Animal Conservation

Animal Conservation. Print ISSN 1367-9430

REVIEW

Good virtual fences make good neighbors: opportunities for conservation

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Keywords
biological fencing; proximity-based sensors; radio-activated guards; real-time sensory deterrent; virtual management.

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Editor: Nathalie Pettorelli
Associate Editor: Phoebe Barnard

Received 22 May 2013; accepted 10 September 2013

doi:10.1111/acv.12082

Abstract

Fences can both enhance and detract from the conservation of wildlife, and many detrimental impacts are associated with creating physical barriers. By contrast, virtual fences can restrict, control or minimize animal movement without the creation of physical barriers, and present key benefits over traditional fences, including: (1) no need for construction, maintenance or removal of traditional fences; (2) rapid modification of boundaries both temporally and spatially based on specific conservation concerns; (3) application of novel conservation approaches for wildlife that integrate monitoring, research and management; and (4) social-psychological benefits that may increase support for conservation. We review the various types of sensory, biological and mechanical virtual fences, and the potential benefits and costs associated with fully integrating virtual fences into protected area management and wildlife conservation. The recent development of real-time virtual fences represents the potential for a new 'virtual management' era in wildlife conservation, where it is possible to initiate management actions promptly in response to real-time data. Wide-scale application of virtual fences faces considerable technological and logistical constraints; however, virtual fences are increasingly popular and soon will offer realistic management strategies for both terrestrial and avian wildlife conservation.

Introduction

The use of fencing dates back to early human agricultural societies, who needed to confine domesticated animals and exclude wildlife, and is an increasingly popular and controversial tool in wildlife conservation (Hayward & Kerley, 2009). Despite clear benefits of fenced boundaries in species conservation for disease mitigation (Bode & Wintle, 2009), large vertebrate restoration (Licht *et al*., 2010), and general protected area design and management (Hayward & Kerley, 2009), fences create an inflexible physical barrier that is difficult, and often costly, to erect and maintain (Hayward & Kerley, 2009). Where effective, fences can cause a negative edge effect, impacting animal movement and the broader ecosystem structure and function. For example, in response to fences, African elephants, *Loxodonta africana*, can either disproportionately utilize areas along fences (Loarie, van Aarde & Pimm, 2009) or avoid fixed electric fence lines (Vanak, Thaker & Slotow, 2010), and either pattern could change vegetative communities and result in a loss of biodiversity (Lagendijk *et al*., 2011). Furthermore, fences can have deleterious effects on non-target species (i.e. species for which the fence was not intended) (Hayward & Kerley, 2009) by causing lethal collisions (Stevens *et al.*, 2012), blocking migration routes (Gates *et al*., 2012) and generally restricting movement of wildlife with population-level consequences (Newmark, 2008; Linklater & Hutcheson, 2010; Cozzi *et al*., 2013). Finally, fences represent symbolic barriers to people that separate human communities from their traditional natural resource base (Lindsey *et al*., 2012), and likely diminish the 'wilderness' experience sought by many visitors to protected areas (Kotchemidova, 2008).

The costs and limitations of creating traditional fences have led to the development of a variety of innovative management alternatives to direct wildlife movement. Like traditional fences, these 'virtual fences' serve to create an enclosure, barrier or boundary, but rely on techniques other than the use of physical objects on the landscape to

Table 1 Conservation costs and benefits of traditional fencing compared to virtual fencing

Component	Traditional fencing[a]	Virtual fencing[b]
Wildlife management	• Hard boundary for complete exclusion or inclusion that helps define ownership • Complete exclusion of undesirable species (including invasive) and human disturbance • Provides reliable barrier to disease transmission • Fence-related edge effects on target and non-target species	• Virtual boundaries can easily be spatially and temporally altered • Fewer fence-related edge effects (predation, overgrazing) • No fence-related mortality • Permits movement of non-target species
Human–wildlife conflict	• Reduces and in some cases completely eliminates human–wildlife conflict	• Reduces human–wildlife conflict and can be focused on individual problem animals
Implementation	• Technology already in place and well tested • High capital outlay, including environmental impact in remote or wilderness areas. • High maintenance, replacement and removal costs • Risk of materials being used for other purposes such as snares for poaching	• Further testing required to assess effectiveness and potential consequences in most species • Relatively low installation cost, but high enforcement cost • For collar-based virtual fences, high installation costs if substantial number of transmitters required • Adaptability and required monitoring make it readily integrated into adaptive management framework
Social-psychological	• Hard boundary ensures confidence of no human–wildlife conflict outside of reserves	• Reserves without visible fences more likely to be perceived as 'wild'

