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CHANGES OF HABITAT PATTERN ALONGSIDE MOTORWAYS IN RESPONSE TO THE DEVELOPMENT OF PHOTOVOLTAIC POWER PLANTS

Stefan Rüter, Katharina Niemann

Abstract: With the expansion of photovoltaic power plants (PVPP) the landscape is subject to major changes. In this paper, we examined spatial-temporal changes of habitat pattern in response to the development of PVPP alongside motorways. A total of 69 power plants were analyzed using a series of spatial metrics and habitat data which were derived from digital orthophotos. The results indicated a broad expansion of PVPP between 2009 and 2016. The majority of plant areas and their surroundings underwent transition from a predominance of arable land to mesophilic grassland and other open space habitats in combination with solar modules, creating a more heterogeneous landscape. Consequently, findings revealed significant increase of habitat richness, patch density, edge density, and the Shannon diversity index. We conclude that PVPP may have a positive impact on roadside biodiversity when they are extensively managed and have a high structural diversity, especially in intensively agrarian used landscapes.

Keywords: Solar farm, landscape change, spatial metrics, biotope, renewable energy, nature conservation

VERÄNDERUNGEN DER HABITATSTRUKTUR ENTLANG VON VERKEHRSWEGEN INFOLGE DES AUSBAUS VON PHOTOVOLTAIK-FREIFLÄCHENANLAGEN

Zusammenfassung: Der Ausbau von Photovoltaik-Freiflächenanlagen (PV-FFA) im Rahmen der Energiewende hat zu Veränderungen in der Landschaft geführt. Es wurde untersucht, wie der Ausbau von PV-FFA entlang von Verkehrswegen straßenrandnahe Lebensräume beeinflusst. Dazu wurden Habitatstrukturen im Bereich von 69 PV-Betriebsflächen über digitale Luftbilder erfasst und ausgewählte Landschaftsstrukturmaße berechnet. Zwischen 2009 und 2016 fand ein erheblicher Ausbau von PV-FFA statt, wobei sich die Betriebsflächen mit ihren Umgebungen von Ackerland in Gras- und Krautfluren und andere Offenlandhabitate veränderten. Durch die Solarmodule wurden kleinflächige Strukturen geschaffen, woraus eine Steigerung der Habitatvielfalt, Patchdichte, Randliniendichte und des Shannon-Index resultierte. Insbesondere in intensiv genutzten Agrarlandschaften können PV-FFA somit das Straßenbegleitgrün ergänzen und einen Beitrag zum Erhalt der Biodiversität leisten.

Schlüsselwörter: Solarpark, Landschaftswandel, Autobahn, Landschaftsstrukturmaße, Biotop, erneuerbare Energie, Naturschutz

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1 INTRODUCTION

The expansion of renewable energies is regarded as a key goal of the energy system transformation in Germany (BMWi 2018a). The implementation of the payment framework of the Renewable Energy Sources Act (EEG) has significantly increased the financial viability and attractiveness of installing photovoltaic power plants (cf. BMWi 2018b, Fraunhofer ISE 2019). Photovoltaic power plants (PVPP), also known as ground mounted PV systems or solar parks, are large-scale photovoltaic systems designed for the supply of electrical power into the electricity grid using solar radiation (Roy & Ghosh 2017). They differ from most building-mounted and other decentralized solar power applications.

By 2010, an area of around 8500 ha had been covered with PVPP in Germany. In the years 2011-2014 the area increased to 15200 ha (Kelm et al. 2014). Walz et al. determined a number of approx. 2000 PVPP in Germany by the year 2014. Due to the payment regulations of the EEG, the expansion of PVPP was primarily concentrated on arable land until 2010 and then shifted to conversion areas and areas along traffic routes. Since 2010, the areas along motorways and railways up to a distance of 110 m have been subject to the payment regulations of the EEG. The purpose of this is to promote the bundling of technical infrastructures and to make the areas in the surroundings of traffic routes available for energy generation (FGSV 2008, Clearingstelle EEG 2011).

With the expansion of PVPP the landscape is subject to major changes. The fenced plant areas are covered with solar panels on a ground-mounted construction and one or more transformer stations (Schmid & Schulz 2009, ARGE Monitoring PV-Anlagen 2007). The areas between and below the solar panels are generally managed as extensive grassland (Peschel 2010). Knipfer & Raab (2013) have found that solar farms may include diverse habitats like small water bodies, ruderal sides, or sparsely vegetated areas. In the course of the construction and maintenance of the facilities, the surroundings of the plant areas also change, for example through the establishment of access roads. As a consequence, habitats in the vicinity of PVPP differ significantly from their previous state as e. g. arable land (Reich et al. 2019).

It has been argued that due to habitat changes PVPP can contribute to biodiversity (Raab 2015), especially in intensively agrarian used landscapes (Niemann et al. 2017). For example, Parker & McQueen (2013) and Montag et al. (2016) showed that extensive management led to an increase of vascular plant species diversity within the power plant areas. Invertebrates such as butterflies and grasshoppers may benefit from increasing plant species diversity, higher edge density, and microclimatic gradients (e. g. transition zones between solar modules and unshielded areas) (Herden et al. 2009). Other studies indicated that PVPP can also serve as habitat for birds (Neuling 2009, Tröltzsch & Neuling 2013, Visser 2016), amphibians (Hübner et al. 2014), reptiles (Knipfer & Raab 2013), and mammals (Herden et al. 2009).

