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WILDLIFE BIOLOGY

Review

What next? Some practical suggestions for future studies on fence ecology

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Practical gaps in knowledge of fence ecology or its specific requirements still exist despite numerous recommendations scattered throughout various articles. We recently carried out two different studies on fences in a French context whose results corroborate this observation, and highlight the need to synthesise and prioritise scientific and technical research. The first study was an exploratory research project on escape devices used to allow ungulates to exit fenced transport infrastructure right-of-way. The second study entailed drafting a guide on the mitigation of the fence's ecological impacts, using solar energy plants as a case study. Both were based on different types of information gathering, ranging from bibliographical research to interviews with governments officials, operating companies, engineering offices, naturalists and hunters' associations. Based on the similarities between these two studies, the urgency of certain needs, and the clear potential for these approaches to extend beyond France's borders, we have identified two key categories for future actions. The first category is a series of six research priorities: Diversifying monitoring of exclusion fencing; Developing practice-oriented fence mapping tools; Further studying the impact of fencing on animal vehicle collisions; Considering animal behaviour in monitoring protocol; Ex-situ testing of devices' effectiveness; and Studying large-scale effects of fencing. The second category comprises six method recommendations: Accurately documenting fences; Early planning of scientific monitoring; Contextualising fencing requirements; Defining effectiveness goals and criteria; Taking advantage of opportunistic Animal-Fence Event observations; and Developing artificial intelligence and computer vision to map fences. All these items are supported by examples drawn from one study or the other. Our conclusions indicate that, in the context of major expansion of fences, such recommendations must be integrated at all stages of development work. If this is not implemented, the free movement of animal species will not be adequately protected and the erosion of biodiversity will be further exacerbated.

Keywords: animal behaviour, ecological impacts, escape devices, fence monitoring, fencing, mitigation.



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Context

Fencing off man-made infrastructures is becoming an increasingly common requirement in construction projects. Fencing is primarily installed to ensure user safety and/or to prevent damage to facilities and their equipment. Based on the specific requirements, fences aim to restrict access by humans and/or animals. However, in all cases, animals are significantly impacted by these barriers. Maintaining the movement of species and mitigating the impact of ecological barriers are essential for conserving biodiversity. Therefore, specifications for fences around industrial sites and transport routes must balance the need for effective wildlife barriers with measures that limit biodiversity erosion.

Generally speaking, 'a classic fence can be described as a physical linear feature with vertical load-bearing components (such as poles) and with connecting non-continuous structures (such as boards, wires, rails, and netting) spanning these components (Xu and Huntsinger 2022).' Recent scientific research is converging on the concept of a collective topic area of 'fence ecology' which examines 'the interactions between fences, organisms, ecosystems, and societal needs' (McInturff et al. 2020). The importance of the sociological contexts has also been highlighted (Xu and Huntsinger 2022). Practically, the relationship between fencing and wildlife can be considered from at least two perspectives: 1) evaluating and optimising fence effectiveness and 2) assessing and mitigating ecological impacts.

Our two recent parallel projects, each addressing both perspectives, have identified practical avenues for future research. The first project evaluated the effectiveness of specific fencing devices, knowing that the effectiveness and ecological impacts of transport infrastructure fencing have already been the subject of a substantial amount of technical reviews, (Carsignol and Tekielak 2019, CEREMA 2021, IENE 2022, as well as the BISON project – Biodiversity and Infrastructure Synergies and Opportunities for European Transport Networks), and scientific studies (Clevenger et al. 2001, Jaeger and Fahrig 2004, Rytwinski et al. 2016, Ford et al. 2022). This project involved reviewing information about the escape devices for wild ungulates in road and rail fences across France and Europe. The second project focused on 'wildlife friendly fencing' for ground-mounted photovoltaic utility-scale facilities (hereinafter called 'solar plants'), fencing practices and knowledge on solar plants facilities projects in France and abroad. Due to the minimal publications on solar plant fencing, the study drew on broader knowledge on fences.

Although conducted separately, these projects complement each other and offer insights into different aspects of fence ecology and associated logistics. First, both projects focused on industrial utilities, but they operate at different scales (a few hundred metres or kilometres for solar plant fencing to several dozens of kilometres for roads or railway fences). Second, the two projects had different goals such as formulating technical recommendations and mitigation measures, or underlining gaps in knowledge for future research.

Third, they were aimed at different audiences, depending on the type of activity (solar, road or rail) or level of involvement in projects. In short, they differed in scale, goals, target audiences, and context, however the comparative analysis has broadened the scope for future fence research. The article aims to provide a combined summary of these recommendations.

It summarises, revisits and reinforces several directions highlighted by our two studies (Buton et al. 2022, Buton 2023) and by other authors, providing further practical examples. We have grouped these guidelines into two distinct categories: 1) six research axis that offer some of the most interesting avenues to be explored, and 2) six method recommendations for quickly optimising fencing practices. These twelve proposals, while not exhaustive, urgently address knowledge gaps and research opportunities, to enhance fencing effectiveness, reduce ecological impacts (as established by Jakes et al. 2018), and improve escape devices (Huijser et al. 2015). In addition, our suggestions may also be relevant to environmental impact assessments prior to the development of any fencing project. The content of the article relates mainly to our experience in France but is also likely to be equally applicable internationally, benefiting researchers, consultants, project managers and organisations involved in species movement and wider ecological connectivity.

Data sources

An exploratory project on escape devices

From 2020 to 2022, the ESCAPE XXL exploratory project was carried out within the framework of the french National Research Programme on Transport Infrastructure, Territories, Ecosystems and Landscapes (ITTECOP) to synthesise knowledge on escape devices for wild ungulates (Buton et al. 2022). Escape devices are mostly used in highway and railway rights-of-way to enable wild ungulates to escape from exclusion fences. The project aimed to characterise and enhance their effectiveness in France and Europe; acknowledging that effectiveness may be interpreted in various ways (Method recommendation no. 4). Such devices contribute to traffic safety by reducing animal–vehicle collisions and decreasing animal mortality due to road-kill. They also mitigate the ecological impact of fences by preventing animals from getting trapped inside them.

Initially, the project consisted of supplementing our existing documentation by carrying out a bibliographic study of scientific articles and grey literature. This proved to be challenging as escape devices may be incidentally mentioned in studies focusing on fencing. The scientific articles were searched on the Web of Science, Scopus, Google and Google Scholar. Requests were made in both English and French. Secondly, a mini-questionnaire was distributed in France and abroad (in English and Spanish) to practitioners, operators, scientists and hunters' associations to identify data sources. This was followed up with further oral or written surveys based on a more comprehensive questionnaire. All identified

publications and reports were then carefully cross-referenced. Pre-existing reviews were very useful (notably: [Huijser et al. 2015](#), [Siemers et al. 2015](#), [Jensen 2018](#)), including accessing the online database of the Wildlife Crossings Project (wcproject.eu). A total of 16 scientific articles or reports and 55 other sources were used for this analysis, plus data from transport infrastructure managers and mainstream media references. A database was developed to cross-reference geographical locations with published and unpublished references, which served as a 'navigation chart' for the study.

