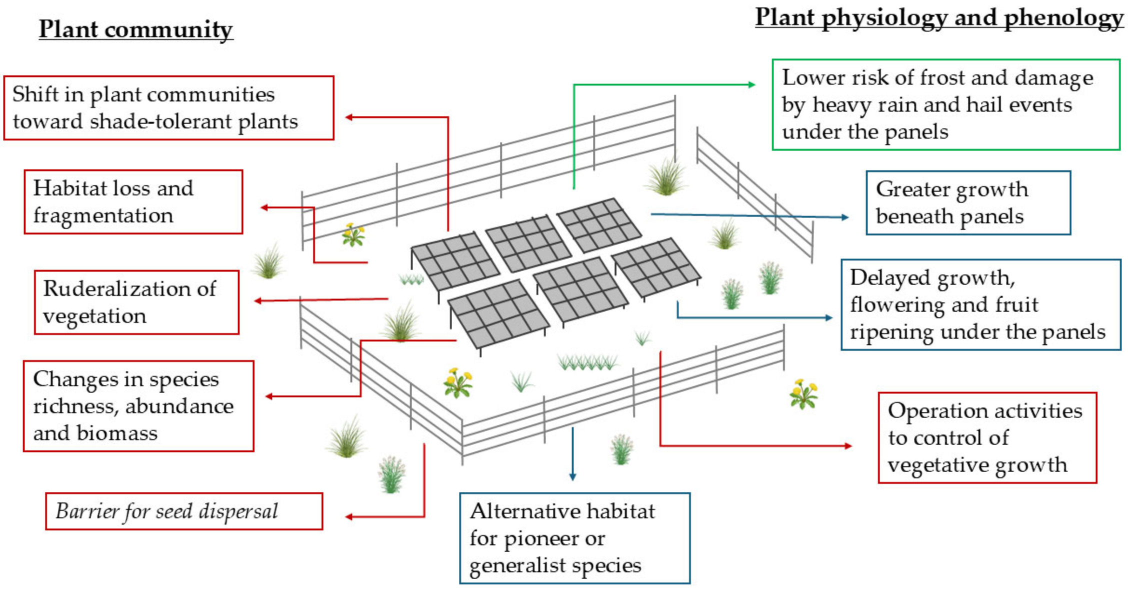

Figure 2. Graphical summary of the main impacts of PVPs on vegetation. Red arrows and boxes indicate negative effects. Green arrows and boxes indicate positive effects. Blue arrows and boxes indicate effects that are either neutral, undefined, or variable, depending on the context. *Italics* indicate potential impacts identified by the literature but not proven to date.

Vegetation development in these new ecosystems is conditioned by some characteristics of the solar facilities, such as the type of panels (fixed vs. tilting), the distance between panels (corridor width) and their height, as they determine the solar radiation incident on vegetation. A study carried out recently highlights that a change in the orientation of panels from the current N-S to SE or SW would increase light distribution at ground level, which may produce notable improvements in the growth of crops, which would receive more sun, without affecting energy production [51]. Alterations of the panels to air circulation are also dependent on the structure of the installations (width of corridors, height of trackers, etc.) and the climate in which they are located, so the effects this may have on vegetation are highly context-dependent.

With regard to plant communities, numerous studies have found that richness and diversity are greater under the panels than in the control areas outside the PVPs [36,39,41,44]. These studies use agricultural crop fields as the control situation, which represent preconstruction land cover but usually host low diversity. In contrast to previous results, studies comparing plant diversity and biomass under the panels (shading), in the corridors between panels (non-shading) and in natural vegetation controls outside the PVP (non-shading), reported less plant diversity (and dominated by grasses) and less above-ground biomass under the solar panels than in the control and corridor areas [40,46].