However, to date, there have been no systematic investigations on the changes of habitat pattern in response to the development of PVPP. Therefore, the overall objectives of this study were to (i) describe the temporal development and spatial characteristics of PVPP and to (ii) analyze the resulting changes of habitat pattern. In conclusion, we provide basic information about the potential impacts of PVPP on habitat capacity.

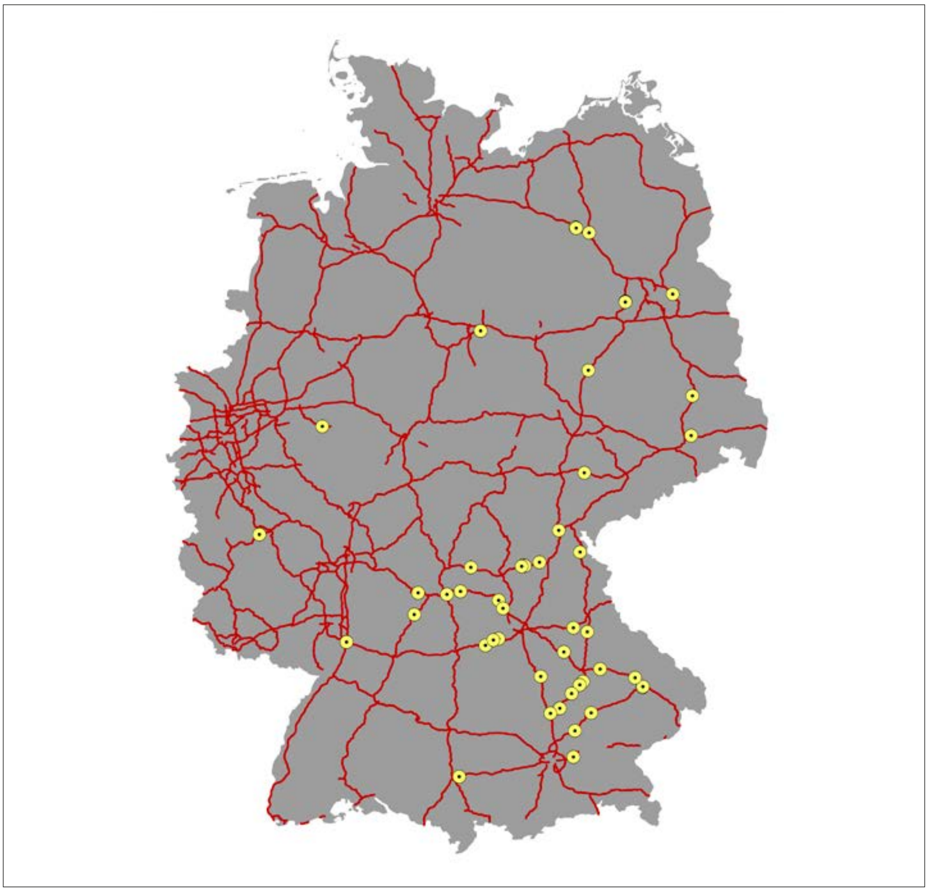

Figure 1: Location of study sites in Germany (points: PVPP, lines: motorways)

2 METHODS

2.1 STUDY SITES

We selected a total of 50 PVPP in Germany as study sites using a random selection approach. The random selection was carried out on the basis of existing data about PVPP alongside motorways taken from Niemann et al. (2017). The majority of study sites were located in south-eastern Germany (Figure 1). All study sites were located at a maximum distance of 50 m from the motorways. 14 of the selected PVPP were composed of more than one delimited plant area. Plant areas were aggregated to the same PVPP when they were situated on the same site of the motorway at a maximum distance of 50 m from the next plant area. Following this definition, 11 PVPP each consisted of 2 plant areas, 1 PVPP included 3 plant areas, and 2 PVPP each consisted of 4 plant areas. Thus, the dataset included a total of 69 plant areas.

2.2 DATA SOURCES AND PROCESSING

The overall time period analyzed in this study was from 2000 to 2016. Habitat data were derived from digital orthophotos (DOP), because DOP have become an important data source and extensively used in habitat mapping and analysis (e.g. Langanke & Lang 2004, Sulzer et al. 2013). With regard to continuous and comparable access to the current and historical data, we used GeoBasis-DE/BKG 2018 as data source. We used the following procedure for each of the study sites to deal with the issue of temporal-spatial data availability: In the first step we identified the DOP with the first appearance of a plant area by checking the data in reverse chronological order. On the basis of this DOP, we were able to describe the status of the nature and the landscape, including the presence of PVPP (Time 2). In the next step, we identified the previous DOP available, showing no power plant, for a spatial reference. We used this DOP to describe the status of the nature and landscape before a power plant was constructed (Time 1) (Figure 2). Thus, it was possible to examine the time period within which a PVPP was constructed (between Time 1 and Time 2).

Habitat data for Time 1 and Time 2 were manually interpreted, classified, and digitized from the DOPs, covering the plant areas and their surroundings. We included the surroundings by computing buffers of 50 m around the plant areas. By this means, habitat changes beyond the plant area borders, but which were potentially related to plant area construction, could also be considered in the analysis (e.g. construction of access paths, development of ecological compensation areas).