This study identified various equipment types, e.g. mainly ramps, trapdoors, gates or trigger-wired 'open-cage' devices. It recorded their distribution in France, and initiated preliminary mapping for Europe and North America. The reported data demonstrates that some escape devices were used by animals leaving fenced rights-of-way. However, many questions remain as to the beneficial or limiting factors and the interpretation of the recorded passages ([Buton et al. 2024](#)).

The drafting of a guide for solar plant fencing

From 2020 to 2023, a good practice guide on exclusion fences for photovoltaic utility-scale power plants was produced with the support of the French Biodiversity Agency ([Buton 2023](#)). The guide involved an extensive analysis of a wide range of available references categorised by taxon and material type, and encompassing the direct or indirect ecological impacts of exclusion fences. The focus of this work was initially on perimeter exclusion fences around solar plants. It was noted that there was a lack of specific studies and data on fencing in this context ([Visser 2016](#), [Guerin 2017](#), [Visser et al. 2019](#)); the guide expanded to include knowledge derived from the broader application of fencing from various purposes, such as ecological conservation, livestock farming and agriculture, transport infrastructure. As opposed to a systematic review, the project initially analysed existing meta-analyses, which offered a general characterisation of ecological impacts ([Jakes et al. 2018](#), [Smith et al. 2020](#), [McInturff et al. 2020](#)), followed by an extensive bibliography of related references. This was supplemented with additional data and expert opinions from scientific, technical and/or ecological networks both in France and internationally, including wildlife care centres and engineering offices. In the end, over 230 publications and reports have been analysed. A project committee was established, including government technical services, biologists, solar plant developers and impact assessment specialists. The committee provided feedback on specific experiences and needs. The project also considered incidental or anecdotal data about wildlife events related to fencing (e.g. injuries) found in specialist or mainstream media as potential sources of information or points of interest for further investigations.

Comparing directions

With hindsight, and although this objective was not clearly identified at the start, our research on solar power plant

fencing installations and supplementary fencing devices (escape devices) has opened avenues for the broader consideration of objectives and themes in applied research. This also extends to environmental impact assessment, encompassing both study tools and methodology. It should be noted that our recommendations are also substantiated by our extensive practical experience of fenced installations, i.e. largely qualitative and probably not exhaustive.

Future directions for studies

The paper synthesizes, revisits and reinforces several directions underlined by our two studies ([Buton et al. 2022](#), [Buton 2023](#)) presented as Research Axis or Methodological Recommendations. It is important to note that there is no assigned priority to their order.

These guidelines result from collaborative discussions between the authors, who come from complementary backgrounds: research, consultancy, public technical agencies. They have been enriched by conversations with developers, managers and practitioners. Additionally, many discussions occurred within the framework of a monitoring committee specifically established for the solar plant fencing work and comprising over 15 participants. Readers are encouraged to refer to the full reports for more detailed results.

Suggestions for research axis

Research axis no. 1: diversifying monitoring of exclusion fencing

To date, the bulk of scientific studies related to fences have traditionally focused on natural or agricultural contexts ([McInturff et al. 2020](#), [Smith et al. 2020](#)). We recommend diversifying case studies around different types of installations, facilities, settlements or building, such as exclusion fences for securing goods or property.

Fencing may negatively interact with wildlife ([Jakes et al. 2018](#)) resulting in direct physical impacts such as injuries and mortality due to collisions, entanglements or impalments of animals (referred to below as 'direct impacts'). For example, direct impacts have been widely documented with Galliform birds, particularly in the context of livestock farming or forestry and notably for mountain species ([Bevanger and Brøseth 2000](#), [Baines and Andrew 2003](#), [GWCT 2013](#)). However, during surveys conducted in France within Galliforms key areas, up to two out of three collisions involved 'non-galliform' species ([Milhau 2019](#)). When considering all types of context, numerous bird species are prone to collide with fences, such as passerines, columbids, birds of prey, anatidae, etc. ([Buton 2023](#)); consequently it is crucial to assess this issue beyond just specific areas.

For instance, the impact of linear infrastructure fencing on fragmentation is well studied, but the potential for direct impacts remains underexplored. Unfenced roads and motorways pose significant wildlife mortality ([Lescroart et al. 2019](#)). This may also occur where fencing is permeable to

certain species or individuals (e.g. mesh size). The effectiveness of fences in preventing animal-vehicle collisions, particularly for ungulates, is proven (Ford et al. 2022), yet Europe lacks comprehensive studies on their direct impacts.

Urban areas also lack accurate studies on direct fencing impacts (e.g. gardens, commercial and industrial facilities, etc.). The issue of fences in an urban context has been notably considered for the European hedgehog *Erinaceus europaeus*, which has emphasised the danger of garden enclosures (Lohmann 2004, Jourde 2008, Hof and Bright 2009 cited by Pettett et al. 2017). Fences can also funnel hedgehogs towards roads, increasing their risk of being run over (Berthoud 1980). A number of organisations are inviting the public to create 'hedgehog highways' through fences and walls to enable wildlife movement between gardens (British Hedgehog Preservation Society and People's Trust for Endangered Species 2022). However, data on hedgehog-fence related injuries are few, which underlines the necessity for more research. For example, entangled in fencing leads to the regular admission of injured animals in wildlife care centres as reported to us in a few interviews we carried out in France; but there is minimal detail on the type and layout of the fences involved. Consequently, it would be useful to collect data on the causes of hedgehog-fence related admission in order to assess risk and establish the link with fencing conditions. Other admissions related to fences could also be registered. On a broader level, we recommend investigating the occurrence of direct impacts due to fences linked to human settlements (residential areas, industry, transport, etc.). This research could identify risk situations, contributing factors and inform the design of appropriate mitigation measures, such as fence marking (Trout and Kortland 2012, Van-Lanen et al. 2017) or repositioning fences in less prominent locations (OGM 2020). The findings may eventually influence environmental impact studies.

