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Applying Ecological Succession Theory to Birds in Solar Parks: An Approach to Address Protection and Planning

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Abstract: Renewable energy production will require large areas of land; production sites should be designed to include biodiversity conservation. Guidance for decision-makers on reasonable coexistence is needed. We use time-series data alongside a meta-study on birds in solar parks, utilizing succession theory to indicate which bird groups can thrive in solar parks. Using an evidence-based and interdisciplinary approach, we documented biodiversity and conditions at a 6 ha site in the newly created post-mining landscape of Lusatia, Germany, for 16 years, grouping avian species depending on the ecosystem state in which they were observed. In a key mid-period of early succession lasting eight years, the avifauna was characterized by successional groups 2, herbaceous plant-preferring, ground-breeding species; and 3, open shrub-preferring species. The preceding and following groups were: (1) pioneer bird species that prefer open ground; and (4), pre-forest species. Comparison of these data with available bird monitoring in solar parks showed that bird species of groups 2 and 3 can also successfully settle in open-space solar parks that have some natural habitat attributes, whereas this is hardly possible for the preceding and following groups. Using this information, opportunities for habitat improvement are facilitated, and potential conflicts can be addressed more purposefully.

Keywords: biodiversity; directed long-term changes; landscape transformation; land sharing; solar energy projects; sustainable practices; theoretical foundations

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1. Introduction

If economic requirements are to be met alongside biodiversity conservation, renewable energy systems must be planned and implemented carefully and in a targeted manner, and it is indispensable to have a clear understanding of which part of the natural spectrum will be affected. All landscapes contain aspects and functions of ecosystems. It is impossible to maximize everything at the same time or in the same place, so the best possible balance between resource use and conservation must be sought (while also considering other aspects, e.g., visual quality; [1]). Due to the relative newness of larger renewable energy systems and/or the reluctance of some researchers to engage with them, the sites have so far been undersampled for biodiversity.

In contrast, ecological succession, i.e., when a new physiognomy takes over, as in the transition from the open-land stage with grasses and herbs to a woody stage, has been well studied over the past 100 years [2–4]. Succession theory can now be applied to deriving good professional practice for the nature-friendly design of renewable energy systems. The energy and climate crises must both be addressed while the biodiversity crisis is at least not further exacerbated; understanding succession against the backdrop of renewable energy sites is key to the balance that is needed.

Succession theory provides the idea that a current situation or association is a precursor for something else to come (facilitation, [5]), that dynamism rather than stagnation is natural, and that a variety of dynamic developments are directional. We are living in a time of unprecedented change and challenge. To meet the challenges of the energy crisis, much more land must be dedicated to solar parks without not exacerbating the biodiversity crisis. The aim is to mitigate competition between different land uses, and to identify and show how commercial and conservation outcomes can be achieved simultaneously (e.g., even in cities, [6]). Previous studies have conceptually outlined such interactions in the design of solar parks [7,8]. Therefore, the realization that solar parks are being built on more and more land and should also take nature conservation aspects into account does not need to be addressed anew. However, sometimes targets for nature conservation overshoot the mark or lack professional evidence, for example when conditions are imposed on certain bird species that ignore the intrinsic nature of these species and the ground-mounted solar plants. Overall, the lack of references or an evidence base makes further research necessary, and the potential of exact field data for nature protection and appropriate management should be exploited.

Understanding how plants, animals and other organisms respond to changes in their environment over time is key to successful restoration, rewilding, and habitat management for the sustainable provision of ecosystem services. Birds respond to changes in ecosystems and are therefore considered sensitive bioindicators [9,10]; this applies primarily or especially to persistent long-term changes in the environment [11]. Thus, wider habitat use by birds and the bird communities that are found in different habitats coincide in the longer term [11], and directional habitat dynamics, e.g., ecological succession, goes hand in hand with succession in bird communities [12]. Forest development phases affect the distribution of breeding birds, as phases represent different forest habitat conditions [13]. Comparatively much more pronounced changes in habitat conditions take place in early successional habitats [14].

We relate changes in the avifauna of an early successional landscape, the Hühnerwasser catchment, to the avifauna of habitats undergoing major changes that are not natural succession: the installation of large photovoltaic arrays in the open landscape and thus the establishment of ground-mounted solar parks. In this way, we transfer findings relevant to bird conservation from areas where fossil energy was extracted (open-cast coal mining) to open areas where renewable energy is or will be produced.

1.1. Hühnerwasser Catchment

In the post-industrial landscape of Lusatia, Germany, the artificial Hühnerwasser catchment (also called Chicken Creek catchment), was created in autumn 2005 in part of the Welzow Süd open-cast lignite mine that was reclaimed after mining. The restoration aim was to reissue the original natural spring that had been completely destroyed by the mining activities as well as its catchment.

Over time, the catchment area developed from exclusively open, bare ground with a pond in 2005, via initial successional stages [3,14], to pre-forest tree and shrub cover in 2021 (Figures 1 and 2). This development came about through nature alone. There have been interdisciplinary scientific investigations on the genesis of the area under the umbrella of the Collaborative Research Centre/Transregio 38: "Structures and processes of the initial ecosystem development phase in an artificial water catchment" [15,16] since mid-2007. Regular and frequent high-resolution vegetation monitoring showed an overall increase in vegetation density and diversity over time [3,14].