Habitats were classified into seven groups and 31 habitat types based on Drachenfels (2016) (Table 1). This classification scheme reflects the intensity of land use and the visual difference of habitat types and, therefore, is in line with common approaches of habitat assessment (Rüter & Opdam 2019). The classification also considered solar panels as a habitat type, because it was argued that these elements can lead to specific habitat qualities due to shaded and vegetated areas with specific microclimate and hydrological conditions (cf. Hassanpour Adeh et al. 2018, Pisinaras et al. 2014, Rück et al. 2011).

In addition to the DOP-based habitat classification and for accuracy assessment, we conducted comprehensive habitat mapping in the field for all 69 plant areas in 2016 (Figure 2). The field survey focused on the mapping of habitat patches within the PVPP and also allowed for more precise mapping of habitats in the plant area surroundings.

2.3 HABITAT PATTERN ANALYSIS

In order to examine the effects of PVPP on habitat pattern, our analysis addressed the questions of habitat composition and configuration (cf. Li & Reynolds 1995, Lang & Blaschke 2007, Walz 2013). Habitat composition was examined to gather insight about how the development of power plants and their related infrastructure in the surroundings transformed habitat types alongside motorways. Hence, we analyzed habitat composition to represent qual-

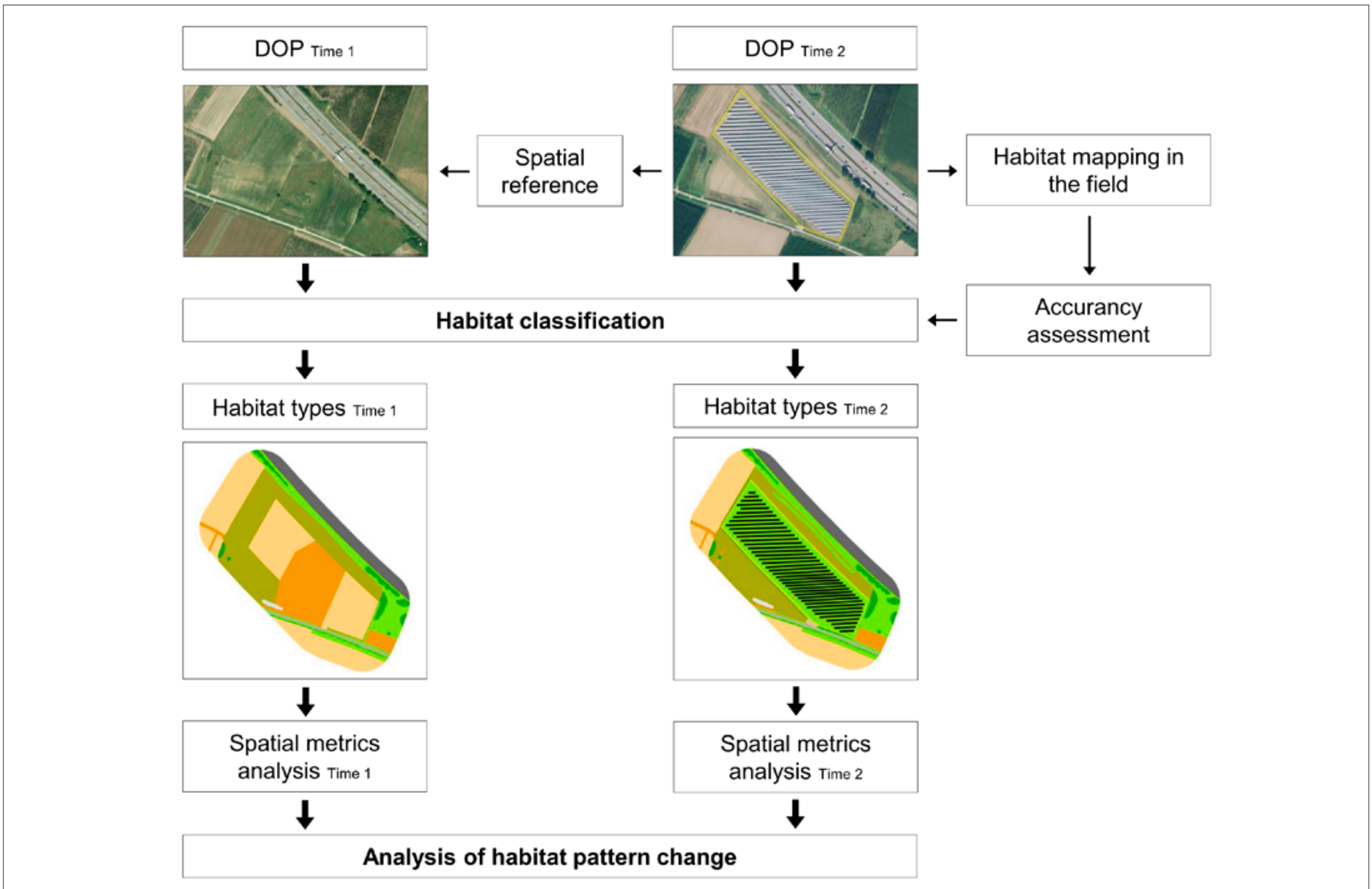

Figure 2: Technical flow chart (Data sources DOP: Image © GeoBasis-DE/BKG 2018)