The effects of PV panels on plant diversity and biomass are diverse, highly dependent on the ecosystem and can even be in opposite directions [13,37,40,41,52]. PVPs enhance vegetation cover and above-ground biomass under the solar panels in grassland, farmland and desert due to protection against high light intensities, while vegetation cover under panels decreases in woodlands. Furthermore, PVPs cause changes in plant community structure, which may not necessarily be reflected in plant diversity shifts [13,36,52]. The vegetation community present in PVPs is mainly composed of ruderal, colonizing and annual grass species, the same species that appear in the early stages of field abandonment [13,36]. This is due, on the one hand, to large-scale land preparation prior to PVP construction, during which the vegetation is generally removed and the soil undergoes a process of degradation (e.g., erosion and compaction). On the other hand, it is due to the natural colonization process after the abandonment of crop fields. As a consequence, plant communities in PVPs are generally primary stages of succession that are re-established and developed during the operation of PVPs and that are kept in this state because of operation activities such as mowing to avoid tall vegetation (Figure 2).

When studying the plant community under solar panels and in the corridors between them in a semi-arid ecosystem, higher richness and species diversity is usually recorded under the panels [36,41,52]. However, these higher indexes do not mean a higher quality or recovery of vegetation under the panels than in the plant community outside the panels since, in this type of ecosystem, mature communities are composed of few species [36]. In this sense, measures such as richness, abundance or diversity are not suitable for studying the effects of PVPs on plant communities in semi-arid areas [36,52]. High values for these indices may indicate modifications in the structure and composition of vegetation, as the panels favor the presence of shade-tolerant or shade-loving species that are not typical of these environments, which does not mean an "improvement in biodiversity" at all. In these cases, where communities are usually composed of a few stress-tolerant or heliophilous species, it is important to identify the species that are part of the mature stage of the community and to use areas of natural or semi-natural vegetation as controls to avoid erroneous conclusions. This is further supported by a restoration experiment in a Mediterranean dry grassland in southeastern France, where solar panels altered the microclimate and significantly hindered the establishment of target species like *Brachypodium retusum*. Despite increased richness in some cases, panels reduced the presence of reference community species [36]. A similar pattern was observed by Armstrong et al. [40] in a desert grassland in the southwestern United States. Their findings revealed increased plant cover and species richness beneath the panels, but this increase was largely driven by opportunistic and non-native species adapted to shaded and altered microclimatic conditions. These changes did not reflect a recovery of native vegetation but rather a shift in community composition, with potential long-term consequences for ecosystem function and native species persistence.

5.4. Wildlife

PVPs have both positive and negative impacts on wildlife (Figure 3). Some of these impacts affect virtually all animal groups, while others are specific to some groups. As previously explained, PVPs often require a large area of land, which can lead to the loss of habitats for wildlife [9]. Fencing PVPs modifies natural habitats, creating patched areas and increasing habitat fragmentation. This is of relevance to migratory species, as it can affect migration routes as well as resting, breeding or wintering sites. PVPs can also create barriers or disturbances that impede access to forage and water resources, mates or breeding sites. For instance, a study on pronghorn (*Antilocapra americana*) in North American rangelands found that PVPs reduced habitat connectivity and limited access to critical resources for both resident and migratory populations, thereby disrupting movement patterns and potentially impacting population dynamics and the ecosystem services they provide [34]. At the PVP scale, soil erosion, loss of vegetation cover and vegetation maintenance actions during utility operation also impact the habitat for wildlife and can increase the risk of local population decline [12,53].