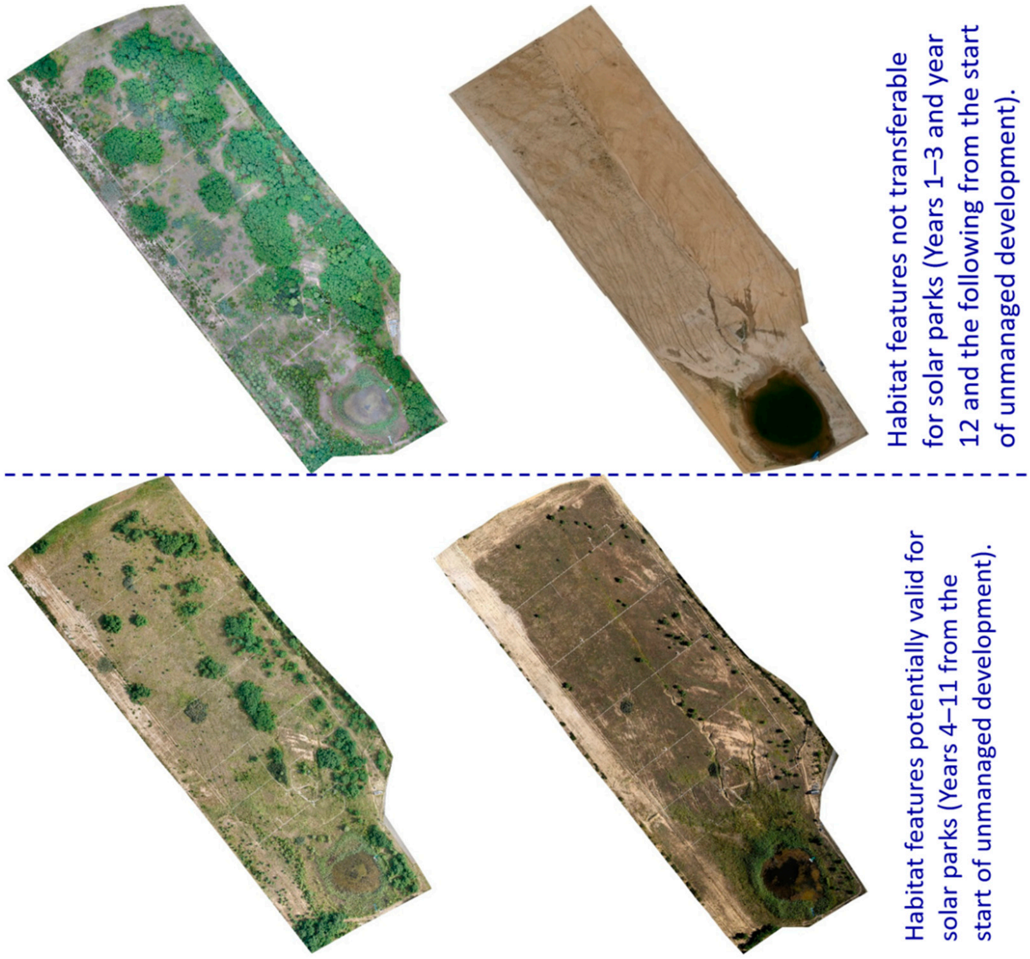

Figure 1. Development of the Hühnerwasser catchment, clockwise from top right—as bare ground in 2007 (**top right**), 2011 (**bottom right**), 2015 (**bottom left**), and 2020 (**top left**). Thanks to the Research Center Landscape Development and Mining Landscapes of the Brandenburg University of Technology Cottbus-Senftenberg for providing the aerial photos, each composed of many drone photos. North is always at the top. A scale bar cannot be given, but the spacing of the paths—which are particularly well visible as grey lines in the 2011 representation (**bottom right**)—is 60 m, and 40 m when close to the pond.

Change over time in the Hühnerwasser catchment (directed dynamics, i.e., ecological succession) has already been demonstrated for vegetation [3] and for soil fauna such as nematodes [17] and tardigrades [18]. In the present study we document the avifauna observed, and integrate the bird data with key floristic data. Results on phased vegetation dynamics from the Hühnerwasser catchment have already contributed to succession theory [3,19]. It has been shown that the bird life of a larger post-mining landscape is also dynamic [20]; in this study we zoom in, so to speak.