Group	Habitat type	Abbreviation
Wooded habitats	Deciduous woodlands and forest plantations	decWo
	Coniferous woodlands and forest plantations	conWo
	Mixed woodlands and forest plantations	mixWo
	Grove	Grove
	Row of trees	rTree
Open space habitats	Sparse orchard on grassland	orchGr
	Mesophilic grassland	mesGr
	Semi-dry grassland	dryGr
	Bare soil	bSoil
	Sparsely vegetated area	sparVeg
	Ruderal sites	Rud
	Clearance cairn	Cairn
Agricultural land	Grassland	GrL
	Arable land	arabL
Freshwater habitats	Reedbed	Reed
	Stream	Stream
	Ditch	Ditch
	Standing water	stWa
	Small water body	smWaB
Traffic and technical infrastructure	Motorway	Motor
	Road	Road
	Railway track	Rail
	Path	Path
	Bridge/underpass	BrUn
	Parking lot	Park
	Other traffic areas	othTr
	Technical buildings	Tech
	Solar panels	Solar
Settlement	Settlement	Settl
	Settlement with green spaces	SettlGreen
Other	Other	Oth

Table 1: List of classified habitat types

Metrics	Abbreviation	Description	Unit
Total area	TA	The total area	ha
Shape index	SI	The normalized ratio of patch perimeter to area in which the complexity of patch shape is compared to a standard shape of the same size (circle)	None
Patch density	PD	The number of habitat patches per hectare	#/ha
Edge density	ED	The sum of the lengths of all habitat edge, divided by the total area, multiplied by 10000	m/ha
Richness	RI	The number of habitat types	#
Shannon diversity index	SHDI	Equals minus the sum, across all habitat types, of the proportional abundance of each habitat type multiplied by the natural logarithm of that proportion	None

Table 2: Spatial metrics selected to describe the spatial structure and habitat pattern of PVPP

Id	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
11	x									x		x			x	x	x
23		x									x				x		
28		x									x				x		x
1		x							x			x				x	x
38a	x					x				x			x		x	x	x
38b	x					x				x			x		x	x	x
38c	x					x				x			x		x	x	x
38d	x					x				x			x		x	x	x
6	x				x		x			x	x		x		x	x	x
12										x		x	x			x	x
48a		x			x				x	x		x	x		x	x	x
48b		x			x				x	x		x	x		x	x	x
29a		x							x					x		x	x
30a		x		x					x					x		x	x
30b		x		x					x					x		x	x
30c		x		x					x					x		x	x
30d		x		x					x					x		x	x
42a		x							x					x		x	x
42b		x							x					x		x	x
44a		x							x					x		x	x
44b		x							x					x		x	x
44c		x							x					x		x	x
46a		x		x					x					x		x	x
46b		x		x					x					x		x	x
47a		x							x					x		x	x
47b		x							x					x		x	x
9	x					x					x			x		x	
36		x							x		x			x		x	x
37		x					x		x		x	x	x	x		x	x
2		x							x						x		
3		x							x						x		
4		x							x						x		
5		x							x						x		
32		x							x						x		x
35		x							x						x		x
41a		x							x						x	x	
41b		x							x						x	x	
45a		x							x						x		x
45b		x							x						x		x
34		x								x					x		
7					x					x	x				x	x	x
20	x										x				x		

Id	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
21		x								x	x				x̲		
22		x									x				x̲		
24		x									x				x̲		
25		x			x						x				x̲	x	x
26		x			x						x				x̲	x	x
27		x			x						x				x̲		x
49a		x									x				x̲		x
49b		x									x				x̲		x
14			x								x	x			x̲		
15			x								x	x			x̲		
16											x	x			x̲	x	x
33		x							x							x̲	
50a	x								x							x̲	
50b	x								x							x̲	
13		x								x						x̲	x
39										x						x̲	
40a	x									x						x̲	
40b	x									x						x̲	
18	x										x					x̲	
17					x						x	x				x̲	
29b		x							x					x		x̲	x
31	x								x						x	x̲	
19		x							x								x̲
8						x					x						x̲
10			x								x	x					x̲
43a			x								x	x					x̲
43b			x								x	x					x̲

Table 3: Temporal development of PVPP derived from DOP. Data were organized according to time for visualization of temporal clusters of PVPP development (x: analyzed DOP, x̲: first detection of PVPP, green marked area: time period within which PVPP was constructed)

itative aspects of habitat pattern. Habitat configuration garners additional information on how PVPP change quantitative aspects of habitat pattern, such as patch size. We calculated spatial metrics as a measure that quantitatively represents both the configuration of the habitat pattern and the spatial distribution of different habitat types. The basis of these metric calculations were the thematic maps representing the study sites at Time 1 without PVPP and Time 2 with PVPP, each comprising of spatial patches categorized in different habitat types (Figure 2).

A set of spatial metrics was used for this study, including total area (TA), shape index (SI), patch density (PD), edge density (ED), richness (RI), and Shannon diversity index (SHDI) (Table 2). TA and SI were applied for the plant area as a total area, delimited from the surrounding by fences, to describe overall area and shape-related characteristics of PVPP. The other metrics (PD, ED, RI, SHDI) were used to examine habitat pattern at the level of the plant area including its surrounding, i. e. to describe the spatial patterns of habitat patches and habitat types, respectively. In this regard, the patch density (PD) and edge density (ED) can reflect in various ways the physical continuity of the landscape and thus deal with the issue of habitat connectivity (e. g. McGarigal 2002, Schumaker 1996, Demers et al. 1995). Richness (RI) describes the number of habitat types and was used to quantitatively describe the habitat composition. The Shannon diversity index represents the heterogeneity of the landscape, where the larger the SHDI, the greater the mixing degree and heterogeneity of habitat types (Lang & Blaschke 2007).