As we have pointed out during the work on solar plant fencing, a significant methodological challenge is distinguishing specific effects of perimeter fences from the enclosed activity or equipment: for instance, understanding whether animals are excluded by a certain type of fence or repelled by what they perceive through it (e.g. for flying species). This could influence the need for mitigation measures or lead to specific solutions. Our work on transport infrastructure exclusion fencing provided insight into studying the influence of enclosed activity on the perception of fences and of related equipment (such as escape devices) by animals. Recommendations include assessing how traffic may influence the effectiveness of mitigation measures (e.g. success of animal exiting through escape devices) and investigating the potential difference between roads and railways (e.g. frequency or noise level of vehicles or trains). This would also apply to the opportunity to use escape devices in other fenced scenarios, such as industrial facilities, canals, etc.

In summary, direct impacts of fences have been proven for many bird species but comparative studies on collision rates by fence specifications (e.g. height, mesh size, diameter and spacing of poles) are scarce, all the more when accounting

for nearby habitats, types of fenced activity or wildlife species and abundance (Buton 2023). In the case of solar plants, studies detailing wildlife fence-related casualties remain uncommon (Visser 2016, Guerin 2017, Visser et al. 2019). Though occurrences are occasionally reported, studies do not attribute a specific level of risk to solar plant perimeter fences in terms of animal injuries, collisions or entanglements. In addition, no direct mortality cases have been reported to us by solar plant operators or engineering offices in France. This may be due to a lack of targeted monitoring. This also raises the question whether this is due to a specific solar context and its influence on wildlife perception of fences (e.g. fence types currently used around solar plants, physical or ecological features of sites, proximity of panels and technical installations). Several follow-up questions arise from this observation. For example, do solar panels act as deterrents, preventing low-flying species from colliding with the fences by creating 'blind walls'? Alternatively, does the close proximity of fences to panels alter wildlife's perception of these barriers? If so, can this perception depend on the geometry of the solar panel alignments (i.e. birds arriving in front of a grassy strip between two rows of panels or facing the panels)? All these questions may relate or be extrapolated to other installations which rely on fencing.

Research axis no. 2: developing practice-oriented fence mapping tools

Fences are widespread over entire territories and their overall presence can be evaluated at a regional (large) scale through different methods, such as GIS fence location modelling (Poor et al. 2014, Buzzard et al. 2022), or by satellite/aerial imagery analysis (Buzzard et al. 2022). In France, 1550 km of fences were mapped in the Loiret department (Devilleger et al. 2010), 66% of which were used to secure roads or prevent human intrusion, including on factory, military or sports grounds, 6% to protect crops or forest plantations and 26% for hunting grounds. In the US, fence lines are estimated to be nearly twice the lengths of roads (Jakes et al. 2018), and recent models indicate that the human footprint, including dense fences, is larger than previously thought in some areas (McInturff et al. 2020).

At a more localised scale, for example in the vicinity of a solar plant project, no standard tools or reference methods exist for functionally mapping fences around future facilities during legally required environmental impact studies (e.g. within 1 to 2 km around a project). As a result, local mapping of fences is generally not undertaken for these assessments. When this issue is raised, manual mapping on site is often suggested as a solution; however, it is commonly avoided due to high workload and cost. Additionally, other linear elements that may hinder wildlife movements (e.g. buildings, low walls, gabions, small ditches or gutters, railings, poles and supports) are sometimes overlooked in impact studies. Therefore, we recommend that work is carried out to define fence mapping protocols adapted to the micro-local scale of environmental impact studies and to their contingencies (i.e. optimisation of the human and financial resources needed for

mapping, difficulty arising from the diversity of equipment and their state of disrepair, implementation deadlines, etc.).

In the solar plant fencing guide, unfenced 'buffer zones' around are recommended to ensure wildlife permeability. An operational mapping tool should enable effective long-term monitoring of nearby fences (e.g. at $t+3$, $t+5$, $t+7$ years). Alongside aerial photograph analysis, evaluating automatic fence recognition applications using field photographs (machine-learning) for environmental impact assessments prior to project development could be beneficial. Assessing how developers, engineering offices and state departments would use these tools is also important.

In tandem, both fence researchers as well as consultancies and engineering offices engaged in post-works environmental impact assessment monitoring, could collect more accurate data on fence specifications (e.g. type, layout, and condition of fences). This collective effort would contribute raw data for future meta-analyses and mapping, and aid in the effectively 'crowdsourcing' of fence data, which might be challenging to obtain via remote sensing or modelling (Method recommendation no. 1).

Research axis no. 3: further studying the impact of fencing on animal vehicle collisions

As we suggest for solar plant environmental impact studies, new fencing in the vicinity of roads or railways is likely to result in cumulative ecological impacts through two primary routes.

Firstly, fencing on a single side of a road is traditionally seen as increasing collision risk by potentially trapping animals within the rights-of-way. Additionally, fencing of adjacent land parcels may confine animals that have crossed the transport infrastructure within a contiguous risk area. This compounding effect requires further research. We recommend reviewing case studies to determine a safe 'buffer zone' around plots near roads for each species, and considering the broader landscape context. These buffer zones should ideally be maintained for the entire lifespan of the transport infrastructure, possibly extending beyond the road right-of-way.

Secondly, the risk that the fencing of a neighbouring plot might direct or funnel flying or terrestrial species towards transport infrastructure should be assessed. This includes understanding factors that increase the risk of animal-vehicle collisions. For example, bats are known to follow certain fences, often as a mitigation strategy to lead them to crossing structures (CEREMA 2018). It has been proven that fences can deflect low-flying bat species; experimental studies revealed that 95% of lesser horseshoe bat *Rhinolophus hipposideros* followed and flew around 4 m high fences rather than flying over them at a higher level (SWILD and NACHTaktiv 2007). Bats also follow hedgerows, which can funnel them towards traffic when perpendicular to roads, increasing risk of collision. Therefore, it is reasonable to consider that fences on adjacent plots might guide chiropterans towards nearby roads, especially if they converge towards roads or extend hedges, subject to fence specifications and adjacent vegetation. Additionally, it is relevant to assess if and under what

conditions conventional height transport infrastructure fences (2 m) can guide low-flying bat species and how this may impact road mortality.

Specific study protocols for these two points should be developed to gain a more comprehensive understanding of cumulative impacts. Additionally, sharing animal-vehicle collision data on transport infrastructure would facilitate future research and outcomes for environmental impact assessments related to fenced projects. It should be noted that this data is readily available; for example, in France, the National Museum of Natural History provided hot spot analyses based on animal-vehicle collisions recorded by Interdepartmental Road Directorates (Billon et al. 2015, Billon 2019, Billon and de Lacoste 2021) and highway and railway companies also operate their own databases.