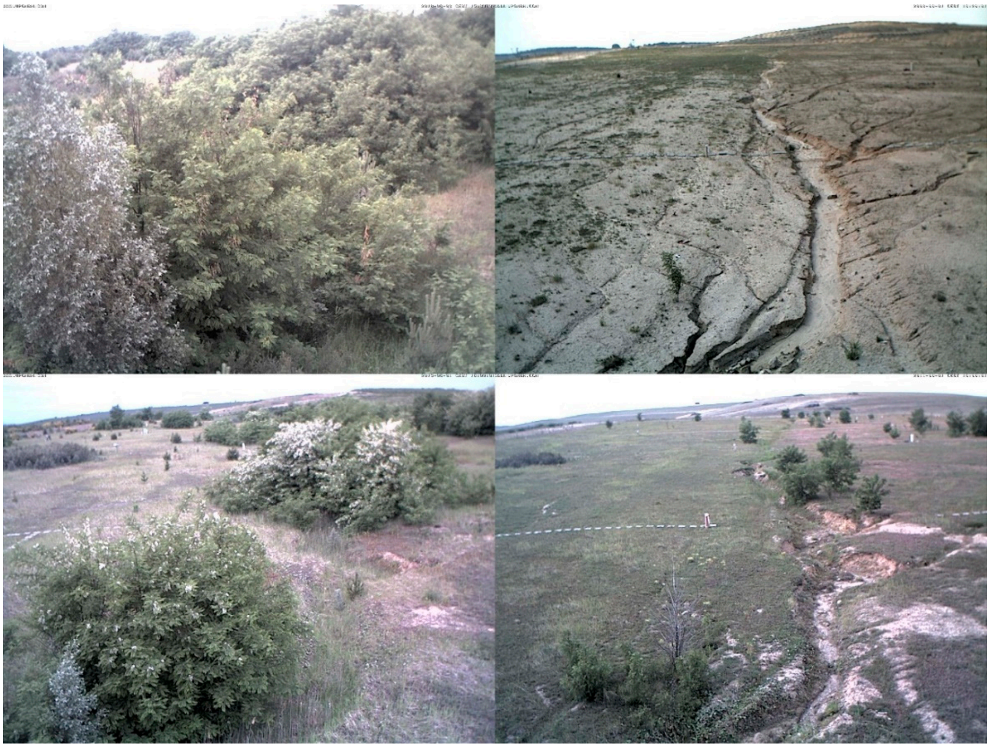

Figure 2. View north over the Hühnerwasser catchment area, from a webcam mounted at 6 m height. The date of each photo is June, clockwise from top right—in 2008 (**top right**), 2011 (**bottom right**), 2015 (**bottom left**), and 2018 (**top left**).

1.2. Solar Parks

The Hühnerwasser catchment is similar to ground-mounted solar parks in that both areas began with more or less open ground conditions; have vegetation that is dominated by grassy strata (temporarily in the Hühnerwasser catchment); have no fertilizers, pesticides or pest control applied; have technical installations that need to be maintained; and are fenced to limit access. In areas of land used as solar parks, natural processes, especially succession, are repressed or restricted from a certain point onwards: The dynamics of plant growth are controlled and limited due to yield expectations and the demand for economic efficiency, and tall plants are not tolerated in the current design of such installations due to yield-reducing shading effects. However, in the course of increasingly strong demands for naturalistic designs of solar parks and also as visual protection, there is a tendency to establish taller herbaceous fringes and woody plants in edge areas, and taller, structurally diverse vegetation enhances pollinators in solar parks [21].

Large areas of land are already used for solar parks, and land-use for solar technologies will continue to increase over the coming years during the transition to sustainable energy [22,23]. Questions about their conservation value are important and topical [24].

Increased numbers of solar power facilities have caused the physical destruction of wildlife habitats, leading to a decline in biodiversity and ecosystem functions, and there is a need for proactive assessment to enforce sustainable site-selection criteria for ground-mounted solar installations [24]. The effects of individual solar parks on birds have been the subject of numerous unpublished reports, often as a requirement of licensing authorities (e.g., in Germany, Poland, and the Czech Republic). Although there have been some reviews, a complete picture providing a useful basis for bird conservation action at solar parks has not yet emerged. The required ecological monitoring periods are short for ground-mounted solar parks, so understanding of area dynamics remains limited. There is an urgent need to increase the informative value of perspectives on bird life in solar parks.

1.3. Comparison and Study Goals

The goal is to document observations of avifauna from the 16-year time-series of the Hühnerwasser catchment in the context of developmental features that indicate increasing complexity, and to compare them with published bird observations from solar parks. We identify possible methodological limitations affecting the comparability of the data. We point out the urgency and propose an approach based on strong ecological relationships for a theoretical framework, drawing on research at the Hühnerwasser catchment. Comparing the two habitats, we ask: what are the similarities and differences in how they are colonized by birds? Our hypothesis is that the successional development of avifauna observed in the Hühnerwasser catchment is also, in part at least, relevant for and applicable to solar parks.

2. Materials and Methods

2.1. Hühnerwasser Catchment

During mining, the area, located south of the former village of Wolkenberg (Lusatia, eastern Germany), was dredged for lignite extraction between 1991 and 1993 [25]; afterwards, the area was inhospitable or even hostile to life for more than a decade. In 2005, part of the former open-cast lignite mine was reclaimed as the 6 ha Hühnerwasser catchment. The fenced catchment area, which has been left entirely to natural processes since its creation, is south-southwest facing with a 15 m difference in elevation on its long side of 400 m [26,27]. An electric fence was added to the perimeter in 2011, so that terrestrial predators are mostly excluded. At the lowest point, a pond has formed in a depression. The area has transitioned from exclusively open bare ground in 2005, via initial succession stages [3], to a pre-forest with tree and shrub cover in the last succession step to date (Figures 1 and 2). It represents a model of ecological succession and allows for empirical real-time series, which now seem even more valuable after pronounced criticism of the space-for-time substitution approach [28].

The observation period of one year was oriented towards the structure of the Hühnerwasser catchment, which became more and more difficult to observe over time due to the progressive vegetation succession with increasingly taller and denser vegetation in many places (common ground explanations: more “habitat heterogeneity”, “niches”, “ways of life” [29,30]). In line with this, the ecological field work of the first author (MKZ) for the main purpose of vegetation monitoring took about two weeks in 2008 and successively increased to two months by 2013 (distributed over ~12 to ~55 on-site inspection days). The work was mostly carried out on weekdays, with MKZ paying special attention to birdlife while walking about 3.5 km of field tracks on each working day. Survey times were spread over the morning, the breaks and finally at the end of the working day, and together they correspond to about one hour per working day. As of 2014, MKZ spent less time on ecological field work overall, somewhere between two weeks and one month. Overall, the survey effort was considered sufficient for the rather small study area [31]: one man-hour of survey time is approximately 10 min/ha for the survey area, which was limited to the Hühnerwasser catchment (6 ha). In fact, during to a single working day, this sampling effort was above guideline values for time per hectare and per survey for qualitative surveys of breeding bird species populations (in different habitats). It meets sampling effort requirements per hectare and per survey for settlement density surveys of structurally poor habitats, but is below the requirements for structurally rich habitats [32]. In fact, our temporal survey effort increased with the succession time series results alongside increasing structural differences, as recommended by experts working in other extensive post-mining landscapes [33]. Years of work on the Hühnerwasser catchment have equipped MKZ with quasi-local ecological knowledge, which supports and strengthens the study design [34]. MKZ recorded birds while carrying out vegetation monitoring in the Hühnerwasser catchment annually from 2008 to 2013, inclusive, with reduced effort in 2014, and from 2019 to 2021, inclusive. Birds were also recorded while ecological field work was carried out at the catchment edge in 2015, and during regular visits in 2016. Field inspections were rare in 2017 and 2018, but observations were provided by other researchers. The observation period was outside the breeding season of many bird species: July and August each year until 2015; from 2016 onwards, it was July.