Metric output values of the study sites were used to illustrate changes of habitat pattern between Time 1 and Time 2 (PD, ED, RI, SHDI). We compared the results using a paired t-test for each metric, assuming normal distribution (tested with Shapiro-Wilk). In addition, and complementary to the metric measures, we plotted the results of the habitat classification for both times (percentage of area comprised of particular habitat type).

In this manner, we were able to identify qualitative changes of habitat composition in response to the development of PVPP.

3 RESULTS

3.1 TEMPORAL DEVELOPMENT OF PVPP

The majority of plant areas (96%) were constructed in 2009 or later (Table 3). For five of these plant areas we identified a distinct construction year: 2012 (Ids 12, 48a, 48b), 2013 (Id 37), and 2015 (Id 31). In the remaining cases, we detected time periods within which the PVPP were constructed, e.g. by the years 2013

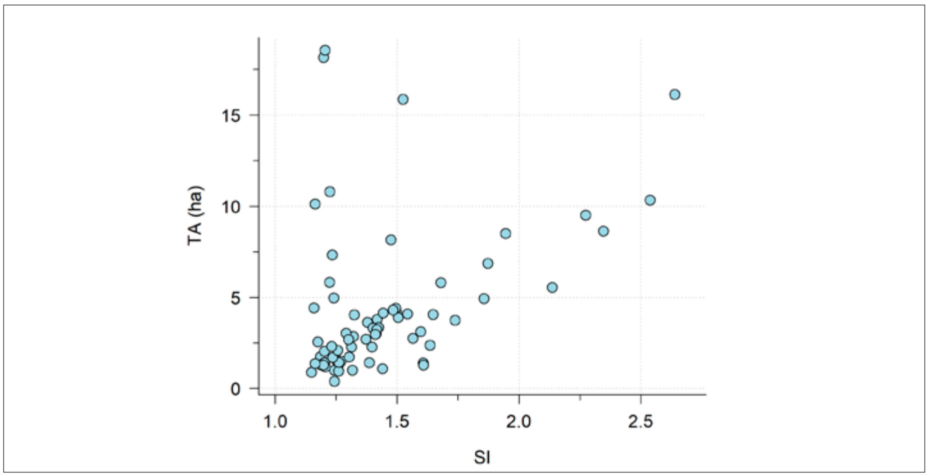

Figure 3: Relationship between total area (TA) and shape index (SI) of the plant areas (n=69)

Figure 4: Example of a typical PVPP alongside a motorway. The PVPP consists of three plant areas (Ids 44a-c). The total area (TA) and shape index (SI) vary between 2.08 ha/1.26, 2.31 ha/1.23 and 3.32 ha/1.40 (from left to right).

Figure 5: PVPP showing a very compact plant area (Id 9; TA: 18.54 ha ; SI: 1.2)

(n=16), 2014 (n=24), 2015 (n=10), and 2016 (n=5).

The first record of a plant area was detected in a DOP from the year 2009 (Id 11). The dataset suggested that the plant area might have been constructed earlier, around the year 2000. However, the data included major gaps for the earlier years due to a time span of eight years for which no DOP was available. The same applies to the plant areas with the Ids 23 and 28, respectively, showing a very broad possible construction period between 2001 and 2010.

3.2 AREA AND SHAPE-RELATED CHARACTERISTICS

The total plant areas varied from 0.4 ha to 18.5 ha (mean 4.4 ha), SI values were between 1.2 and 2.6 (mean 1.5). The majority of PVPP showed TA values up to 5 ha in combination with a shape index between 1 and 1.5 (Figure 3). Hence, the most common shape of the plant areas was an approximate rectangular shape aligned alongside motorways (Figures 4 and 5).

3.3 CHANGES OF HABITAT PATTERN IN RESPONSE TO PVPP DEVELOPMENT

The areas, later converted into plant areas, were previously characterized by arable land (Figure 6). We found that 41 of 69 plant areas (59%) were 100% arable land before the PVPP were constructed, and another 19 plant areas (28%) were classified partly as arable land. Nine areas showed agricultural grassland with varying percentages, between 19% and 100% of the total area. Mesophilic grasslands and ruderal sites were each mapped in seven cases. We found that two areas were 100% characterized by either mesophilic grassland or ruderal sites. Wooded habitats (deciduous woodland, grove) were classified at under 20% in two cases.

Following the construction of PVPP, the overall number of habitat types within the plant areas increased from 9 to 13. The maximum number of habitat types in a PVPP also increased (from 4 to 9). The habitat composition showed changes from a former predominance of arable land to domination of mesophilic grassland (median 64%) in combination with solar panels (median 35%) (Figure 7). The solar panels were usually positioned in rows. The vegetation underneath the solar panels is comparable to mesophilic grassland or, in some cases, sparsely vegetated areas (Figures 8a, 8d), but differs from the unshielded areas. Technical buildings were present in almost all plant areas (90%), but covered only small areas (Figure 8c). Other habitat types characterizing PVPP were ruderal sites, sparsely vegetated areas, and bare soil (Figure 8d). In some plant areas we mapped clearance cairns, reedbeds, ditches and small water bodies, which were not present before PVPP construction.

The results indicated significant differences of all tested spatial metrics between Time 1 and Time 2 (Figures 9 a-d). The plant areas and their surroundings (in total 676.2 ha) underwent rapid changes of habitat pattern during that period of time. This was mainly a result of the modified habitat composition and habitat configuration within plant areas linked to the construction of PVPP (cf. Figure 6, Figure 7). However, PVPP construction also resulted in habitat changes in the surroundings of the plant areas, e.g. through the creation of roads and paths (Figure 8a) or through the establishment of ecological compensation areas (Figure 8b). Consequently, richness values were significantly higher in Time 2 with PVPP (RI: $p<0.001$, Figure 9c).