Research axis no. 4: considering animal behaviour in monitoring protocol

In wildlife conservation, the value of descriptive behavioural studies understanding population responses to management actions is well established (Caro 2007). Several studies have assessed how mammals cope with fences. Notably, Xu et al. (2021) developed an innovative spatial and temporal explicit approach (BaBA for barrier behaviour analysis) that enables a nuanced understanding of animals' responses to fences and classifies animal-barrier encounters into six behaviour categories: 'quick cross, average movement, bounce, back-and-forth, trace and trapped'. Applying BaBA to pronghorn *Antilocapra americana* and mule deer *Odocoileus hemionus* on > 6000 km of fencing in USA, they demonstrated how the method can be used to identify problematic fence segments for particular species and how it can help to locate remediation measures. Using camera traps in Kenya, Wilkinson et al. (2021) developed a guide to classifying fence-specific mammal behaviors, and showed that seasonality, human activity, habitat visibility, and proximity to an adjacent protected area were each correlated with species-specific crossing locations. The authors emphasised that 'one-size-fits all' conservation fence designs may be ineffective and costly for restraining movement of many wildlife species.

In France and Europe, field monitoring focuses mainly on detecting animal passage through escape devices using track traps or digital camera traps. The activity, route and behaviour of animals prior to using an escape device are seldom documented. One notable exception is occasional tests carried out in enclosures (Meunier 2000). Additional behavioural approaches may help in understanding how species access, perceive and use escape devices. We recommend developing consistent protocols to observe and quantify, at different radii, both exit or refusal rates, including possible counter-entry, drawing on existing North American studies as a reference framework (Siemers et al. 2015, Huijser et al. 2016, Jensen 2018, Gagnon et al. 2020). Furthermore, simply recording exits through an escape device should not be interpreted without understanding the use of fenced rights-of-way by animals (e.g. actual arrival of certain animals in front of a feature, or even possible refusal to cross it – see

also Method recommendation no. 4). Any successful passage after several attempts may indicate a 'progressive passage' requiring learning and habituation to the feature. Similarly, we recommend that different radii of observation to evaluate the influence of the fence layout, the type of escape device and any additional equipment (e.g. 'bumpers', laying heather on fences, scented or salted attractants – Fig. 1) should also be evaluated. The distance between the escape device and the transport infrastructure can also play a role; in North America, Siemers et al. (2015) showed that mule deer *O. hemionus* exited more often rights-of-way through ramps that were located relatively close to the road and we suggest conducting the same study for European species and using a wider range of distances.

The behaviour of animals around a fence and the way they manage to cross it can also depend on their rationale for visiting the site or crossing it. This is why we advocate adopting a behavioural approach through on-site observations to help understanding the motivations for a target species entering and exiting fenced areas (transport infrastructure, solar plants, etc.). For instance, investigating the reasons for animal entry into right-of-ways before installing escape devices is crucial. Local factors, such as plants or water sources and salt, are likely to attract animals within the right-of-way (Groot Bruinderink and Hazebroek 1996) and it is reasonable to assume that their presence may interfere with the animal's willingness or urgency to exit through a given escape device, possibly preferring to prolong its stay within the right-of-way. Thus, Lehnert (1996) utilised the evidence of the willingness of mule deer to forage within fenced road right-of-ways to inform modification of innovative specific crosswalk devices. In practice, effective maintenance or removal of such attractive factors, combined with fencing reinforcement, could also reduce the risk on animal intrusion. Likewise, for solar plant fencing, we also recommend understanding and determining the pathways of animals around and through the fences, in order to better assess the use of animal passages located at

the foot of the fence (i.e. to facilitate movement through an enclosed area), and their use of unfenced buffer zones or corridors (Sawyer et al. 2022, Reck et al. 2023). This approach would help in understanding the factors governing the use of these unfenced areas.

Research axis no. 5: ex-situ testing of devices' effectiveness

Considering both the safety issues associated with fenced installations (road traffic accidents, electrocution, etc.) and security issues (theft, vandalism, etc.), it can be problematic to directly test the reaction of animals to specific or innovative fencing types or layout on site. Therefore, we recommend increasing the number of ex-situ tests in fence ecology, building upon existing research and testing for microfauna (Conan et al. 2022), ungulates (Meunier 2000, Stull et al. 2011), etc. The feasibility of such investigations should align with ethical principles and animal welfare regulations. Ex-situ tests can identify critical design flaws, such as the ineffectiveness of fine mesh screens for some species (Conan et al. 2022) or validate specifications (e.g. tests reported on specific escape devices for wild boar *Sus scrofa* during our ESCAPE XXL project). Depending on the results of the ex-situ phase, only subsequent in-situ testing can consider other factors such as scale (e.g. length of fence), site constraints (e.g. disturbance due to enclosed or neighbouring activities) or operation, etc.

In particular, we propose testing specific ramp designs within enclosures that are low enough to aid not just red deer *Cervus elaphus* and roe deer *Capreolus capreolus* but also wild boar, known for their comparatively limited jumping abilities. In order to reduce the risk of reverse entry (i.e. from outside the fenced enclosure), we suggest these low ramps include an open-work feature (i.e. guardrail or barrier) at the top, similar to designs tested in North America with local species (Huijser et al. 2015, Siemers et al. 2015, Gagnon et al. 2020). This design would allow an animal to step through and jump from the ramp's top facilitating exit from the fenced right-of-way, while also deterring entry from outside.

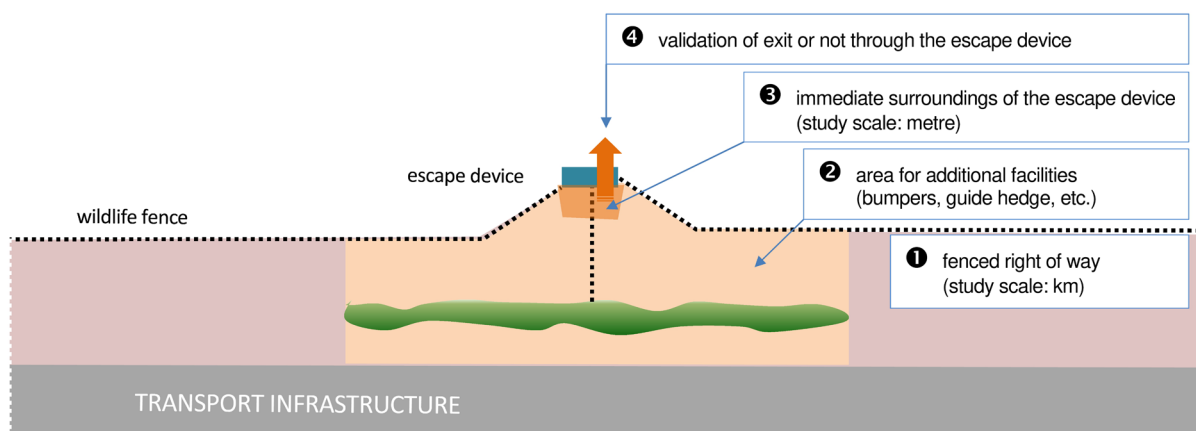


Figure 1. Principle of progressive instrumentation radii around an escape device in future in situ monitoring (source: Buton 2022).