At the Hühnerwasser catchment, all bird species seen were documented and very often also photographed. Bird calls were also noted during all fieldwork. The resulting data form a unique 16-year qualitative time-series.

2.2. Solar Parks

Bird observations from the Hühnerwasser catchment were compared with data from a comprehensive review of birds in solar parks in Germany by Badelt et al. (2020, [35]). Solar parks vary greatly in size, from ~1 ha to >100 ha in exceptional cases; the Hühnerwasser catchment falls within this range. Both solar parks and the Hühnerwasser catchment have technical applications or are of technical origin, and so technical installations are present on site (in the Hühnerwasser catchment, these include weather stations, measuring devices such as precipitation collectors, a wind turbine and solar panels, and a shipping container). Both sites are surrounded by fences and only authorized personnel have access. Some solar parks have ponds; sometimes there is a legal obligation to create ponds.

3. Results

3.1. Hühnerwasser Catchment

Over the 16 years of observation, 51 species of bird have been documented at the Hühnerwasser catchment. Table S1 lists [3,36–39], for each avian species, the year of first and outstanding subsequent sightings in the Hühnerwasser catchment from its creation in 2005 to 2021, as well as important botanical innovations in its development. Below, this information is presented together with other zoological and botanical notes. Species that were observed breeding and/or were considered summer residents due to prominent and frequent appearances were classed as breeding birds. Paying special attention to species with absolutely unambiguous breeding occurrences, data from the entire survey relevant to the development status of the site or to conservation were used to classify the bird species into four successional groups (Table 1):

1. Group 1: pioneer bird species that prefer open ground;
2. Group 2: herbaceous plant-preferring, ground-breeding species;
3. Group 3: open shrub-preferring species;
4. Group 4: pre-forest species.

Table 1. Successional groups of the avifauna in the Hühnerwasser catchment area, and bird species occurring in solar parks in Germany. Based on the year in which a species was first documented and the years in which it was most commonly seen (Table S1), species were placed in one of the four successional groups (group 1: pioneer bird species that prefer open ground, group 2: herbaceous plant-preferring, ground-breeding species, group 3: open shrub preferring species, group 4: pre-forest species). Some species that were consistently seen as breeding pairs or were approximately equally abundant in different periods were assigned to more than one group. The expected successional groups were based on documented habitat preferences. The birds listed as using solar parks somewhere in Germany are species of the open countryside that are threatened in Lower Saxony [33].

Bird Species (Family)	Observed Successional Group	Expected Successional Group	Species That Use Solar Parks in Germany as Breeding Habitat (BB) or for Foraging (FG, [35])	Species not Observed in Solar Parks, with Comments [35]
Charadrius dubius (Charadriidae)	1	1		×
Numenius arquata (Scolopacidae)	1	2		× "Probably not as breeding habitat, but for foraging possibly usable outside the [solar] modules."

Table 1. *Cont.*

Bird Species (Family)	Observed Successional Group	Expected Successional Group	Species That Use Solar Parks in Germany as Breeding Habitat (BB) or for Foraging (FG, [35])	Species not Observed in Solar Parks, with Comments [35]
Oenanthe oenanthe (Muscicapidae)	1	1		×
Acrocephalus scirpaceus (Acrocephalidae)	2	2		×
Alauda arvensis (Alaudidae)	2, 3	2	× (BB)	
Anthus campestris (Motacillidae)	2	1		×
Coturnix coturnix (Phasianidae)	2	2	× (BB)	
Emberiza calandra (Emberizidae)	2	2	× (BB)	
Falco peregrinus (Falconidae)	2	-		× [1]
Hirundo rustica (Hirundinidae)	2	-	× (FG)	
Lanius collurio (Laniidae)	2, 3, 4	3	× (BB)	
Motacilla flava (Motacillidae)	2	2		×
Perdix perdix (Phasianidae)	2, 3,	2	× (BB)	
Sturnus vulgaris (Sturnidae)	2	-	× (FG)	
Tachybaptus ruficollis (Podicipedidae)	2, 3, 4	3		×
Anthus trivialis (Motacillidae)	3	3	× (BB)	
Circus aeruginosus (Accipitridae)	3	3	× (FG)	
Emberiza citrinella (Emberizidae)	3	3	× (BB)	
Picus viridis (Picidae)	3	3		× [2]
Saxicola rubetra (Muscicapidae)	3	2	× (BB)	
Sylvia communis (Sylviidae)	3	3		× [3]
Acrocephalus arundinaceus (Acrocephalidae)	4	4		×
Cuculus canorus (Cuculidae)	4	4		× "Probably usable as breeding habitat and for foraging."
Fringilla coelebs (Fringillidae)	4	4		× [4]
Streptopelia turtur (Columbidae)	4	4	× (BB)	
Turdus merula (Turdidae)	4	4		× [5]
Turdus philomelos (Turdidae)	4	4		× [5]
Turdus pilaris (Turdidae)	4	4		× [5]

[1] But *Falco subbuteo* is listed as foraging. [2] *Picus viridis* is not threatened. However, the reference does not mention *Jynx torquilla*, which is critically endangered in Lower Saxony. [3] But *Sylvia nisoria* is listed as a breeding bird. [4] *Fringilla coelebs* is not threatened, but the reference lists *Carduelis cannabina* as a breeding bird and *Serinus serinus* and *Carduelis carduelis* as foraging. [5] The *Turdus* species are not threatened.

