Case study on the use of a high-mounted agrivoltaic system by mammals – results of a camera trapping survey over a one-year period

Lara Diekmann, Jennifer Łyko & Felix Zitzmann

Institute of Environmental Planning, Leibniz University Hannover, Herrenhäuser Str. 2, 30419 Hannover, Germany, e-mail: diekmann@umwelt.uni-hannover.de

Abstract: Agrivoltaic systems involve the dual use of land for agriculture and solar energy generation and, as such, in the context of renewable energy expansion can reduce the competition for land between photovoltaic expansion and food production. So far, however, there is a lack of knowledge on the effects of this combined land use type upon biodiversity. To gain initial insights, we used camera traps to investigate the habitat use of a small-scale, high-mounted agrivoltaic trial plot and an adjacent control plot (identical land use, but without solar panels) by large and medium-sized mammals over a one-year period in northern Germany. Our results showed no major differences between the plots regarding the number of recorded mammal species and their activity. Visit frequency and use intensity of the individual species hardly differed between the agrivoltaic plot and the control plot. However, the species found were common and adaptable (e.g. brown hare, roe deer, red fox, raccoon) and it remains unclear how other, less adaptable species might react. In addition, it is questionable whether these results can be transferred to larger agrivoltaic facilities or other systems (e.g. tracking modules) and further research on this question will be needed.

Keywords: biodiversity, species richness, solar energy, renewables, camera traps.

Introduction

Driven by technological innovation and political support, the expansion of renewable energies, particularly solar energy, is progressing at an increasing rate (Nijsse et al. 2023). This development will lead to a stronger competition for land, especially between energy generation and food production (Nonhebel 2005, van de Ven et al. 2021). To contain this conflict, agrivoltaic systems could be a possible solution, as they are a dual land-use, combining energy generation with solar panels and agricultural production on the same land (Dinesh & Pearce 2016, Widmer et al. 2024). At the same time, the adaptation of agrivoltaic systems will – similar to conventional ground-mounted photovoltaic systems – lead to landscape changes due to visual impacts and changes in land use and openness (Sirnik et al. 2024). At present there is a lack of knowledge about the environmental effects of agrivoltaic systems on biodiversity (Gomez-Casanovas et al. 2023). It is assumed that some species may avoid agrivoltaic systems due to the UV-light emitted by supporting structures and that larger mammals could be affected by reduced movement ability (Schwarz & Ziv 2024). To our knowledge there are no existing field studies on the effects of agrivoltaic facilities on mammals. The few existing studies on mammal use of conventional solar parks emphasize that security

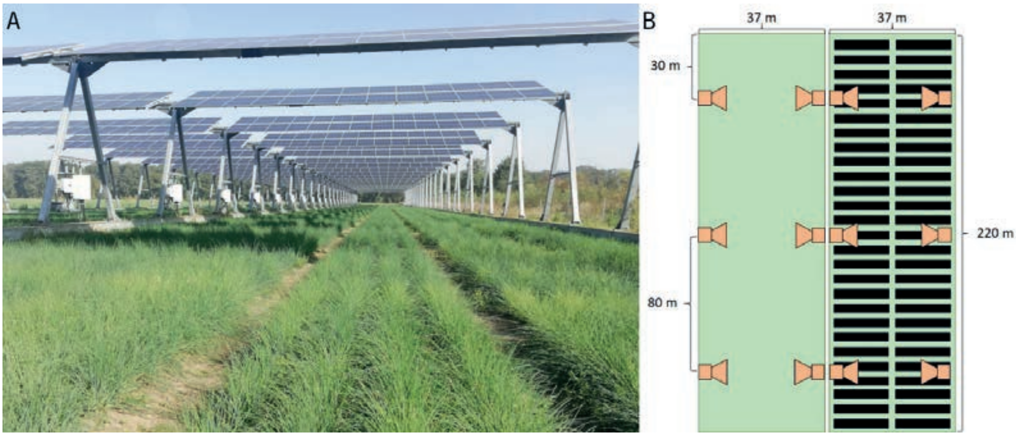

Figure 1. A. The agrivoltaic includes 24 rows of south-facing solar modules at a height of approx. 6 m. B. Both the agrivoltaic plot and the control plot had a size of 37 x 220 m and were surveyed with six CTs each (three at the east and three at the west side of each plot).

fences, typically installed around these facilities, can pose movement barriers, especially to large mammals, while small- and medium-sized mammals usually can pass through ground clearances under or gaps within the fences (Bennun et al. 2021, Sawyer et al. 2022). However, these findings are not transferable to agrivoltaic facilities since these are usually not fenced and may therefore have no or limited barrier effects on larger mammals. Furthermore, agrivoltaic facilities also differ considerably from regular solar parks in terms of land utilization: While the vegetation in conventional solar parks generally comprises extensive grassland, agrivoltaic focuses on agricultural use which may also affect their attractiveness for mammals. Overall, it is unclear whether mammals use or avoid these novel structures in our landscapes. To gain initial insights into this topic, we conducted what we believe is a first case study over a one-year period at a small-scale agrivoltaic facility in northern Germany. Our aim was to determine which large and medium-sized mammals use this agrivoltaic system and if there are any signs of avoidance behaviour or differences in visit frequency or use intensity in comparison to an adjacent control plot with identical land use, but without solar panels.