Patch density and edge density were also both significantly higher in Time 2 (PD: $p<0.001$, Figure 9a; ED: $p<0.001$, Figure 9b). This was mainly an outcome of the solar panels that effected close transitions between the technical infrastructure and open space habitats within the plant areas.

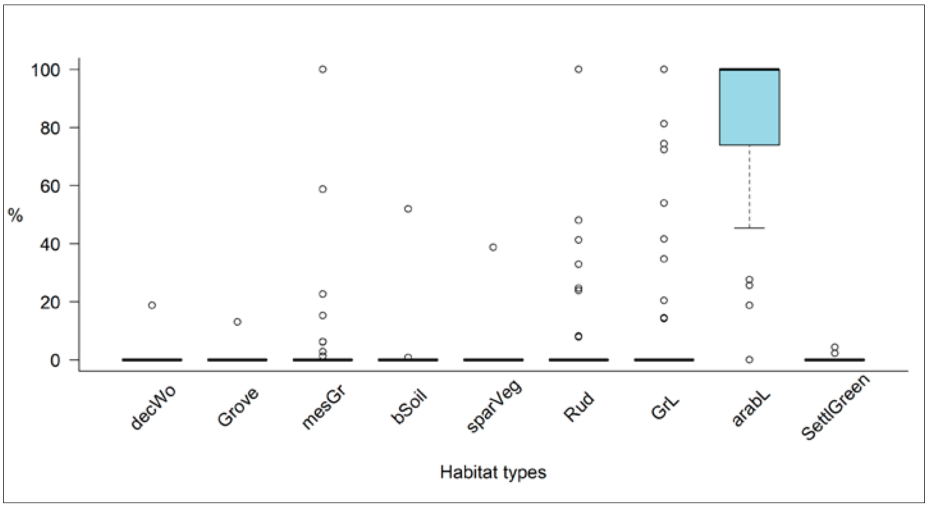

Figure 6: Percentage of area (later converted into plant area) comprised of particular habitat types (n=69 plant areas). See Table 1 for further description of habitat types.

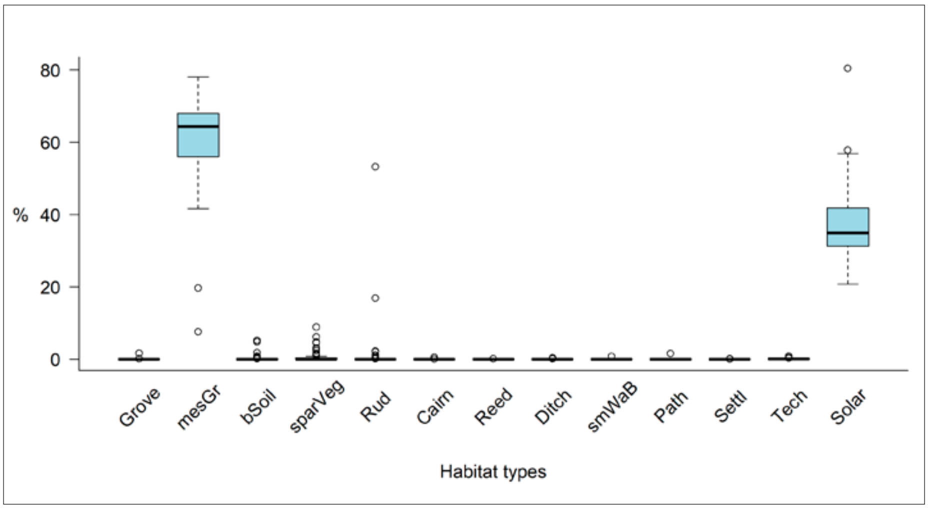

Figure 7: Percentage of plant area comprised of particular habitat types (n=69 plant areas). See Table 1 for further description of habitat types.