Research axis no. 6: studying large-scale effects of fencing

Jakes (2018) and Mc Inturff (2020) have highlighted the importance of research across different scales. We have observed that Environmental Impact Assessments of solar plants or roads often focus on the immediate vicinity (typically hundreds of metres or few kilometres). However, cumulative, indirect or chain-linked impacts may occur at larger scales. A fence may be considered 'good' on a small scale, but 'bad' on a larger scale. These large-scale impacts intersect with other well-known factors contributing to the fragmentation of natural habitats (e.g. transport infrastructure, urbanisation). We propose that the ecological impacts of each new fencing installation, regardless of its nature, should be assessed from a broader perspective. Every new fence is essentially a new component in the expanding network of fences. This approach requires a deeper understanding of these complex large-scale effects, not just on wildlife (e.g. migration, etc.), but also on habitats and flora. It requires better mapping (Research axis no. 2), supported by advanced high-tech tools for characterising fences (Method recommendation no. 6).

Method recommendations for research and environmental impact studies

Method recommendation no. 1: accurately documenting fences

Fencing is a globally ubiquitous feature (Xu and Huntsinger 2022). It is also highly diverse in its forms and uses, and is subject to evolution over time (e.g. ageing, technical enhancements). Our research, mainly focused on metal structures

like wire mesh, already includes a wide variety of designs. Acknowledging that fence ecology is a nascent research area, we encourage the accurate recording of fence types used in any study without generalising to a global and ubiquitous concept of a fence. We believe that comparing results between sites requires consideration of actual fencing materials, as each type of fence (e.g. flexible or rigid fence, mesh size and dimensions, barbed or smooth wire: see Fig. 2) and layout (e.g. fences buried or above ground, type or reinforcements at the bottom or on the top) is likely to have different effects (Table 1). However, such detailed fence information is seldom factored into wider analysis. We recommend that studies provide comprehensive fence information, with appendices within research reports containing photographs and annotated diagrams denoting wire mesh, ground level and fence post detail (e.g. diameter, material and spacing of fence poles, ground anchors and reinforcements, fence burrs or top extensions, etc.). The colour of each component could be specified with a qualifying adjective ideally a standard colour code, as well as their material (e.g. type of metal, synthetic material, paint and galvanising). The general state of obsolescence and condition should also be described, as damage may alter the effectiveness of fencing or, conversely, cause hazards to wildlife (e.g. sharp wires). Wilkinson et al. (2021) demonstrated the correlation between fence maintenance and animal behaviour, underlining the importance of fence condition in understanding its effects on wildlife. It would also facilitate designing effective fencing policies that address long-term presence, maintenance and decay of fences, as well as removal when redundant or unneeded.

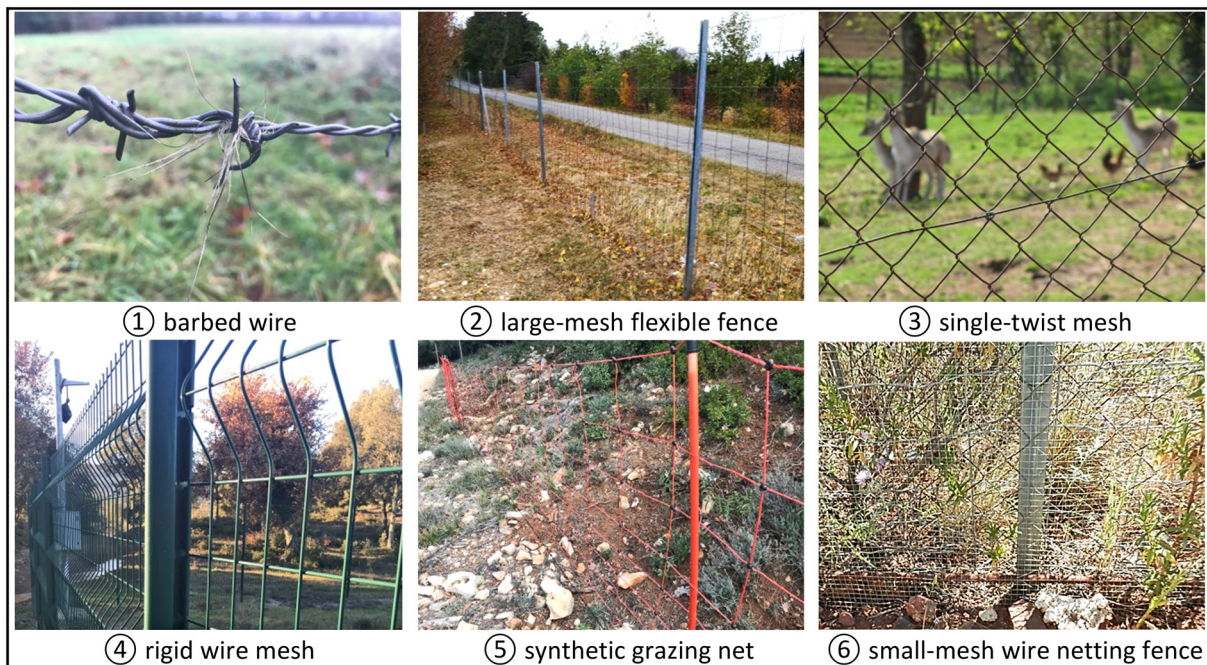


Figure 2. Illustration of the main types of fencing encountered, showing the differences in wire: barbed (1) or non-barbed (others), rigid (4) or soft (5), the differences in mesh size: small (6) or large (2 and 5) and the differences in material: metallic (1, 2, 3, 4 and 6) or plastic (5). (credit: 1, 2, 3, 4 and 5: C. Buton – Cabinet X-AEQUO, 3: Ch. Saint-Andrieux – OFB)

Table 1. Examples of direct negative effects of fences (in all contexts and activities worldwide). CO: collision (injury or death) – EN: entanglement and/or snaring – EL: electrocution or electrification. Boxes left blank indicate a lack of data, but not a certainty of no impact (adapted from [Buton 2023](#)).