The extent to which the observed group (based on occurrence as documented in Table S1) matched the expected group (based on documented habitat preference) was assessed (Table 1). Deviations arise for only three bird species: Eurasian curlew (*Numenius arquata*; observed earlier in succession than expected), Tawny pipit (*Anthus campestris*; later than expected) and Whinchat (*Saxicola rubetra*; later than expected). Two species consistently occurred in low numbers (just one breeding pair): Red-backed shrike (*Lanius collurio*) and Little grebe (*Tachybaptus ruficollis*).

Of the 51 species recorded, 28 could be placed in one or more successional groups. Explanations of the group classifications follow, along with details of intersections with the flora of the catchment (see Table S1).

1 Group 1: pioneer bird species that prefer open ground

The first three observation years (2006 to 2008) were dominated by the open-ground-preferring species Little ringed plover (*Charadrius dubius*; Figure S1—top right), which breeds on bare soil substrate, and Northern wheatear (*Oenanthe oenanthe*), which does not need much more than that [40]. 2008 was the only year in which Eurasian curlews were seen at the pond. Starting from very little, vegetation cover increased strongly during 2008, driven by the species *Trifolium arvense* [3], which unfolds properly at the end of June at the earliest, when it pushes out its bushy inflorescences. The ground beetle *Cylindera arenaria viennensis* was the dominant species among the above-ground invertebrates [17].

2 Group 2: herbaceous plant-preferring, ground-breeding species

During the next four years (2009 to ca. 2012), bird life in the dry part of the catchment began to differ from that in the semi-aquatic area around the pond. A pair of little grebes bred in the marginal area of the pond; the species had been observed in late summer 2008 in non-breeding plumage. Reed warblers (*Acrocephalus scirpaceus*) were documented in 2011; since then, these species have had increasingly better hiding places. Barn swallow (*Hirundo rustica*) and Common starling (*Sturnus vulgaris*) flew in large flocks into the reeds at dusk to roost. In the dry part of the catchment, the Yellow wagtail (*Motacilla flava*) was the dominant species, probably raising several broods per year (Figure S1—bottom right), and sometimes arriving in flocks in the evening. Tawny pipits were confirmed, Corn buntings (*Emberiza calandra*) were confirmed to be breeding, and Reed buntings (*Emberiza schoeniclus*) were suspected to be breeding. Grey partridges (*Perdix perdix*) and Common quail (*Coturnix coturnix*) occurred and found dust-bathing sites. Peregrines (*Falco peregrinus*) hunted about 1 m above the ground. Skylarks (*Alauda arvensis*) were present, but difficult to document; since observations were very rarely made before June when song-flights could have been observed. In contrast, red-backed shrikes were easily seen on tall woody plants and instruments, such as the two weather stations in the Hühnerwasser catchment. In 2009, *Tabanus* species larvae and pupae, and Tipulidae (gnats), and in 2010, *Gryllus campestris*, were common, and were likely to be important as food for insectivorous birds.

3 Group 3: open shrub-preferring species

More suitable conditions for the red-backed shrike emerged in the next period (from about 2013 to about 2016). A new breeding bird family (Accipitridae) arrived in the Hühnerwasser catchment, with the Marsh harrier (*Circus aeruginosus*; Figure S1—bottom left) being its first representative. The species Tree pipit (*Anthus trivialis*), Yellowhammer (*Emberiza citrinella*), Whinchat (*Saxicola rubetra*) and Common whitethroat (*Sylvia communis*) were new in this period, though the first two already had congeners in the area. Skylark, grey partridge and little grebe continued to be common. Skylarks were seen and heard more frequently, as more observations were made in spring while observers were supervising student work or field trip groups. Grey partridges were easier to see in the field because they flew more often. Little grebes were increasingly difficult to notice due to the overgrown shore area of the pond. The third period was characterized by a new level of structural complexity in the vegetation, associated with considerable herbivory, representing a key energy flow [41]. At the beginning of the third period, aphids were detected for the first time; also, the comparatively highest number of active nests of the paper wasp *Polistes nimpha* [42], a diversity of species of butterfly caterpillars and very high numbers of *Lymantria dispar* caterpillars were found. This was followed in 2014 by a mass occurrence of Common voles (*Microtus arvalis*) [43]. Many species of raptors were observed during overflights. At this time, the vegetation included mosses and ground lichens almost everywhere, and the increasing complexity of the system's structure also manifested itself in the first hemiparasite (mistletoe) and the first orchid with tiny dust seeds and depending on mycorrhiza.