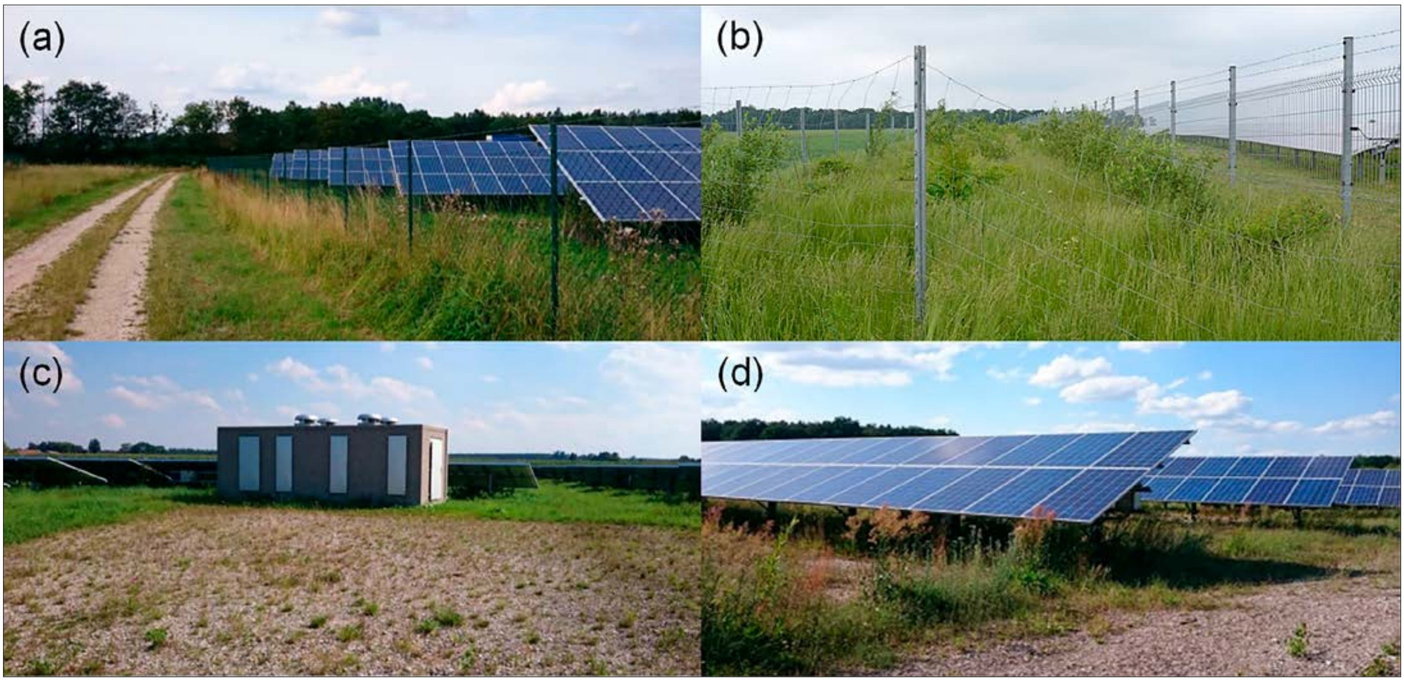

Figure 8: Examples of typical habitats types within the plant areas and in the surroundings: (a) mesophilic grassland and gravelled path along the fenced plant area, (b) ecological compensation area with planted groves, (c) transformer station, and (d) solar panels and mosaic of bare soil and sparsely vegetated areas

Along with PVPP construction, the predominant agricultural landscape was progressively substituted by open space habitats and technical infrastructure, creating a more heterogeneous and complicated landscape as evidenced by the increase of the Shannon diversity index (SHDI: p<0.001, Figure 9d), in which habitat types were more equally distributed.

4 DISCUSSION

Changes in land-use and the associated changes in landscape structure and habitats are regarded as important drivers of the decline in biodiversity and ecosystem services (cf. Millennium Ecosystem Assessment 2005; Chapin III et al. 2000). To meet the needs of nature conservation and management, reliable data on the ongoing processes of land-use change are necessary (Walz & Syrbe 2013). So far, investigations on photovoltaics and nature conservation have primarily been carried out for individual PVPP (e. g. Knipfer & Raab 2013, Neuling 2009). This study examined spatial-temporal changes of habitat pattern for a more insightful selection of PVPP and, hence, provides insights into some general trends in landscape change in response to the development of PVPP in Germany.

The majority of study sites were located in south-eastern Germany, especially in Bavaria. Other studies have also shown a concentration of PVPP in southern and eastern Germany (Klessmann et al. 2014). For instance, Kelm et al. (2014) showed that almost 30% of the capacity of PVPP is installed in Bavaria. The expansion of PVPP was driven mainly by the instigation of the payment framework of the Renewable Energy Resources Act (EEG), which supported the building of PVPP on agricultural land. There was, at the same time, a decline in the price of solar panels. Consequently, the spatial distribution of study sites reflects the current expansion of photovoltaic power plants within the federal states and biogeographic regions of Germany.

We used digital orthophotos which are a common data base for habitat classification (Kirsch-Stracke & Reich 2004) and land-use change analysis using GIS (Baessler & Klotz 2006). Other studies about ground mounted PV systems have used satellite images (Schröder 2017), data from OpenStreetMap and from the installation register of the Bundesnetzagentur (Eichhorn et al. 2019). These data also allow for the spatial detection of PVPP to a different extent, but despite this, do not allow for detailed habitat assessment. However, accuracy assessment of DOP-based habitat classification also showed that some habitat patches were difficult to interpret by remote sensing alone. This applies in particular to the vegetation below and between the solar panels. These structures especially showed a high diversity due to extensive management and, thus, should be mapped in the field for habitat assessment.

The results indicated a broad expansion of PVPP between 2009 and 2016. Although we were not able to identify the exact year within which a plant area was constructed, our findings are in line with other studies (e. g. Kelm et al. 2014, Kost et al. 2018). The identified time period reflects the effects of the payment regulations of the EEG. Since 2010, the expansion of PVPP has been concentrated alongside traffic routes (and also conversion areas) to make these areas available for energy generation (FGSV 2008, Clearingstelle EEG 2011).