FENCE TYPE (EXAMPLES)	FLYING SPECIES (EXAMPLES)			TERRESTRIAL SPECIES (EXAMPLES)						
	birds	bats	insects	small-sized terrestrial fauna		medium-sized terrestrial fauna	ungulates			
				small mammals	reptiles, amphibians		cervids	wild boar		
barbed wire <i>(fig. 2 photo ①)</i>	CO: proven	CO: proven	still to be studied			CO: probable	EN: proven			
large-mesh flexible fence (height ~ 1 m to 1.40 m)	CO: proven	general case: no negative effects but question to be investigated on a case-by-case basis in the immediate vicinity of the breeding sites and water areas			Probable (reported without precision with turtles and snakes depending on mesh size) (especially if electrified)		EN: proven (especially if combined with barbed wire)			
large-mesh flexible fence (height ≥ 2 m) <i>(fig. 2 photo ②)</i>	CO: proven					EN: reported CO: proven – if stressed animals)				
single-twist mesh <i>(fig. 2 photo ③)</i>	CO: reported (to be confirmed)			EN: proven (e.g. hedgehog)						
rigid wire mesh <i>(fig. 2 photo ④)</i>				EN: proven (e.g. hedgehog)						
synthetic grazing net <i>(fig. 2 photo ⑤)</i>				EN: proven (especially if electrified)		EN: reported if not taut	EN: proven especially if not electrified and not taut			
damaged, loose or sagging fences				EN: proven		EN: reported	EN: proven			
small-mesh wire netting fence <i>(fig. 2 photo ⑥)</i>							EN: proven (occasionally)			
smooth metal wire, electrified or not	CO: proven (especially if the wire is taut)							EN: reported		
electric fencing in general	EL: reported					EL: reported	EL: proven	EL: reported	EL: reported	EL: reported

Method recommendation no. 2: early planning of scientific monitoring

Post-construction monitoring are often legally required. The challenge for a project owner is to produce objective data to determine whether the mitigation measures specified in the impact assessment have achieved the expected results. It is crucial to follow a systematic approach that ensures objectivity and replicability. Ideally, such data would also be useful for broader research applications. The key prerequisite is to undertake a systematic approach based on: 1) contextualizing the study with a bibliographical review of existing information and knowledge; 2) clear definition of the study challenges or hypothesis to be tested; 3) an experimental protocol adapted to the monitoring objective; 4) statistical analysis of the data to determine objectively whether the observed effect is significant and; 5) critical analysis of the results and subsequent discussion ([Kaldonski et al. 2020](#)). In summary, a scientific approach enables an objective testing of monitoring results, as opposed to informal post-construction monitoring, which will only highlight trends ([Sordello et al. 2019](#)).

We would encourage undertaking post-construction assessments as part of a before-after-control-impact (BACI) protocol to address spatial and temporal variations ([Conner et al. 2016](#)). Nevertheless, we acknowledge that a BACI protocol

may not always be possible in the context of post-construction monitoring legally required within an environmental impact assessment or imposed by the authorities in their permits, e.g. when the project is located at a single site. For example, as noted during our work on solar plant fencing, it may be difficult to fence off only part of the perimeter (e.g. to study the impact of the presence or absence of fencing on the site) where human access to the facility is to be restricted for security reasons. However, early engagement of researchers in the construction process with the project owner may enable consensus and foster innovative monitoring approaches.

This implies considering the requirements of the subsequent monitoring protocol from the design stage. This is not just a question of being able to gather baseline data prior to development impact (i.e. the ‘zero point’ corresponding to the protocol’s objectives). It is also a question of ensuring that the operations carried out during the construction phases (e.g. disturbance by construction vehicles at the target site) do not interfere with the monitoring, and vice versa. It is key that the correct information and involvement of all stakeholders (in particular, construction workers and subsequent operating company) feed into the protocol (i.e. technical decisions, anticipation of disturbance effects, etc.) which will determine the effectiveness of the monitoring

programme. We recommend that the monitoring protocols are co-designed with the project owner, the ecologist, biostatistician (as required) and operational staff, at the design stage of development projects and with periodic joint reviews during its implementation.

Method recommendation no. 3: contextualising fencing requirements

Each fencing project has specific goals (e.g. fences to exclude humans or wildlife, escape devices to move animals out of a fenced transport infrastructure right-of-way) that should be well defined and agreed with relevant stakeholders before implementation. In particular, from our experience on solar plants, we have highlighted the necessity for clearly defining the level of tightness or permeability of exclusion fences around each plot so as to 1) set up technical fencing specifications, 2) consider measures to mitigate ecological impacts and 3) monitor results on the long term.

Each project is also subject to multiple technical requirements to ensure its longevity and effectiveness (e.g. layout and design of poles and fences). It must also comply with specific constraints that apply more generally to the sector of activity (e.g. security, safety, regulations, right-of-way maintenance procedures). All of these constraints must be fully considered in any research, including overall technical and budgetary feasibility. For example, during the ESCAPE XXL project, an issue arose in relation to the proximity of escape devices to the traffic and the potential risk of a vehicle leaving the road (i.e. ramp effect with a vehicle colliding with an escape device). Therefore, with a view to supplement later versions of guidance (CEREMA 2021), we suggest inclusion of a legal analysis to determine the risks and constraints associated with a site's specific context (e.g. types of infrastructure, road geometry, traffic volume); although no incident involving any escape device is known to us to date. In addition, an understanding of legal implications for stakeholders, (e.g. infrastructure managers, device designer) is also required to account for scenarios such as escape device failure (e.g. animals using the escape device in reverse and entering the fenced right-of-way, resulting in road traffic accidents). The occurrence of reverse entries have been documented in North America and are often contingent on species, type of escape device and layout, or additional equipments (Reed et al. 1974, Gagnon et al. 2020). However, based on the literature review undertaken for this study, there were no reports identified of car accidents directly attributable to reverse entries.

In practice, we encountered two schools of thought among designers and operators for ramp-type escape devices. Some argue that the jump height cannot be lower than the minimum height recommended by national standards for wildlife exclusion fences (e.g. 2 m minimum for roe deer in France (Carsignol and Tekielak 2019)), even if this limits the rate of successful exit. Other designers advocate lower heights to facilitate animal egress. This particularly emphasises the importance of undertaking tests on ramps as proposed above (Research axis no. 5). Additionally, legal risks associated with activities or facilities near escape device may

need consideration (e.g. risk of an animal exiting on a secondary road through an escape device). We believe there is a need to reconcile the results of a scientific approach only, and the legal examination of the application. For example, we have previously highlighted the gap between the empirical or statistical methods developed to analyse priority risk areas (i.e. hot spots) for animal-vehicle collisions and the case-by-case legal review following a road accident resulting from an animal (Lescroart et al. 2019). The factors considered in court rulings can vary significantly from scientific calculation methods. Therefore, it is crucial to analyse legal ramifications alongside scientific research to ensure practical applicability.