Materials and Methods

Study sites

Our research was conducted on an agrivoltaic trial plot built in 2022 in the north-east of Lower Saxony (district Lüchow-Dannenberg, northern Germany; coordinates: 53°00’13.5”N 11°10’26.5”E). The area is characterized by agriculture (arable land and grassland) with a forest in the north and structured by hedges and tree rows. The agrivoltaic trial plot has a size of approx. 0.8 ha (37 x 220 m) with 24 rows of high-mounted, south facing solar panels at a height of approx. 6 metres (Figure 1A). We investigated large and medium-sized mammals on two sample plots: the agrivoltaic plot itself (Agrivoltaic) and a directly adjacent plot without solar panels (Control). Both plots were of the same size and were sown with chives (*Allium schoenoprasum*) in September 2022. The chives on both plots were cultivated as a perennial crop, meaning intensive farming with frequent harvesting (about every 20 days during the vegetation period) and disturbance for maintenance (fertilizer or pesticide use several times a month in the growing season).

Survey methods

Mammals were recorded with camera traps (CTs) (Dörr SnapShot Mini Black 12 MP HD, Dörr GmbH, Neu-Ulm, Germany). We used six CTs per plot (Figure 1B) which triggered a Passive Infra-Red (PIR) sensor (Welbourne et al. 2016). The CTs were set to take a series of three images within three seconds per trigger, increasing the chance of identifying the species. After a delay of ten seconds the next trigger was possible. The CTs were active continuously from 17 January 2023 to 23 January 2024 (372 days).

On both plots, CTs were positioned facing the crop (Figure 1B) with three CTs installed on the western and three on the eastern side of the plots. The distance between these CTs was 80 m and a distance of approx. 30 m was kept from the northern and southern edges of the plots. As the detection range of the installed CT models is around 10–15 m, a major part of the area between the CTs (width of the plots approx. 37 m each) was covered. The CTs were mounted on the AGRIVOLTAIC sub-construction and on metal poles on CONTROL at a height of 70 cm with an inclination angle of approx. 5° towards the ground.

Data preparation and analysis

After the surveys, all information (date, time, location of CT, detected species) of images with large and medium-sized mammals was transferred to a table for further analysis. We only considered images of wild mammal species with at least the size of a red squirrel (*Sciurus vulgaris*). One table row was created for each detection (consisting of a series of three images, see CT settings). Based on this, the following values were calculated as indicators for the habitat use of mammals for the individual CTs, for the two plots (joint consideration of the six CTs used per plot) and overall (joint consideration of all CTs used): the number of detected species, number of detections and percentage of days (out of 372 days in total) with detection of the respective species. For all calculations, one camera day was defined as 24-h period beginning and ending at 12 a.m. (cf. Zitzmann & Reich 2022), including the entire dawn, dusk and night time, which are the main activity periods for most of the mammal species. Data was analyzed descriptively, as we only conducted investigations on two plots (AGRIVOLTAIC, CONTROL) for our case study and because the six CTs used per plot were nested within the same site and thus were not independent from each other.

Results

All CTs were continuously active during the investigation period (372 days per CT, 2232 camera days per plot and 4464 camera days in total). Overall, 3639 detections of mammals were made, distributed equally between AGRIVOLTAIC and CONTROL (Table 1). For more than 98% of the detections the species (or at least genus) could be identified. For 60 detections (1.6%) determination was not possible due to the poor image quality. Overall, six mammal species were detected: five of them on AGRIVOLTAIC and six on CONTROL. More than 60% of all detections were of the brown hare (*Lepus europaeus*) (Table 1). Roe deer (*Capreolus capreolus*; 24.6%) and red fox (*Vulpes vulpes*; 9.4%) also accounted for higher proportions. In contrast, raccoon (*Procyon lotor)*, martens (*Martes* spec; see$_1$ in Table 1) and especially wild boar (*Sus scrofa*) accounted for much fewer detections.

Of the detected species, the brown hare used both AGRIVOLTAIC (53% of days, with n=372 days) and CONTROL (62% of days) most regularly (Table 2, considering all CTs per plot). Roe deer and red fox were also regularly (23–31% of days) detected on both plots. The visit frequency on AGRIVOLTAIC and CONTROL were comparable for each of these three most common species. Raccoon and *Martes* spec. were only detected on a few days (max.