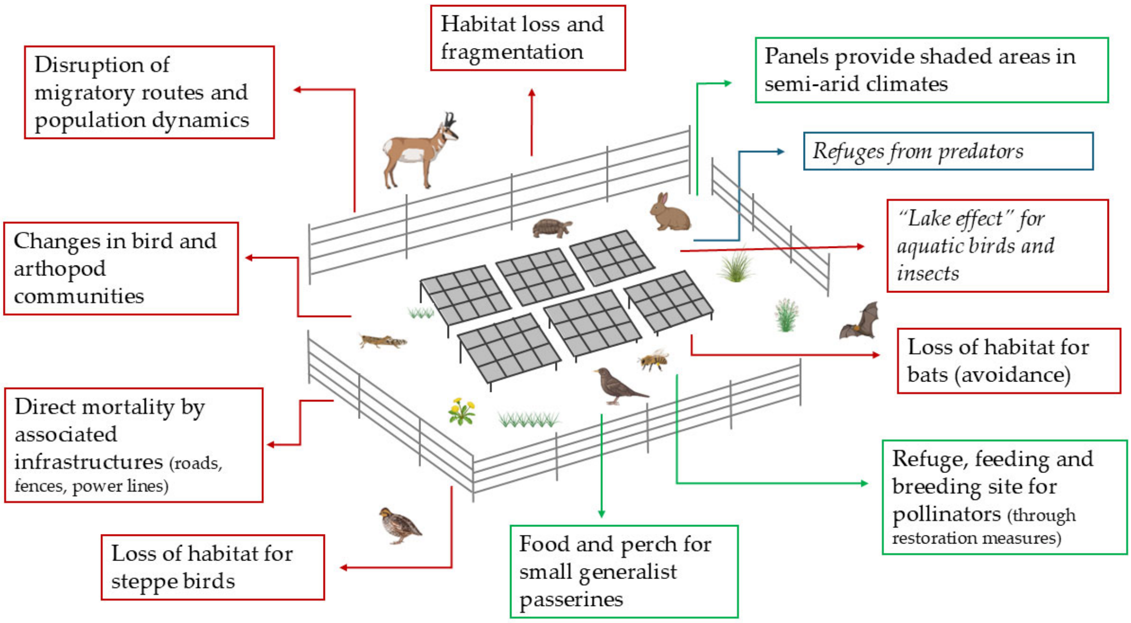

Figure 3. Graphical summary of the main impacts of PVPs on wildlife. Red arrows and boxes indicate negative effects. Green arrows and boxes indicate positive effects. Blue arrows and boxes indicate effects that are either neutral, undefined or variable, depending on the context. *Italics* indicate potential impacts identified by the literature but not proven to date.

Structures and facilities associated with PVPs (including power lines and roads) increase the risk of wildlife collision and direct mortality [14,54]. In addition, PVPs increase noise, vibrations, lighting and human activity during the construction and operation phase, which can negatively impact wildlife and lead to behavioral changes in local populations [54]. Nocturnal species and species that use polarized light for orientation and navigation may be especially affected by artificial light, potentially altering their activity patterns and behavior [14]. Furthermore, the electromagnetic fields generated by solar panels may also disrupt animal behaviors [14].

Positive impacts of PVPs have also been described for wildlife, such as sites that provide shaded areas in semi-arid climates. Theoretically, PVPs may also act as refuges from predators or hunting grounds for carnivores and raptors. But by providing positive effects for some species, it will actually harm other species, producing disequilibrium at the ecosystem level. However, although these are expected effects of PVPs, to our knowledge, there have been no studies to evaluate them, and the presence of mammals and raptors within PVPs is generally reported anecdotally [55,56].

Regarding the study of wildlife in PVPs in drylands, there is a significant bias in the literature toward two animal groups: passerine birds and pollinators (mainly honeybees and bumblebees), while other groups are under-represented. In the framework of the latest policies and recommendations to cope with global change, the importance of pollinators for achieving the SDGs is highlighted [57]. Experts agree that PVPs offer considerable potential to mitigate the causes of the decline in pollinator populations, but there is currently limited scientific understanding, especially in light of the cumulative effects of projected PVPs [2]. Within this international framework, PVPs are recently including management interventions to enhance pollinator biodiversity, such as providing foraging and reproductive resources for pollinators [35,58,59](see Section 6).

Currently, studies on pollinators focus mainly on honeybees, bumblebees and butterflies, comparing abundance inside and outside PVPs [55,56,58,60]. These studies detect higher butterfly and bumblebee abundance inside PVPs, where plant species have been sowed, than in control plots located in agricultural fields, so it is considered that PVPs favor the presence of pollinators, which are also beneficial for the surrounding crops. These studies show the benefits of actions taken within PVPs to favor pollinators in agricultural environments, where intensification and the use of agrochemicals have drastically reduced the populations of pollinators and other arthropods. In this sense, PVPs can act as a refuge, feeding and breeding site for these species. In contrast, Grodsky et al. [53] detected a lower richness and abundance of non-bee insect pollinators (including beetles and flies) inside solar installations in the Mojave Desert than outside them. Although the study was conducted at a Concentrated Solar Power Plant facility, a similar displacement of non-bee insect flower visitors is likely to occur at PVPs in desert and semi-arid habitats where pollinator-friendly measures are not implemented.

