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Editorial

Fences: the silently, sprawling network

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Introduction

From fortified borders to decorative garden walls, fences form ubiquitous widespread networks that sprawl across the global terrestrial landscape. Fences and walls are one of the oldest tools used by people to manage other people and wildlife, e.g. by marking territorial boundaries, separating livestock from wild animals, or monitoring the movement of people through border controls. There is no reliable measure of extent of the global fence network, however it is estimated to be at least 10 times that of the global road network (Jakes et al. 2018), which is currently more than 64 million km (Dulac 2013), and expected to reach 90 million km by 2050 (Laurance et al. 2014). Despite the enormous extent of the fence network, fences are rarely subjected to environmental impact assessments, and the ecological impacts of fencing are severely underestimated and understudied (Jakes et al. 2018, McInturff et al. 2020, Buton et al. 2024).

The main purposes of a fence – to fragment, isolate, and/or reduce interactions – often align with negative ecological impacts, while meeting the goals to protect livestock, prevent access of invasive species, or control the spread of diseases (Terborgh et al. 2001, Woodroffe et al. 2014, Jakes et al. 2018, Mysterud and Rolandsen 2019, McInturff et al. 2020). Fences and walls are erected through all landscapes, including those that are ecologically important and protected. One example that has received a lot of media and political attention is the recently constructed border fence between Poland and Belarus, which cuts through Białowieża Forest, the best preserved lowland temperate forest in Europe and transboundary World Heritage Site (Jaroszewicz et al. 2021). Such barriers have the goal to hinder the flow of people, and consequently also block the movement of wildlife and challenge landscape connectivity (Olson and van der Ree 2015, Linnell et al. 2016), which can trigger a cascade of direct and indirect ecological impacts (Nowak et al. unpubl.). Border fences are also used to control the spread of diseases, such as African Swine Fever (ASF). With the aim to reduce the movement of infected wild boar and contain ASF, fences have been built along numerous country borders in Europe, e.g. the 70-km long fence at the German–Danish border which runs directly through Natura 2000 areas (Eilenberg and Harrisson 2023, Klein et al. 2024). Similar border fences to control ASF exist at the German–Polish border, and are planned to be installed at the Norwegian–Swedish border. The fragmentation effect of border fences is often apparent, however the impacts caused by fences that are for example along roads and railways, denote property borders, or enclose protected areas, are often underestimated. Without proper research of the downstream or indirect impacts to ecosystems, the negative impacts of fences will continue to be overlooked and unaccounted for.

This special issue provides a collection of articles in which authors present different perspectives on fences and how we, as humans, use fences to communicate with the natural world and manage wildlife. Finally, the issue provides guidelines to improve fence design and implementation, and discusses research steps to move forward in the field.

You shall not pass: typical uses of fences in wildlife management

The ends justify the means – or at least it seems so in the use of fences for wildlife management (Jakes et al. 2018). Whether a fence is deemed to be good or bad, and the resultant ecological consequences to be acceptable or not, depends largely on the intended goal of the fence.

The use of enclosures or exclosures is a common practice in wildlife management, for example to reduce predation pressure on vulnerable animals, reduce interspecies competitions, and control the spread of disease. For example, Miszei et al. (2023) demonstrate that fenced enclosures can help to reduce predation pressure on the threatened Hungarian meadow viper *Vipera ursinii rakosiensis*. By controlling where wildlife is in the landscape, fences can have varying impacts on species dynamics, which depend on environmental conditions, the type of fencing, and the age of the fences. For example, livestock protection exclosures may be used by wild animals attempting to avoid large predators. In their study, Forti et al. (2024) showed that, during the grazing season, moose *Alces alces* were equally or more likely to be inside fenced enclosures designed to protect sheep *Ovis aries* from predation, suggesting that the moose may take advantage of the electrified fencing and seek refuge in the exclosures. However, over the winter, when the fence was not electrified, moose used the exclosures less. The authors also noticed that when inside an exclosure moose browsed less on their preferred young trees, leaving them to the sheep, possibly demonstrating interspecies competition for resources within the exclosure refuge.