Table 1. Number of detected species and number of detections on both plots (with *n*=6 CTs per plot) and in total (*n*=12 CTs) during the survey period of 372 days.

	Agrivoltaic	Control	Total
European hare *Lepus europaeus*	1051	1205	2256 (62%)
Roe deer *Capreolus capreolus*	515	380	895 (24.6%)
Red fox *Vulpes vulpes*	156	186	342 (9.4%)
Raccoon *Procyon lotor*	33	21	54 (1.5%)
Genus *Martes*[1]	25	6	31 (0.9%)
Wild boar *Sus scrofa*	–	1	1 (0.03%)
Not determinable	40	20	60 (1.6%)
No. of species	5	6	6
No. of detections	1820	1819	3639

[1] The majority of images with representatives of genus *Martes* could only be identified to genus level, as characteristics for reliable species identification were rarely recognizable. Therefore, all detections with representatives of the genus *Martes* were considered together in the analyses. In some of the pictures, however, the stone marten (*Martes foina*) could be identified with certainty, while in none of the pictures could the pine marten (*Martes martes*) be reliably identified.

Table 2. Percentage of days with detection of the species during the investigation period (372 days) by at least one of the CTs used per plot (with *n*=6 CTs) und in total (*n*=12 CTs); Values in Brackets = No. of CTs with detection of the particular species.

	Agrivoltaic	Control	Total
Brown hare	53.0 (6)	61.8 (6)	72.0 (12)
Roe deer	22.6 (6)	29.6 (6)	40.3 (12)
Red fox	23.9 (6)	31.2 (6)	44.1 (12)
Raccoon	5.9 (6)	3.0 (5)	8.6 (11)
Genus *Martes*[1]	5.9 (5)	1.6 (4)	7.5 (9)
Wild boar	–	0.3 (1)	0.3 (1)

[1] See Table 1

6%) but also on both plots while wild boar was detected on just a single day on Control.

At CT-level (*n*=6 CTs per plot), mean and median values as well as standard errors regarding the number of species and number of detections per CT hardly differed between Agrivoltaic and Control (Table 3), but the range of values in numbers of detections was larger on the Agrivoltaic. Species-specific visit frequency and use intensity of the three most common species within the two plots hardly differed (Table 3), but especially for the brown hare, the range of values was larger on the Agrivoltaic, indicating big differences between individual CTs in this plot.

Discussion

The number of mammal species detected and overall mammal activity of Agrivoltaic and Control were comparable. Species-specific results showed that the three most common species (brown hare, roe deer, red fox) were recorded on slightly more total days on Control, but visit frequency of these species on CT level hardly differed between Agrivoltaic and Control, showing no clear difference in habitat utilization between both plots. However, all species detected are quite adaptable and also regularly occur in human settlements (stone marten, raccoon, red fox) or intensively used agricultural landscapes (hare, roe deer) (Hewison et al. 2001, Bateman & Fleming 2012, Santilli & Galardi 2016). Thus, they are used to anthropogenic structures and an avoidance behaviour towards the agrivoltaic system was therefore not to be expected, especially as studies from ground-mounted solar parks already confirmed habi-

Table 3. Mean values (±SE), median values (±SE), minimum and maximum of the measured variables per CT on the two surveyed plots (with *n*=6 CTs per plot).

	Agrivoltaic	Control
No. of species		
Mean	4.8 ± 0.2	4.7 ± 0.2
Median	5.0 ± 0.7	5.0 ± 0.8
Min - Max	4 - 5	4 - 5
No. of detections		
Mean	303.3 ± 49.9	303.2 ± 28.5
Median	319.0 ± 12.5	319.0 ± 9.5
Min - Max	138 - 512	155 - 370
Visit frequency[1]		
Brown hare		
Mean	20.9 ± 2.6	21.6 ± 1.7
Median	22.3 ± 2.8	20.0 ± 2.3
Min - Max	10.8 - 29.0	16.9 - 27.4
Roe deer		
Mean	9.1 ±1.5	9.0 ± 1.3
Median	9.4 ± 2.1	8.9 ± 2.0
Min - Max	4.6 - 13.4	4.6 - 14.2
Red fox		
Mean	5.6 ± 0.7	7.2 ± 0.9
Median	5.4 ± 1.5	7.8 ± 1.7
Min - Max	3.5 - 8.6	4.0 - 10.2
Use intensity[2]		
Brown hare		
Mean	175.2 ± 28.0	200.8 ± 19.0
Median	169.0 ± 9.4	216.5 ± 7.7
Min - Max	64 - 284	103 - 242
Roe deer		
Mean	85.8 ± 18.1	63.3 ± 12.5
Median	71.0 ± 7.5	65.0 ± 6.3
Min - Max	42 - 163	25 - 96
Red fox		
Mean	26.0 ± 3.7	31.0 ± 4.0
Median	27.0 ± 3.4	33.0 ± 3.6
Min - Max	13 - 39	16 - 44

[1] Visit frequency=Proportion of days [%] with presence of the particular species per CT
[2] Use intensity=No. of detections per CT

tat use, e.g. by hares and red fox (Herden et al. 2009, Montag et al. 2016).