Among the most important factors for the presence of pollinators are floral diversity, the presence of late flowering plants, the creation of hedgerows, sown vegetation and allowing naturally established vegetation. On the other hand, the management techniques used in PVPs that are most harmful to pollinators are spring cutting (because it reduces flower load), mowing and agrochemical application [58]. To benefit pollinators, good quality hedgerows are important structures that provide foraging resources and shelter and support breeding pollinators. Good quality hedgerows are those that are continuous and unbroken hedgerows containing at least three woody plant species that provide forage to pollinators throughout the season [61].

The type of PVP (fixed-mount vs. solar tracking panel) also appears to be an important factor influencing the assemblage of pollinators and other arthropods in PVPs. Thus, Graham et al. [35] found that pollinators respond even to the microclimate created by solar tracking panels with respect to insolation (full-shade vs. partial-shade). Specifically, the abundance, richness and diversity of pollinators in partial-shade plots and full-sun plots were similar and, in both cases, higher than those detected in full-shade plots. In another study conducted in the Atacama Desert (Chile) [39], no differences were detected in either arthropod richness or diversity under solar tracking panels or in control plots outside the panels, but differences were detected with respect to fixed-mount PVPs; in addition, the taxonomic composition was different under the panels. Interestingly, these authors conclude that the differences found may be due to microhabitat selection, regardless of the microclimatic conditions.

However, the positive effects of PVPs on pollinators should not mask other poorly studied impacts, such as the change in arthropod community structure and composition detected by [39], whose long-term consequences for the ecosystem are unknown; the lack of comparative studies with natural habitats, where diversity and abundance may be higher than in agricultural lands; the lack of studies at the ecosystem and food web level, of which pollinators are a link; or the possible bottom-up and top-down effects of PVPs on ecosystems [12]. In this sense, vegetation change and/or the loss of some plant species in PVPs can affect specialist insect species through the loss or shortage of food resources or shelter [62], with repercussions for the rest of the food web. Moreover, the loss of some insect species may have negative consequences for plants that depend on insect pollination, such as cacti [53], and ecosystem services. Photovoltaic panels reflect polarized light, which attracts aquatic insects that mistake them for water bodies where they lay their eggs, making the PVPs an ecological trap ("lake effect") [14]. Some authors have suggested that PVPs generate electromagnetic fields that may affect insect foraging behavior, communication and migration [53]. Moreover, noise pollution has negative consequences for both acoustic and non-acoustic oriented insects, although specific studies of PVPs on the latter two topics are practically non-existent to date [53,54].

Passerine birds are the group that has attracted the most attention with regard to their use of PVPs in drylands, although the number of studies is quite limited. Regarding the effect of PVPs on passerines, the results of studies are not consistent, suggesting that the effects of PVPs on birds depend, on the one hand, on the foraging behavior and spatial requirements of each species [63], and, on the other hand, on the control situation selected. Montag et al. [56] detected a higher diversity of birds within PVPs than in the surrounding farmland. The authors suggest that this is likely to reflect a shift from a homogeneous to a more heterogeneous habitat with more foraging opportunities. However, when comparing bird species richness and density between a PVP and semi-natural habitat, Visser et al. [64] found that both richness and density were lower than in the boundary and adjacent untransformed landscape. Accordingly, DeVault et al. [65] reported that PVPs could potentially alter bird community structure. In this study, they detected lower bird species richness within PVPs than in adjacent grasslands, although the density of birds within PVPs was higher than in adjacent grasslands.

PVPs provide food, shade and perches that are selectively used by some small generalist and open country/grassland species [64,65]. However, ground-nesting birds seem to avoid nesting in PVPs [56], so the concentration of PV facilities may pose a serious threat to the survival of steppe passerines. The effects of PVPs on other non-passerine bird groups have not been extensively studied [66], but existing studies suggest that corvids and raptors avoid PVPs [64,66].