4 Group 4: pre-forest species

The last period so far included the years from about 2017 to 2021. Some group 2 and 3 bird species still occurred, without being dominant; they included red-backed shrike and little grebe. The latter was joined by the Great reed warbler (*Acrocephalus arundinaceus*) in the pond edge area overgrown with increasingly impenetrable vegetation. For the first time, a large number of different songbird species determined the overall impression, including at least three species of the family Turdidae, which were breeding or, in the case of the Fieldfare (*Turdus pilaris*), overwintering. The Turtle dove (*Streptopelia turtur*) was very present acoustically in 2020. The relationships between organisms in the catchment started to become more multi-layered and complex, as shown not least by the presence of the beetle *Clytra laeviuscula* [44], which is dependent on the care of ants for its individual development. The appearance of the site seemed to please Eurasian jay (*Garrulus glandarius*), which was seen bringing in fruit. The brood parasite Common cuckoo (*Cuculus canorus*) was observed flying over and heard calling. Great tits (*Parus major*) were present as well as Common chaffinch (*Fringilla coelebs*), the latter successfully breeding in the branches of a black locust tree in 2021 (Figure S1—top left). Some of the trees were over 10 m high; in tree stands, especially on the eastern side of the catchment, there was a severe lack of light, giving the impression of the shady interior of a forest. The fern *Botrychium matricariifolium* was found, indicating that pioneer forests had replaced open-ground biotopes [45]. Prothallia of *Botrychium* species live saprophytically from mycorrhizal fungi.

In 2021, no group 1 and 2 birds were seen at the Hühnerwasser catchment, except for starling and little grebe. However, dozens of skylarks were found in the spring outside the Hühnerwasser area on adjacent areas that had been developed into fields.

Some species were recorded rarely in the Hühnerwasser catchment. Peregrines were seen hunting in 2009; several hunting flights took place close to the ground (lower than the height of the surrounding fence), so there was a strong Hühnerwasser catchment connection. An Eurasian hoopoe (*Upupa epops*) was only seen once, in 2010. Adjacent observations included Great grey shrike (*Lanius excubitor*; 2008), Common crane (*Grus grus*; from 2010), Black stork (*Ciconia nigra*; 2011) and White stork (*Ciconia ciconia*; from 2013). One Wryneck (*Jynx torquilla*; 2014) was very probably on autumn migration. Surprisingly, a pair of Goldeneye (*Bucephala clangula*) was encountered at the Hühnerwasser pond in the middle of the breeding season on 5 May 2015. At that time there were no large, deep tree cavities at the catchment, so it was clearly too early in succession for this species to breed. Mute swan (*Cygnus olor*; 2016), Grey heron (*Ardea cinerea*) and Common raven (*Corvus corax*) were only observed flying over in 2009, the latter species often mobbing birds of prey. In 2015, one eviscerated Brown hare (*Lepus europaeus*) and one eviscerated young Roe deer (*Capreolus capreolus*) were found in the catchment or inside the double fence on the west side of the catchment, apparently preyed upon by birds of prey.

That birds of prey also flew directly into the catchment was evident from the prey remains found. The feathers of plucked birds were discovered in the Hühnerwasser catchment with increasing frequency from 2014 onwards (Table S1). A few years before 2014, a bird skeleton of unknown species was found. The earliest recorded bird death was in October 2010, when a Song thrush (*Turdus philomelos*) was found near the equipment container which had solar panels. In 2016, a raptor was observed flying below the treetops for the first time, probably an Eurasian sparrowhawk (*Accipiter nisus*) or Northern goshawk (*Accipiter gentilis*).

The high numbers of the invasive caterpillar *Lymantria dispar*, which had become naturally rare from one year to the next, had also never been reported before. In addition, unusual observations were also made, such as the pioneer bird species little ringed plover staying next to grass tussocks of *Brachypodium sylvaticum*, a species normally found in forests in Europe [46]. Whinchat appears only once in the list, and European stonechat (*Saxicola rubicola*) not at all, but in the immediate vicinity of the Hühnerwasser catchment they are sighted regularly (*S. rubetra*) or more rarely (*S. rubicola*).

The methods we applied, namely empiricism and the principle of a continuous observer, led to a large number of observations. These have been summarized above and in the following diagram (Figure 3), where the solid curves show the abundance of the four different bird groups over time, as also shown in Tables 1 and S1.

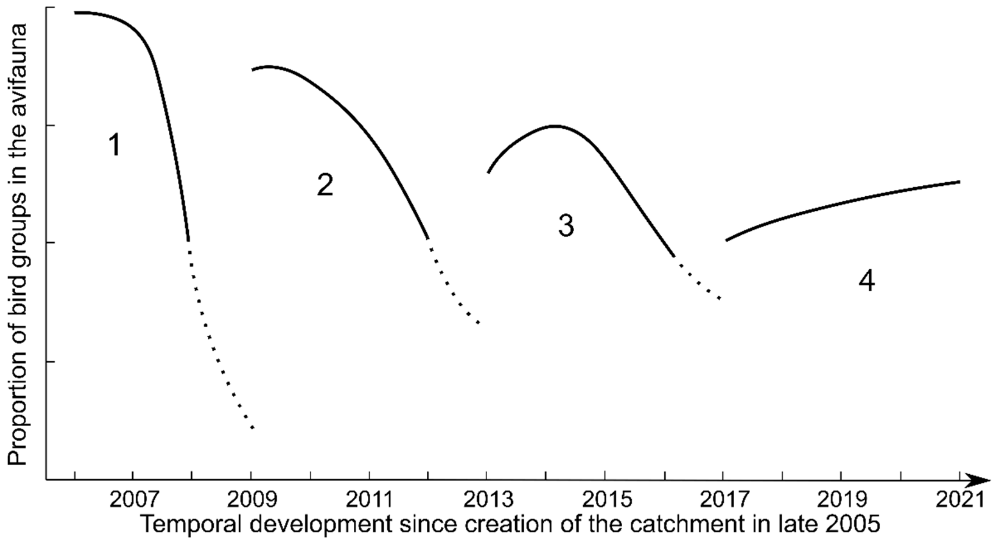

Figure 3. Schematic overview of the abundance of the four bird groups as they successively occurred in the Hühnerwasser catchment. The four stages are characterized in the text. The dominance of each bird group is likely to be lower than that of previous groups, because the 6 hectare catchment is undergoing a development towards increasing habitat heterogeneity.