Landscape pattern analysis is considered essential to the study of pattern-process relationships, which constitutes the foundation of landscape ecology (cf. Forman & Godron 1986, Turner et al. 2001). While there is a variety of purposes for landscape pattern analysis and related scales (Uuemaa et al. 2009), the focus of this paper was on using spatial metrics to quantify habitat pattern of PVPP on the local scale. We found that the majority of plant areas and their surroundings underwent transition from former predominance of arable land to mesophilic grassland and other open space

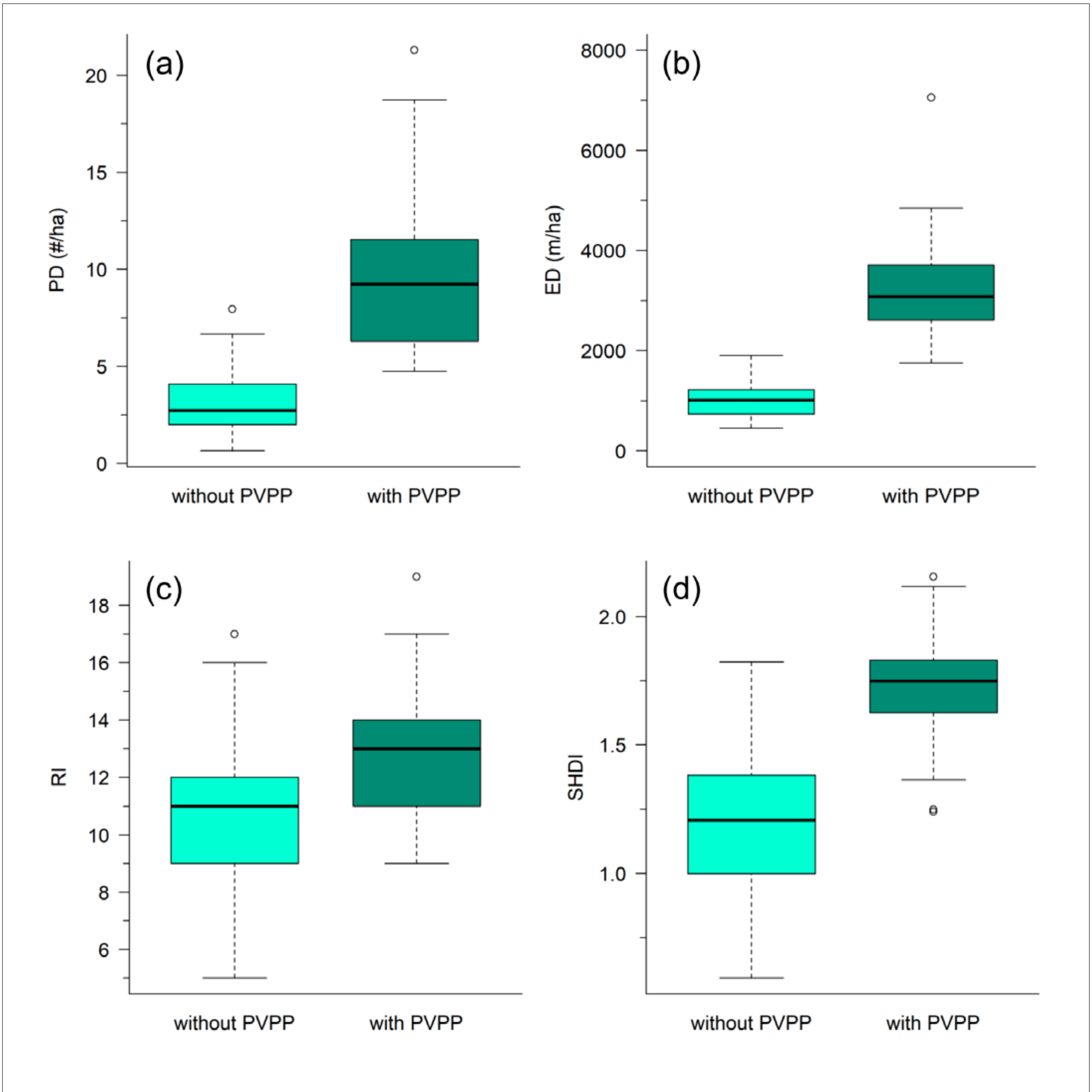

Figure 9: Changes in spatial metrics in response to PVPP development: (a) patch density (PD), (b) edge density (ED), (c) richness (RI), and (d) Shannon diversity index (SHDI). Spatial metrics were applied at the level of plant areas including their surroundings (n=69).

habitats. As a result, habitat richness, patch density, edge density, and the Shannon diversity index increased significantly. Since the positive impacts of PVPP on flora and fauna have already been proven in numerous studies (e.g. Montag et al. 2016, Raab 2015), the study underlines the potential of spatial metrics as indicators for biodiversity (Walz 2013).

Positive impacts on biodiversity may be caused by land use change from agricultural farmland to extensive grassland in the plant area. Species from open spaces and grasslands, e.g. butterflies and grasshoppers, may especially profit as the plant areas can function as a part of their habitat networks (Reich et al. 2019). However, it is important to point out that the development of PVPP may also cause conflicts with existing habitat networks, e.g. because of barrier effects and possible habitat loss (Niemann et al. 2017). For instance, a number of studies have presumed that fencing of the plant areas contributes to barrier effects for large and medium sized mammals, especially within habitat systems for species of forest biotopes (cf. Herden et al. 2009; Turney & Fthenakis 2011). However, the effects are species-specific and depend on the spatial context (e.g. distance to other habitats or populations), which makes further investigations necessary.

From a broader perspective and in view of further development of PVPP, the development of additional natural habitats and extensively used grassland must still be the priority of nature conservation. Therefore, power plants must not replace habitats of any kind but be planned in a way that is consistent with nature conservation standards. PVPP can serve as a habitat for a number of species when they are extensively managed, have a high structural diversity and are connected to other habitats, especially in intensively used agrarian landscapes.

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