Non-passerine steppe birds are at risk across Europe because of agricultural intensification and habitat and nest destruction. This group is one of the most affected by PVPs, as they need an unbroken line of sight to breed [67–69]. These species are particularly sensitive to landscape-scale changes, and the accumulation of PVPs in the distribution range of these species represents a significant loss of habitat and a major threat to their survival [67,69]. The impacts on this group of birds should be incorporated as one of the critical factors when determining the site for the construction of PVPs. However, as mentioned above, other criteria for site selection are prioritized and compensatory measures are often proposed to mitigate the negative effects on this group, although the effectiveness of such actions on the survival of these species has not been demonstrated.

Other negative impacts on birds that have been described, although with little supporting evidence, include death from collision with panels and associated power lines [54,64,70]; incineration of birds as they pass through the solar "flux" at Concentrated Solar Power Plants [66]; and attraction by the reflective surface of solar panels ("lake effect")—birds (mainly waterfowl and shorebirds) may mistake the reflective surfaces of PV panels for water bodies and attempt to land on them, resulting in injury or even death due to impact or because once on land they are unable to take off [54].

The number of scientific publications on the effects of PVPs on mammals is limited compared to research on birds or pollinators. Except for a few studies on species of conservation concern [34,62,71,72], the use of PVPs by mammals in arid or semi-arid areas is limited to anecdotal reports without a scientific approach [55,56]. These reports cite the presence of mammals (rabbits, foxes, roe deer, badgers) within game-fenced PVPs, but apart from these occasional observations, nothing is known about whether PVPs have an attracting or repelling effect on mammals nor about the impact on their behavior and populations. The exception to the lack of studies on mammals is bats, for which some studies have been conducted on their abundance and richness inside PVPs [73–75]. These studies point to a lower presence and/or activity of bats inside PVPs than outside them, suggesting an avoidance effect [56,74]. This can be explained by the fact that bats are not able to identify solar panels (and other anthropogenic materials and structures) correctly, mistaking them for water bodies, and as a consequence of habitat loss and fragmentation.

On the other hand, studies on conservation concern species report different effects of PVPs on wildlife. Cypher et al. [72] describe the success of conservation measures carried out in several PVPs to encourage the use of the facilities by the San Joaquin kit fox. In contrast, Grodsky et al. [62] and Sawyer et al. [34] describe the barrier effect of PVPs on wild ungulate populations. The construction of PVPs within their home range represents a significant loss of habitat, disrupts their migration corridors, reduces connectivity between habitats and alters their behavior. Finally, it is worth noting the absence of studies on the effects of PVPs on other animal groups such as rodents or reptiles [76], with the exception of the desert tortoise, whose case has been described in Section 4.

6. Discussion

Photovoltaic power generation systems are undergoing a rapid evolution toward more efficient and cost-effective technologies. However, despite improvements in performance, solar energy still requires large areas of land, which creates a potential conflict between environmental protection, electricity generation and other land uses. Moreover, many questions remain unsolved about the direct and indirect effects of land-use change, the panels and the associated infrastructure on biodiversity and the functioning of these novel ecosystems in drylands [12].