3.2. Solar Parks

A total of 28 bird species which are threatened in Lower Saxony are documented as breeding or foraging in a total of eight German solar parks by Badelt et al. (2020, [35]). Of the 16 bird species that breed in solar parks ([35], Table 9), 56% (nine species) also occurred in the Hühnerwasser catchment. The remaining 12 bird species ([35], Table 10) used solar parks for foraging; three of these species were also found in the Hühnerwasser catchment, one of them breeding (Table 1). Thus, there are 12 species in common among the 28 bird species found in the solar parks and the 28 in the Hühnerwasser catchment (Table 1).

Of the Hühnerwasser catchment successional groups, groups 1 and 4 (with, in total, 10 species) have only one species that is also found in solar parks (≙10%; there are two species in common [≙17%] when Red-backed shrike and Little grebe, which cannot be assigned to just one group, are also included). Most of the species common to the Hühnerwasser catchment and solar parks (11, ≙92%) are in Hühnerwasser catchment groups 2 and 3. Conversely, of the 18 species in groups 2 and 3, 11 (≙61%) species (eight breeding, three foraging) are listed by Badelt et al. (2020, [35]) as occurring in solar parks. In groups 1 and 4, ten bird species (12 if Red-backed shrike and Little grebe are included) were recorded in the Hühnerwasser catchment, of which one (or two) bird species (≙10 and 17% respectively) is (are) also listed as breeding at solar parks [35].

Indicated by the integrative diagram in Figure 3, it is the second time period in which the most significant intersection of bird species occurs, which are also sustainable candidates for solar parks. This statement is prepared by comparing the four groups in Tables 1 and S1.

4. Discussion

Consideration of the entire Hühnerwasser timeline (Table S1) shows both clear successional changes in avian species [47] and an ever-present intrinsic conservation value of the dynamic landscape of the Hühnerwasser catchment for birds. The four different bird groups distinguish themselves quite plausibly, clearly, and distinctly from each other. The successive replacement of such groups in wildlife populations appears to be a strong pattern coupled with ongoing progressive vegetation dynamics, i.e., primary succession, in the Hühnerwasser catchment area (see [12,48] for comparison). This also means that only 16 years after the creation of the catchment, the species of the first groups have largely disappeared. Thus, at the highest level of Pickett et al.'s (1987, [4]) hierarchy of succession, 'differential species performance' is clearly present in our 16-year time series; the four groups and their sequence are likely to be readily transferable to many other systems.

The developments traced and the evidence of the changing bird assemblage in this empirical study show that the Hühnerwasser catchment area has been and is a vital ecosystem, despite the previous heavy disturbance of the environment by open-cast mining. Many bird species were recorded in the 6 ha area in only short time windows, when the conditions there were right for them; over time this added up to substantial numbers of species and individuals using the site. Conditions can be right for birds in two ways: firstly, for breeding, if good conditions can be expected for at least one season; and secondly, for visiting, if birds derive a short-term benefit from a visit or if their home-range size far exceeds the size of the Hühnerwasser catchment, as is the case e.g., for the peregrine. The accessibility of the area is an obvious prerequisite for this, and visiting species may also have been testing the area for suitability. For example, the goldeneye may be under some pressure to move to new habitats, as its abundance is increasing in the surrounding area [49].

The documented observations from the Hühnerwasser catchment may go beyond significance for individual species of conservation concern, as suggested by [50] for post-industrial landscapes in the region. The Hühnerwasser catchment may be particularly important because of its spring area. Alternatively, post-mining landscapes may have become more important for regional bird life in the last 20 years.

1 Mid-period early successional avifauna and solar parks

Ongoing biological research at the artificial Hühnerwasser catchment brings benefit in understanding ecological conditions and potential in other areas, including large, fenced areas. Ground-mounted solar parks are similar to the Hühnerwasser catchment, but more uniform over time.

Dedicated solar park operators take measures to ensure that their parks do not completely exclude wildlife. Biotope management measures and ecological monitoring requirements can also be prescribed by the administration as part of the planning permission for ground-mounted solar parks. The goodwill of solar park investors and operators and the strength of the permitting authorities give hope that the research-implementation gap in avian conservation [51] will not become particularly large here.

Data used in the present study [35] show that more bird species use solar parks than were found in a study of three solar parks in Brandenburg state, Germany [9]. However, the question raised by these authors, whether specialized threatened species are resilient enough to withstand the fundamental change in habitat structures caused by the placement of solar panels, remains open for many species. Monitoring reports and studies of solar parks are generally limited by having short observation periods (often between two and six years). Due also to yearly variation in conditions, most recently the last few exceptionally dry years [52], these reports and studies only depict the situation in manageable small time periods, and extrapolation of data to longer periods is not usually possible. The present study provides initial evidence that gains for an overall theoretical framework can result from an understanding of concrete, empirical succession series. It is desirable to encourage further studies with surveys of birds over time, which should then have the same comparative methodology and survey effort at all sites.

The present analysis of birds of the Hühnerwasser catchment over 16 years does provide information that is relevant for the management of solar parks. Under typical conditions, bird species from group 1 (pioneer bird species that prefer open ground) probably only settle in solar parks temporarily, if at all. These species require open ground conditions, i.e., bare soil. Even if vegetation succession is limited by maintenance measures such as mowing, ground-mounted solar parks in temperate climates have little medium- or long-term potential for this species group. Changes that would be required to encourage group 1 species in solar parks (e.g., the creation of persistently unvegetated areas and cairns for the northern wheatear, or far more demanding measures for other group 1 species) are not feasible or disproportionately costly. While birds in groups 1, 2 and 3 all use open areas (defined as having woody cover up to a maximum of 30%, [53]), members of group 4 (pre-forest species) require more woody cover plants. Since trees create shade, the provision of habitat for avian species in this group is not compatible with solar parks.