Another common use of fences in wildlife management is along roadsides, to prevent wildlife access to roads and reduce the risk of wildlife–vehicle collisions. This means that the fences will inherently disrupt and prevent connectivity in the landscape, and create a barrier. Botting et al. (2023) explore this concept, in a comparative study of modeled red deer *Cervus elaphus* and wild boar *Sus scrofa* movement through a landscape with roads and fences. The authors found that fences amplified the barrier effects created by roads; however, these barrier effects can be reduced by the installation of wildlife crossing structures – structures that are designed specifically to allow for the movement of wildlife from one side of the road to the other without having to enter the path of traffic. This study highlights the need to consider the landscape context in studies on movement and connectivity and to address the cumulative effects of different networks – for example road, railway, and fences. Such consideration can be somewhat rare in wildlife ecology and management, but is essential to holistically assess the impacts of different interventions or practices on wildlife and the environment.

Sometimes the effects of the fence can diminish over time, if wildlife learn to overcome the barrier and enter the areas from which they should be excluded. In other words, the apparent barrier may diminish over time. In Watt et al. (2024), the authors demonstrate that elk *Cervus canadensis* and other local species changed their space use or movement behaviour for a short time after fences were installed to redirect wildlife from areas where plains bison *Bison bison bison* were reintroduced into Banff National Park. However, impacts of the fence on non-target species that were documented in the first three years of fence installation waned over time. Thus, it is important to evaluate the cumulative impacts of fences over time and to explore downstream impacts to target and non-target species.

Message in a bottle: what do fences signal to wildlife?

Fences for wildlife management do not only act as physical barriers, but also as signals in the landscape, communicating 'no-go zones' to animals. This communication function can be envisioned when the animals still behave as if there was a fence, but the fence in question was removed a long time ago. This is the case of red deer in Šumava forest in Czechia, bordering Germany and Austria. Despite the removal of border fences fifteen years ago, the Šumava red deer move as if the fences were still there (Krenova and Nowak uunpubl.). Virtual fences are not physically impassable, but they send different signals (auditory, visual, olfactory, electric) to communicate with wildlife. For example, 'fladry' flags act as symbolic barriers, which can be easily crossed but are actually effective markers deterring wolves and coyotes (Musiani et al. 2003). Over time, and through learned behaviour, fences signal to wildlife the areas where they are allowed and where they are not. This communicative role that fences play in human–wildlife interactions is discussed by von Essen et al. (2023) under an ecosemiosis framework. Ecosemiosis (bio- and zoo-) aims at understanding how animals communicate among themselves and with humans. The authors discussed that fences can be imperfect and miscommunicate in various ways due to, for instance, insufficient knowledge of the animals' motivations or vague signals which are also received by non-target species. This miscommunication could then result in animals outsmarting humans, or 'wrongly' learned lessons. In this sense, a fence protecting wildlife from traffic collisions will only work if humans understand and acknowledge the reason(s) why animals want to cross the road. This essay represents an innovative and inspiring perspective on fence ecology, which remains largely unexplored – how fences often miscommunicate and lose effectiveness when animals are not recognized as active participants in negotiating space and access alongside humans.

De-fencing the landscape: bridging the knowledge–action gap

Fences are also not all built the same, nor are they all designed to target the same species. Brieger and Strein (2024) demonstrate that a variety of different fence styles exist, and the type of fencing necessary depends on the specific climbing and digging abilities of the species of interest. Based on their experiences from German highways and federal roads, the authors summarize their findings into five main design considerations: 1) don't use traditional classic galvanized high-tensile fences, i.e. those made of knot braid. Rather, opt for chain wire or welded wire mesh fences; 2) use plates made of recycled synthetic material or concrete foundations to prevent digging under fences; 3) use wire fence panels on the top of the fences to restrict the ability of individuals to climb over fences; 4) reduce vegetation in and around fences to maintain their integrity and function; and 5) construct fences close to the road. It is important to understand the target species of the fencing measures, to ensure the correct measures are taken to effectively reduce their access to roads and reduce wildlife–vehicle collisions. Otherwise, fences could have unintended consequences for both target and non-target species, including entrapment in poorly maintained fences (Trouwborst et al. 2016, Pokorny et al. 2017).