Under the DPSIR framework, most studies emphasize the “Pressure” and “Impact” components, while fewer address the “Responses” or underlying “Drivers”. After the literature review, some points and limitations detected are worth mentioning. Research on the characteristics of vegetation in PVPs usually relates to a short period, both after PVP construction and the duration of data collection, and there is a lack of long-term studies to detect the effects and analyze the evolution of communities. Moreover, there is a lack of physiological and phenological studies on wild vegetation species; and there is also a significant lack of studies on community scale, seed dispersal and colonization processes. On the other hand, the use of biodiversity indices without considering functional characteristics and the structure and composition of local plant communities in their mature stages can lead to erroneous interpretations of the results. Regarding the literature on fauna and PVPs, most studies focus on avifauna and pollinators, while other animal groups are hardly studied. Furthermore, the literature to date refers mainly to very basic aspects (richness and abundance) without considering impacts on behavior, fitness or population dynamics, among others. Therefore, more research on wildlife and PVP interactions is needed to fully understand the impacts and how to mitigate any negative effects. In addition, the literature usually addresses the effects of PVPs with a focus on isolated processes or species, but ecosystems are made up of many species and their interactions with the biotic and abiotic environment. Therefore, it is foreseeable that PVPs will not have an effect on a single species but rather that they may affect the ecological network. PVPs can affect the interactions among soil, plants and animals, triggering bottom-up and/or top-down processes. Understanding the effects of PVPs on interactions between species and ecological processes is essential to determine their impact on ecosystem functioning [62]. In addition, there is no scientific monitoring of the evolution of ecosystems after the establishment of PV facilities [33]. Monitoring studies focus on the PVP/facility level, but there is a lack of research at the landscape and ecosystem levels. Moreover, the cumulative environmental impacts of existing and proposed renewable energy projects should be taken into account, both prior to construction and during operation, to ensure biodiversity conservation, especially in light of the increased pressure that climate change will exert on arid ecosystems [62]. It should also be noted that some processes respond faster than others. Thus, changes in floristic or animal composition can be detected shortly after PVPs are constructed, while other processes, such as changes in soil physicochemical properties, edaphofauna responses, infiltration or runoff, have slower response times and require long-term monitoring. But, as this review has shown, scientific research to date is limited to very basic (but much needed) questions about the pressures and impacts of PVPs on biodiversity. However, more complex studies are needed that include different levels of ecosystems and at large spatial and temporal scales, as well as studies of vegetation physiology and phenology, population dynamics or fauna behavior, in order to have a clearer picture of how biodiversity and ecological processes change in these novel photovoltaic landscapes.

To address the conflict between environmental protection and electricity generation, dual use of the land for solar PV has been commonly tested in recent years, which fits better with the idea of sustainable development because SPP will contribute to SDG 7 and 13 but also to SDG 2. Thus, agrivoltaic systems, which integrate crop production and PV power generation, have appeared. Agrivoltaics offer a potential solution to the production of electricity and rising food demand, potentially solving the land occupation problem. Although agrivoltaics are mainly focused on crop production or livestock raising, some agrivoltaics have also started to incorporate measures to favor the presence of pollinators, which will contribute to SDG 15 [58,77–80]. Sowing and the naturalization of PVPs with flowering plants are also actions undertaken to support pollinator insects and beekeeping. In recent years, many PVPs have made a special effort to increase the supply of flowering plants to favor pollinators, especially bees, through beekeeping associated with PVPs [58,77–79].

In recent years, multifunctional "solar landscapes" schemes have been designed and managed to deliver a wide range of ecosystem services. These systems seek to integrate different functions, services and dimensions, such as biodiversity, provisioning and regulating functions, visibility or cultural services [59,81,82]. This new approach in designing and assessing PVPs aims to convert "gray" infrastructures into Green Infrastructures in accordance, e.g., with the EU Biodiversity Strategy for 2030. Green Infrastructures are promoted by the European Union policy for both rural and urban areas. Under this Green Infrastructure framework, if solar plants are properly planned, localized, developed and managed over time, they can provide environmental, economic, educational, recreational and social benefits at multiple scales [16,79,82,83], again in line with the SDGs.

Currently, some of the existing PVPs consider the implementation of restoration measures after construction as a response to reducing environmental degradation and contributing to the recovery of ecosystem services [79,83]. In arid and semi-arid areas, low and variable rainfall, as well as other stressors such as low soil nutrient availability, make ecosystems highly susceptible to land degradation, and they are difficult to restore after such degradation [84]. The construction of PVPs implies a remarkable habitat change with respect to the previous situation and the pre-existing ecosystem. But arid and semi-arid ecosystems are resilient and, if the factors hindering spontaneous regeneration are eliminated and thresholds are not surpassed [85], ecosystems will usually recover by themselves. Based on our review, in PVPs, these limiting factors are the following:

- Changes at the landscape level that hinder the use of habitats by fauna (habitat loss) and movements across the landscape (habitat fragmentation);
- Altered soil properties that hinder plant establishment;
- An altered microclimate because of the shadow created by the panels;
- Ruderalization of communities, which produces losses of valuable species.