The discussions and research undertaken for the solar plant fencing guide emphasised the importance of specifying, on a case-by-case basis, the constraints that a developer might face regarding perimeter fencing. This is also relevant to other facilities or infrastructure types; and it includes considering if fencing is required, for what reason, level of security/safety or detailed specifications, etc. These factors not only influence the nature and type of site work but also affect the research protocols applicable to a given site. Understanding and addressing these nuances is essential for the effective implementation and study of fencing in various infrastructural contexts.

Method recommendation no. 4: defining effectiveness goals and criteria

In our work on escape devices, we have highlighted that users and scientists have different ways of interpreting their effectiveness. These understandings are related to the perceived objectives for these devices and the criteria used to assess effectiveness. This statement is equally applicable to other ecological measures or devices. For example, defining an effective escape device raises questions about what constitutes success. Should the safe passage of a single animal be considered as conclusive in that it potentially prevented an accident as suggested by FDC13 (2012)? Is it possible to set a threshold, i.e. a minimum 'exit' success rate for a target species or animal? In North American comparative studies, cost-benefit analyses included only those escape devices that demonstrated efficiency rates of 80% or higher, either for enabling large mammals to exit fenced rights-of-way or for preventing reverse entries (Huijser et al. 2015). Conversely, before concluding that a device is ineffective, the absence of its use must obviously be analyzed in the light of the presence or absence of animals in the right-of-way. Observing the non-use of an escape device on a given site, on its own, does not conclusively indicate its ineffectiveness.

In our work, we have carried out a quick search of the various aspects underlying the notion of effectiveness (or its common synonyms: efficacy, efficiency, etc.) based on the French translations. However, an in-depth semantic analysis may identify further considerations. For example, effectiveness may relate to functionality in terms of possibilities or potential functions offered by the device, i.e. whether it actually allows animals to leave a fenced area. Introducing a notion of performance may involve assessing the percentage

of successful exits in relation to the initial number of animals inside the fenced area (in situ or during ex situ tests). As an integrated criterion, this may also involve assessing the impact of equipment installation on accident rates. In a behavioural approach, assessing the effectiveness implies characterising how animals cross or refuse to use an escape device (e.g. routes toward the device, time before exiting). Refusal can equally be difficult to define: for example, does an unsuccessful attempt to activate a mobile escape device (e.g. trapdoor, gate) qualify as refusal? Is the presence of an animal in front of such a device without trying to operate it to be considered as a refusal? If so, from what distance? Lastly, how should animals be classified if they refuse to cross the escape device in the first instance, but then return to successfully pass through it later? From a behavioural perspective, effectiveness might also imply estimating the increased time spent by animals inside the right-of-way, although this may be difficult to assess on-site. It can also raise a question of comparative efficiency as the ability to produce maximum results with minimum effort or expense. Comparative analysis of devices can then be carried out in terms of return on investment. Escape devices have been the subject to several cost benefit analyses in North America, but such studies are limited in Europe, apart from inventories of only supply costs (Buton 2022). This approach would also require a detailed comparative analysis of installation costs and contingencies under comparable site and access conditions, as well as a delineation between new work and work on existing infrastructure. For cost benefit analyses, we suggest referring to the parameters used in North America (Huijser et al. 2015). This includes factors such as construction (from planning to installation), maintenance and repairs, reduction of animal mortality (e.g. big game), etc. There may be other ways of defining effectiveness and we underline the importance that studies on mitigation measures (not just escape devices) clearly indicate which approach has been selected.

In relation to human–wildlife conflict, various aspects of technical efficiency (i.e. influencing animal behaviour) and ecological effectiveness (i.e. achievements of final ecological goals) is linked with the social acceptability of solutions in an overall Social Effectiveness concept (Volski et al. 2021). A practical example is demonstrated in our work on solar plants during which stakeholders identified the necessity to integrate landscape and environmental approaches during the environmental impact assessment process. For instance, one way of mitigating potential risks of bird-fence collisions could be to reinforce the visibility of fences by adding specific markers to divert birds as demonstrated in other contexts (Van-Lanen et al. 2017). However, this may alter the overall integration of the fence within the landscape by creating a visual intrusion for local stakeholders/communities. When considering the possible interaction between ecological and societal constraints in the broadest sense (including visual sensitivities for neighbouring residents, applicable technical standards, legal framework and jurisprudence, terms of insurance, etc.), we align with Xu and Huntsinger (2022) when they advocate ‘a comprehensive framework that situates

fencing within coupled human and natural systems, or social-ecological systems’, as well as considering how societal constraints influence technical choices, with the possibility of co-evolution and potential feedback loops.

Method recommendation no. 5: taking advantage of opportunistic animal–fence event observations

In France, and possibly in other countries, wildlife incidents involving fences are not well-documented, with the notable exception of studies on mountain Galliforms. This lack of documentation may be attributed to the low likelihood of passers-by directly witnessing such events (although incidental observations were reported to the authors on a few occasions). This also includes encountering a carcass with obvious indications of fence entanglement or collision. Other difficulties correspond to the biases commonly reported in any mortality monitoring programme, such as scavenger activity, the observer’s acuity in a given environment and for given body sizes, the frequency of observation, the distance of search from the fence and determining cause of mortality based on evidence present (Visser 2016, Jenkins et al. 2017, Milhau 2019). A general lack of awareness, along with the absence of guidance and training also contributes to poor documentation. In line with the principle of ‘citizen science’, we propose establishing an on-line public participatory tool to record cases of collisions, entanglements or impalements of wild animals on fences of all types. Such participatory surveys have already highlighted the adverse impacts of fences and resulted in the development of guidance, e.g. in Switzerland by the Swiss National Association for Animal Protection (Schlup and Furrer 2021). BirdLife in South Africa (<https://www.birdlife.org.za/what-we-do/landscape-conservation/what-we-do/birds-and-fences/>) and the Entangled Wildlife Australia project (bit.ly/3q1EHPH) have created online crowdsourcing tools. The implementation of such a platform dedicated to fences in France could provide case studies (including photographs), locate incidents (geo-referencing) or collect additional data (questionnaire). This platform could be hosted on the internet (with an accompanying smartphone application), possibly within a wider framework of general participatory data collection platforms already in use and popularized, such as Vigienature in France (www.vigienature.fr). It should be possible to design several levels or a hierarchy of information (e.g. public/expert level) to use the tool in the framework of specific inventories. The objective of such a permanent participatory survey would be: 1) documenting local examples (for instance in France, but with potential extension to Europe scale), 2) allowing a multi-year analysis, 3) suggesting appropriate mitigation measures and 4) identifying specific and new research themes for scientific investigation. It is also probable that targeted publicity of such a platform will raise public awareness and encourage the submission of observations. Of course, procedures for validating the information collected will have to be defined. Importantly, the new French legislation no. 2023-54 of February 2023 which limits the enclosure of natural areas may also support public interest and participation. This

legislation not only restricts fencing dimensions but also mandates that fences must not harm or trap wildlife. It would be beneficial if the future application decree defined these terms. The participatory inventory we suggest would significantly contribute to a better understanding of these situations.