The proper maintenance of fences is essential to achieve their ultimate goal. For instance, electric fences are a well-known measure to mitigate human–wildlife conflicts, and they have proven to be the most effective method to protect livestock from large carnivore attacks (Smith et al. 2018, Oliveira et al. 2021). Hedmark et al. (2024) tested in a field experiment how fence installation affects voltage level. They examined the voltage of rubber-coated wire, commercially supplied, during contact with soil, ground, and wet vegetation and compared it with conventional metal wire (control). In all cases, contact with these elements short circuited. The highest voltage drop occurred when the wires were directly in contact with the ground (90% loss) and wet vegetation (70%). There were no differences between the two types of wire. The conventional metal fence wire, which is cheaper, performed as the rubber-coated wire, and both did work well provided their maintenance is adequate.

Fence ecology lies in the science-to-application pipeline and must be nurtured from practical experiences. In this sense, it is a research field that involves interdisciplinarity and a close collaboration between researchers and practitioners. Buton et al. (2024) identified general research priorities and provided recommendations based on two different studies on fencing of man-made infrastructures. The first study explored escape devices for ungulates to exit fenced transport infrastructure, while the second focused on mitigating the impacts of fences in solar energy plants. By combining literature review and interviews to all types of stakeholders, the authors identified six research priorities: 1) the study of exclusion fences must diversify and include more types of fences, like those in an urban context, and more direct impacts, such as animal collisions and injuries with fences; 2) mapping fences combining different mapping tools according to established protocols that include fence specifications, pointing to 'crowdsourcing' of fence data as a promising option; 3) cumulative impacts of fences, namely how fences in the vicinity of a road or railway can funnel flying and terrestrial species towards transport infrastructure and affect animal–vehicle collisions; 4) go beyond mere animal detection and gain understanding on their behavioural response to fences, including learning, habituation, and motivation; 5) increase the ex situ tests of fence devices to identify design flaws and validate specifications; and 6) investigate fence effects across spatial scales and assess large-scale impacts. The authors concluded the paper with important recommendations for fence research: accurately documenting fences and inclusion of detailed fence information into wider analysis; early planning of scientific monitoring and before-after-control impact (BACI) protocols; contextualizing fencing requirements, including technical and legal ones; defining clear goals and criteria to properly assess fence effectiveness; taking advantage of opportunistic animal–fence event observations and properly document all of them, including collisions, entanglements, and impalements; and developing artificial intelligence and computer vision to map fences.

Final remarks: opening a gap in the fence

This issue addresses 'fences', in a semi-permeable sense – some individuals cross while others cannot. However, the fortification of fences and walls is increasing, and fences are thereby becoming increasingly impermeable. This is a present-day ecological issue that deserves more attention (Linnell et al. 2016, Trouwborst et al. 2016, Jakes et al. 2018). One of the biggest challenges is recognizing that fences are largely part of an ever-growing human-infrastructure network, and that fences do not function alone. The impacts, particularly barrier impacts of fences, act in conjunction with other landscape features, such as roads and railways. Landscape-level and cumulative effects of fences are not yet well understood (Jakes et al. 2018). Future studies should evaluate the cumulative impacts of fences and other infrastructure (as in Botting et al. 2023), and over time (as in Watt et al. 2024). In the cases where the barrier effect is indeed maintained, this can lead to population isolation, which would not be apparent right away after fence construction. Since changes to genetic structuring within populations takes a few generations to become apparent and measurable, it is important to continue to explore the impacts of fences, even years after their construction, to accurately ascertain their ecological impacts.

Following existing frameworks, such as those proposed in McInturff et al. (2020) provides a good foundation to begin to evaluate the wide range of ecological impacts of fences on the environment. In addition to the ecological impact, it is important to realize that fences also serve social and economic roles and are usually erected by humans for reasons other than (or in addition to) those having to do with wildlife. As such, the emerging field of 'Fence Ecology' would benefit from taking multi- and inter-disciplinary approaches in understanding the impacts of fences on the landscape and to improve the design and planning of future fence projects (Jakes et al. 2018). Fence ecology will require the integration of the history of fences, socioeconomic and cultural aspects, and (international) policies with conservation biology, landscape ecology, ecosemiosis, and spatial planning, while adopting tools and methods provided by remote sensing, artificial intelligence, and engineering for better mapping and mitigation. Including end-users into fence design and management in a genuine co-production process would improve conservation and management outcomes (Sabo et al. 2024). Fences can no longer sprawl silently across the landscape, and there is an urgent need to address their severe, global impacts in wildlife and landscape ecology and management. Fences must be taken seriously as important drivers of global change. Gaining insight into how they shape species, communities, and ecosystems across different spatial and temporal scales remains an essential yet unresolved task.

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