But such limiting factors are very similar to the limiting factors in the restoration of agricultural lands. This means that by combining the framework for agricultural land restoration [86] and new restoration techniques in drylands, e.g., species selection [87], improved plant production techniques [88], innovative implantation techniques [89,90] or the use of biological interactions to improve restoration outcomes [90], and the increased knowledge of the restoration ecology of drylands [91,92], there are a set of tools fit for purpose to restore PVPs in drylands.

More specifically, some restoration tools that could be applied are as follows:

1. In the framework of agricultural land restoration, creating specific elements to benefit wildlife and particular services [86]. Actions can include (1) creating living fences; (2) planting isolated trees to take advantage of their disproportionate positive value for biodiversity conservation and potential for seed dispersal; (3) the creation of pollinator-friendly areas using plant enrichment; (4) the introduction of beetle banks, stone walls, stone mounds and other strategic refuges for fauna; (5) the introduction of perches and nest boxes for birds; (6) the introduction or restoration of drinking troughs; (7) the reconstruction of rural architecture specifically intended to restore and value cultural services but also serving as a refuge for fauna.
2. In the context of PVPs, where mowing is an integral part of the management, it is key to create ecosystems based on short plants as grasslands, which, in fact, form the spontaneous vegetation in many drylands. Grassland species are usually introduced by means of sowing, but in most drylands around the world, there are two main challenges to seed-based restoration: (1) finding enough seeds and of high enough quality, and (2) the low establishment rates of sown seeds. To overcome these obstacles in relation to seeds, seed coating and scarification technologies can improve germination rates and seedling establishment in arid conditions to improve success with low quantities of seeds [93]. With regard to soil, techniques such as mulching, harrowing and creating microhabitats (e.g., pits or other site preparation techniques) can enhance soil moisture retention and seedling survival [94,95].
3. Another option is using seed bank transfer—removing the top 2–3 cm of the substrate before PVP construction and subsequently placing it over the surface of the PVP. This ensures the permanence of species from the original community [96] but would be more effective on natural rather than agricultural land.
4. Regarding seedling establishment, techniques like nursery mycorrhization, tree shelters, organic amendments, gravel covers, plastic mulches or hydrogels can enhance the survival and growth of seedlings in dryland restoration projects. These methods are particularly effective when combined [97,98].

Nevertheless, some limitations can hinder the recovery of the ecosystem in PVPs and need to be taken into account when choosing the restoration goals and reference ecosystem. Vegetation near and under the panels needs to be short and will be mowed regularly; hence, some areas will be kept at early successional stages and will never reach the state of a fully recovered ecosystem, e.g., shrublands or open forests typical of some drylands. Moreover, some species will not be able to survive inside PVPs regardless of restoration because (1) their habitat cannot be reconstructed in a PVP or (2) PVPs profoundly change the appearance of the landscape and are not perceived as suitable by some species anymore.

A restoration technique compatible with some of these limitations is grazing. The integration of grazing with rational planning into PVPs as a restoration management tool in drylands is a challenge that has not been studied enough [10,82] but can offer several opportunities:

- Controlling vegetation growth, substituting regular maintenance operations, minimizing or even eliminating the use of herbicides, lawnmowers and weed eaters, which have negative impacts on the environment and can also damage PVP systems [99], also reduce greenhouse gas emissions [100] and contribute to fertilizing the soil.
- Livestock grazing is also compatible with pollinator projects, such as the creation of habitats for wild pollinators or the placement of beehives [101].
- Solar grazing enterprises could increase and diversify the income of sheep farmers and thus benefit the livelihoods and financial viability of rural communities [100].

This integration between energy production and food production would contribute to the achievement of SDGs 2 and 7, particularly in drylands, where agricultural production is low and grazing has been a traditional way of using marginal lands unsuitable for agriculture. Moreover, if properly managed, grazing can be an ecological restoration tool that would help reduce the degradation caused by PV plants and assist in achieving SDG 15.