Nevertheless, it cannot be ruled out that other mammal species than those detected by us now avoid the area due to the establishment of the agrivoltaic facility, or that the habitat use of the detected species considerably decreased, as we did not perform a before-after-comparison. Furthermore, it is conceivable that Agrivoltaic also influenced Control, as they were directly adjacent. Animal movement was thus not independent between both plots as individuals might have been deterred by the agrivoltaic system and thereby also be detected less frequently on Control compared to regular agricultural fields in the surrounding area. Overall, however, no strict avoidance of the investigated agrivoltaic system was observed, but regular use of the common species was detected.

One advantage of agrivoltaic facilities over traditional ground-mounted photovoltaics for mammal species is clearly the lack of fencing. This allows mammals of all sizes to use or cross the area without barriers, which is shown in our study by the frequent presence of roe deer. In contrast, the fencing of ground-mounted photovoltaics can lead to habitat loss and fragmentation, especially for large mammals (Sawyer et al. 2022). On the other hand, ground-mounted photovoltaics are relatively undisturbed due to their mostly extensive grassland use and consist of various microhabitats (e.g. locations under solar panels, between panel rows and edge areas; cf. Zitzmann et al. 2024). In contrast, (intensive) agricultural use on agrivoltaic facilities leads to more frequent disturbance and a more homogeneous habitat structure, which reduces the availability of food and cover, potentially making agrivoltaic systems generally less attractive for some species. The attractiveness of agrivoltaic facilities certainly also depends on the landscape context. For hares at least, the intensity of land use is less important for habitat use than the habitat diversity in the landscape (e.g. different crops and structural diversity) (Santilli & Galardi 2016). This matches the high presence of brown hare in our study on both Agrivoltaic and Control, despite intensive agriculture, and might indicate that especially small-scale facilities could possibly be of minor conflict potential for this species.

Finally, it must be emphasized that our study focused on a small-scale agrivoltaic facility. Thus, there were no real central areas, but it actually consisted exclusively of edge zones. Therefore, our results are not transferable to large-scale agrivoltaic facilities where central areas might be avoided by mammals. Furthermore, the type of agricultural land use (the type of crop along with the required management and its intensity), as well as the distance to other habitats such as forests will certainly have a strong influence on their attractiveness for and their use by mammal species (cf. Månsson et al. 2021). Accordingly, there is a need for further research on the effects of agrivoltaic on mammals and also on other species groups, especially at larger facilities, in different landscapes, with different crops (e.g. legumes or orchards) and different technical systems (e.g. vertical modules or tracking systems).

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Samenvatting

Case study over het gebruik van een agrivoltaïsche opstelling door zoogdieren – resultaten van een cameravalonderzoek over een periode van één jaar

Agrivoltaïsche systemen omvatten het dubbel gebruik van land voor zowel landbouw als voor de opwekking van zonne-energie. Hierdoor kunnen ze de concurrentie om land tussen de uitbreiding van fotovoltaïsche installaties en voedselproductie verminderen in het kader van de groei van hernieuwbare energie. Tot nu toe is er echter weinig bekend over de effecten van dit type landgebruik op biodiversiteit. Om eerste inzichten te verkrijgen, hebben we cameravallen ingezet om gedurende een periode van één jaar op een locatie in Noord-Duitsland het gebruik door middelgrote en grote zoogdieren van een kleinschalige agrivoltaïsche proefopstelling met verhoogd (6 m) geplaatste zonnepanelen een aangrenzend controleperceel (met identiek landgebruik, maar zonder zonnepanelen) te onderzoeken. Onze resultaten toonden geen grote verschillen tussen beide percelen wat betreft het aantal waargenomen zoogdiersoorten en hun activiteit. Ook de bezoekfrequentie en de gebruiksintensiteit van de individuele soorten verschilden nauwelijks tussen het agrivoltaïsche en het controleperceel. De waargenomen soorten, zoals haas, ree, vos en wasbeer, zijn echter algemeen en flexibel in hun aanpassing, waardoor het onduidelijk blijft hoe andere, meer kritische soorten zouden reageren. Bovendien is het onzeker in hoeverre deze resultaten overdraagbaar zijn naar grotere agrivoltaïsche installaties of andere systemen (zoals meedraaiende zonnepanelen). Verder onderzoek is daarom nodig.

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