Method recommendation no. 6: developing artificial intelligence and computer vision to map fences

Aligned with research axis no. 2, we propose to test the integration of computer analysis of fence images obtained by remote sensing with recognition of fence types using artificial

Table 2. Summary of the six research axis and six method recommendations, with brief explanations and the main sources of recommendations (work on solar plant fencing or on escape devices).

Recommendations	Details	Sources of recommendation	
		Work on solar plant fencing	Work on escape devices
Research axis			
No. 1: diversifying monitoring of exclusion fencing	<ul style="list-style-type: none"> studying ecological impacts of fences surrounding different types of installations, facilities, settlements or buildings distinguishing potential specific effects of perimeter fences from effects due to the enclosed installation or equipment collecting data on animal–fence related admission in wildlife care centres 	X	X
No. 2: developing practice-oriented fence mapping tools	<ul style="list-style-type: none"> testing mapping protocols suited for environmental impact studies of projects 	X	
No. 3: further studying the impact of fencing on animal vehicle collisions	<ul style="list-style-type: none"> defining safe unfenced ‘buffer zone’ around plots close to roads assessing the risk that the fencing of a neighbouring plot guide or funnel animal towards transport infrastructure sharing of animal–vehicle collision data from transport infrastructure 	X	
No. 4: considering animal behaviour in monitoring protocol	<ul style="list-style-type: none"> documenting animal route and activity prior it uses a mitigation feature (e.g. escape device, passage at the foot of fence, unfenced corridors between enclosures, unfenced buffer zone surrounding a project) studying exit or refusal rates, including possible counter-entry studying the use of the rights-of-way by animals and their reasons for entering / exiting fenced areas 	X	X
No. 5: ex-situ testing of devices’ effectiveness	<ul style="list-style-type: none"> testing within enclosures specific ramps for deers and wild boars 		X
No. 6: studying large-scale effects of fencing	<ul style="list-style-type: none"> study the cumulative effects of a growing network of fences across an entire region, adding them to other factors of fragmentation (transport infrastructure, urbanisation, etc.) 	X	
Method recommendations			
No. 1: accurately documenting fences	<ul style="list-style-type: none"> providing full information on fence materials, dimensions, layout, colour and state of obsolescence 	X	
No. 2: early planning of scientific monitoring	<ul style="list-style-type: none"> following a scientific approach to monitor environmental impact mitigation measures (definition of goals, adapted protocol, statistical data analysis, critical analysis of results) following a before-after-control-impact (BACI) protocol if possible co-designing of protocols by the project owner, ecologist, biostatistician and operational staff, at the design stage of development projects, with periodic joint reviews during implementation 	X	X
No. 3: contextualising fencing requirements	<ul style="list-style-type: none"> before research/implementation, considering with stake holders fencing goals and comprehensive constraints, including technical and budgetary feasibility, legal risks, and societal constraints 	X	X
No. 4: defining effectiveness goals and criteria	<ul style="list-style-type: none"> indicating the definition used for effectiveness in each research or studies upon a mitigation measure or ecological device analyzing the semantics associated with the notion of effectiveness studying the possible interaction between ecology and societal constraints 	X	X
No. 5: taking advantage of opportunistic observations of animal-fence events	<ul style="list-style-type: none"> setting up an on-line public participatory tool to record collisions, entanglements or impalements of wild animals on fences (with public/expert level, data validation procedure) 	X	
No. 6: developing artificial intelligence and computer vision to map fences	<ul style="list-style-type: none"> improving aerial/satellite image analysis combined with on-ground fence-type recognition backed up by artificial intelligence and deep learning in order to assess the cumulative impacts of fences at different scales and to support territorial governance of issues relating to the ecological impacts and effectiveness of fences 	X	

intelligence. Depending on study scope, remote sensing can be based on satellite or high-resolution aerial drone. In particular, the automatic 'labelling' could rely on deep learning, using both specific field surveys and possibly crowd-sourced data. For each of these uses, quick and practical input tools should be developed, for example on tablets or smartphones. Photo upload and metadata information utilities could be adapted either to expert users or general public. This growing integration of technology would aid in mapping fences and evaluating their cumulative impacts across various scales. This approach would not only assist in assessing the ecological impacts and effectiveness of fences, but also support their integration into territorial planning documents and environmental assessments of plans and projects. By doing so, it would enhance the governance of territorial issues related to fences, contributing significantly to informed decision-making in environmental planning and management.

Conclusion

Our two in-depth synthesis on fencing focusing on escape devices and perimeter fencing of solar plants, have highlighted or consolidated key guidelines applicable to any study related to fencing, regardless of its purpose. These guidelines, outlined in Table 2, contribute to the technical development of the nascent field of fence ecology.

Each new fencing project presents an opportunity to expand knowledge, capitalise on lessons learned and improve future project outcomes, provided that protocols are implemented, designed and monitored with scientific rigour. This is also contingent on engaging with fence users in a genuine 'co-production process' as recommended by Hyde et al. (2022). Users' constraints and perceptions can influence the range of feasible mitigation measures at a given location, their adoption by users, and acceptance by stakeholders, as well as conditioning the terms of possible assessment protocols. Integration of social factors and implementing a multi-partner approach offers a significant opportunity for applied research, aiming to make wildlife friendly fencing maximally functional for users and widely adopted. We recognise that the knowledge of fencing issues is still largely unfamiliar and there may be wider reluctance to address this agenda; consequently, this will require a great deal of information dissemination and awareness raising to mainstream fence ecology.

Finally, preventing ecological impacts may require working at scales that go beyond the territorial scope of a project or the regulatory contingencies of official impact assessments. This means that the cumulative effects of fragmentation should be considered at larger scales in environmental impact assessments. We recommend that these considerations, including the coordination of research, knowledge improvement, diagnosis, action and feedback, be managed by a governance body formulated to match the scale of the territories. Such an approach will ensure a comprehensive and integrated perspective in addressing the ecological impacts of fencing.

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Caryl Buton: Writing – original draft (lead). **Nicolas kal-donski:** Writing – review and editing (equal). **François Nowicki:** Writing – review and editing (equal). **Christine Saint-Andrieux:** Writing – review and editing (equal).

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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