In this sense, pasture restoration by grazing in PVPs has several nuances due to PVP functioning and climatic conditions [101] and will depend on the design of a good grazing plan that considers the following ideas:

- Choose the grazing animal according to the risk of damage to solar panels by animals and vice versa [10].
- If possible, design the panels to fit the grazing, e.g., elevated panels that allow the free movement of animals provide improved animal welfare and more desirable microenvironments (shade) for plant diversity and biomass production [102,103].
- Stocking rates must be calculated to establish a rotational grazing system [101].
- Local pastoralists' knowledge is indispensable [104] and needs to be taken into account when designing grazing plans.
- Move livestock throughout the landscape, from species-rich natural pastures to PVPs, to help the dispersal of suitable species [105].
- Consider sowing some forage species in the early stages of restoration to encourage sward establishment.
- An intense monitoring program is necessary to ensure that livestock rotations are performed properly, that there are no problems between grazing and the actions necessary for the normal operation of the PVPs, e.g., maintenance tasks, and that livestock do not damage the infrastructure or harm themselves.

Finally, whichever restoration method is used, Before–After–Control–Impact (BACI) designs are recommended when studying the impacts of renewable energy on the environment [106] to improve understanding of the impacts and evaluate restoration actions, e.g., by means of the Five-Star System and Ecological Recovery Wheel [107]. In both cases, do urge a critical examination of the selection of reference or control systems, as they have great repercussions on the results obtained. It is also important to consider the species composition of local communities in their mature stages so as not to misinterpret the results in the use of biodiversity indices.

In conclusion, while solar energy production has positive long-term effects on the environment by reducing greenhouse gas emissions, it also has many negative pressures and impacts on ecosystems, ranging from microclimatic and soil alterations and changes in vegetation and arthropod communities to habitat loss and fragmentation, which, in turn, can compromise the achievement of the SDGs. Consequently, it is important to recognize and assess the benefits and risks to find reasonable solutions that enable renewable energy development, conservation of the environment and biodiversity and other land uses. Proper site selection, habitat restoration efforts, best management practices and the incorporation of wildlife corridors or exclusion zones can help minimize negative impacts and promote coexistence between renewable energy development and ecosystem conservation. To make the energy transition to renewable energies such as photovoltaic energy compatible with biodiversity conservation, it is necessary to act at different levels. As large PVPs—located in rural/natural environments—are necessary to supply energy for transportation and industry, their ecological restoration is fundamental. Finally, it is essential to carry out more research to understand the effects of renewable energies on the environment in order to be able to act on them.

7. Conclusions

After the bibliographic review, some aspects stand out.

1. Novelty. The recent emergence and expansion of PVPs (and other renewable energies), which means that there are large gaps in knowledge on their effects on ecosystems.
2. PVPs affect natural areas of high ecological value. First, the literature shows that many valuable natural areas are affected by the construction of PVPs, which indicates a limited consideration of biodiversity during the process of site selection for PVPs.
3. PVPs create novel ecosystems. PVP construction produces changes in microclimatic and soil conditions that affect the pre-existing biodiversity, altering the functioning and composition of the previous plant and animal communities and creating a novel ecosystem that needs to be studied in detail.
4. The complexity of systems and interactions have not been considered. The literature usually addresses the effects of PVPs with a focus on isolated processes or species, but PVPs may affect the ecological network. Understanding the effects of PVPs on interactions between species and processes is essential for determining their impact on ecosystem functioning.
5. There is a lack of long-term monitoring and complex research on these novel ecosystems. There is no scientific monitoring of the evolution of ecosystems after the establishment of PV facilities, and there is also a lack of research and monitoring at the landscape and ecosystem levels or on the cumulative environmental impacts of existing and proposed renewable energy projects. Moreover, scientific research to date is limited to very basic (but much needed) questions about the effects of PVPs on biodiversity, and more complex studies at large spatial and temporal scales are needed.
6. Grazing can be used as a useful restoration tool in PVPs. Although ecological restoration in semi-arid environments is a challenge, incorporating a well-designed grazing plan can contribute to restoring plant communities and improve the quality of the habitat.
7. Current knowledge on ecological restoration in PVPs in drylands is scarce, and more applied research is needed.

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Abbreviations

The following abbreviations are used in this manuscript:

GW	Gigawatts
IEA	International Energy Agency
MW	Megawatts
PV	Photovoltaic
PVP	Photovoltaic plant
SDGs	Sustainable Development Goals

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