Species from groups 2 and 3 (herbaceous plant-preferring, ground-breeding species and open shrub-preferring species) are most likely to be resident in ground-mounted solar parks. Questions remain about which changes to system design and maintenance could be made to encourage the birds to settle within the parks. However, within solar parks, conservation efforts are most likely to succeed if they are focused on the 15 Hühnerwasser catchment bird species in successional groups 2 and 3: the Reed warbler, Skylark, Tawny pipit, Tree pipit, Marsh harrier, Common quail, Corn bunting, Yellowhammer, Red-backed shrike, Yellow wagtail, Grey partridge, Green woodpecker, Whinchat, Common whitethroat, and Little grebe.

Despite the suitability of habitat found within ground-mounted solar parks for these and other species of semi-open landscapes, there is a serious risk: with the installation of a solar park, characteristics or conditions can be lost that particularly affect dynamic processes (e.g., succession dynamics). The construction of solar parks can therefore lead to losses or changes in characteristic habitat dynamics, so that ecological processes that existed before the installation of the park alter or are prevented from taking place.

2 Avifauna of early and late succession

Bird species of very early successional states, group 1 of the Hühnerwasser catchment, require areas of bare ground. By their nature, these habitats are short-lived, but they are common at raw material extraction sites [54]. The construction of more solar parks will lead to a more fixed landscape, or less chance of disturbance due to vegetation clearance, resulting in less early successional habitat. Due to increasing density of structures in urban areas, temporary habitats are likely to become rarer there as well [55]. Up to ten pairs of little ringed plover breed in the Welzow Süd open-cast mining area [56]. A significant percentage of the breeding population (50%) was found in the Hühnerwasser catchment in 2007 (five pairs, [37]); the 6 ha site was obviously very attractive in terms of headwater character and terrain morphology for this group 1 species. However, the subsequent disappearance of this species, very conspicuous in its courtship display, shows that it did not accept the Hühnerwasser catchment for long: it had to look for new, barren, early successional habitats. In the current practice of open-cast mining, which has been going on in Germany again since 1948 after the Second World War, new, bare-ground habitats are constantly being created, from which pioneer species with large dispersal distances can benefit [57]. Since the German government has decided to phase out coal, open-cast mining will end in the not-too-distant future. The last coal-fired power plants must be taken off the grid by 2038 at the latest [58]. Until then, other early successional habitats, such as ecologically functional riverine floodplains, are needed [59,60] to compensate for the loss of corresponding replacement habitats that existed for decades in raw material extraction areas. Allowing the natural dynamic development of such habitats is the central solution. To prevent valuable species in group 1 (open ground-preferring pioneer birds) from suffering increasingly significant habitat loss as open-cast mining is replaced by solar parks, the natural dynamics of large rivers, which repeatedly create suitable, temporary, bare-ground habitats, should be promoted. For the conservation of bird species in group 4 (pre-forest species), however, it is important to allow forest dynamics to take place so that late successional habitats can also develop.

Solar parks tend to be organized in a more complicated way than the ‘group 1’ years of development in the Hühnerwasser catchment area. Solar parks are likely to provide significant and more stable support for bird species classified in groups 2 and 3. The reasons for this can be intuitively guessed from the appearance of the area (Figures 1 and 2) and traced through the chronological sequence presented in Table S1, drawing on overlaps with botany, and some explanation of zoology beyond birds in the text.

As attempts to make solar parks sustainable gain momentum, so will systematic studies. And as the scientific and popular [61] gaze turns more towards renewable energy systems, benefits will certainly be discovered. Low-lying natural vegetation in solar parks can develop to become very rich in species and inflorescences because it remains unfertilized (typical effect of decreasing soil nutrient levels [62]). With such preconditions, it could be that in future, among semi-natural and industrial environments, solar parks will be valued as places that provide cultural ecosystem services via a sense of happiness when time is spent there [63]. We believe that this provision may be increased by the presence of suitable bird species.

5. Conclusions

The high co-occurrence of group 2 and 3 bird species in our empirical data on succession and in the reports from solar parks shows that the avifauna in these succession groups (herbaceous plant-preferring, ground-breeding species and open shrub-preferring species) share habitat requirements, and can find suitable habitats in solar parks. Providing the minimum requirements for the colonization of such sites by birds is relatively inexpensive, and can almost be achieved through the normal maintenance management of solar parks. However, it must be recognized that solar park areas have fixed habitat features and hardly provide for species occurring earlier or later in succession. This is because the preceding and following periods in the succession timeline are characterized by conditions that prevent the management of solar parks (bare ground and pre-forest), so solar parks cannot protect the avifauna typical of these periods (groups 1 and 4). With this information, opportunities for habitat restoration and potential conflicts can be weighed up in a more informed way. In particular, if an area destined for use as a solar park is likely to be home to bird species other than those in groups 2 and 3, it is essential that an environmental impact assessment is carried out before the solar park is built and that the results are taken seriously. One big difference between solar parks and the Hühnerwasser catchment at the time of creation is that solar parks are built on land that already has value for wildlife. Monitoring reports on the colonization of solar parks by birds should be more precisely targeted, so that future solar parks can be managed to bring benefits for ecosystem restoration and ecosystem services, along with providing sustainable energy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11050718/s1, Table S1: Timeline of successional changes in avifauna of the artificial Hühnerwasser catchment (Lusatia, Germany). Figure S1. Breeding birds in the Hühnerwasser catchment, one example for each successional group.

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