[a]Sources: Hayward & Kerley, 2009; Hayward, 2012; Lindsey *et al.*, 2012.
[b]Sources: Anderson, 2007; Kotchemidova, 2008; Lee *et al.*, 2009; Umstatter, 2011; Gates *et al.*, 2012; Slotow, 2012.

alter animal behavior (Umstatter, 2011). The earliest virtual fences involved the placement of sensory deterrents or biological barriers that dissuade particular wildlife species from moving into or outside of a particular area. More recently, proximity-based sensors have been placed on animals to deliver auditory or electronic cues that discourage wildlife movement across predefined boundaries (Hawley *et al*., 2009; Rossler *et al.,* 2012). Subsequently, real-time satellite- or cellular phone-based tracking have been used to create real-time virtual fences (RTVFs) that also serve as a broader platform to integrate spatial and temporal flexibility in the virtual management of wildlife populations (Slotow, 2012).

We review the potential benefits and costs associated with more fully integrating virtual fences into protected area management and wildlife conservation. By avoiding physical boundaries, virtual fencing provides a number of distinct benefits compared to traditional fencing (Table 1). However, just as in traditional fencing (see Hayward & Kerley, 2009), conservation managers need to weigh the considerable economic, logistical, ecological and social-psychological costs and benefits associated with the use of virtual fencing (Table 2). Below, we (1) summarize the various types of virtual fences, (2) discuss the costs and benefits of virtual fencing, and (3) review the behavioral, technological and social-psychological challenges that currently limit their broader use in addressing animal conservation issues.

Current virtual fence techniques

Sensory deterrents

The use of scent, auditory and visual movement deterrents has a long history in wildlife management. Strategic placing of carnivore urine, with high concentrations of sulfurous metabolites from meat digestion (Parsons & Blumstein, 2010; Ferrero *et al*., 2011), is used in deterring prey species (Osburn & Cramer, 2013). For herbivores, repellents are used to limit movement (Osborn & Rasmussen, 1995) and reduce browse damage on plants (Kimball & Taylor, 2010). Compounds can be applied topically, or systemically integrated into plants through noxious compound (e.g. Selenium) supplementation or genetic manipulation (Mithöfer & Boland, 2012).

The use of auditory frightening devices has a wide and important use in creating virtual fences around areas of conservation or management concern (Shivik, Treves & Callahan, 2003; Belant & Martin, 2011). For example, in marine systems, underwater acoustic harassment devices can be effective in limiting predation by marine mammals on wild and farmed fish (Terhune *et al.,* 2002). Visual barriers (Gray, 2009; Avila-Flores, Boyce & Boutin, 2010) and deterrent cues such as flags or strobe lights also are commonly used to create virtual fences with mixed success (Musiani *et al*., 2003; Shivik, 2006; Walter

Table 2 Summary based on existing literature of the costs and benefits of traditional and virtual fence techniques. Rankings are based on a positive (+) or negative (–) scale, where positive means greater benefit or less concern based on our review of existing literature. The number of positive or negative symbols indicates the intensity of beneficial or detrimental effects, respectively. Question marks indicate areas in need of further research

		Enhancing protected area management	Integrating monitoring research and management	Ease of application/ maintenance	Potential permanence/ longevity	Non-target impacts	Behavioral challenges	Technological limitations	Public opinion/ animal welfare concerns
Traditional fencing		+/–	– – –	– – –	+ +	– – –	+	+ + +	– – –
Virtual fencing techniques	Sensory deterrent	+	– –	+ + +	– – –	+	+	+ + +	+
	Biological virtual fencing	+ +	+	+ + +	+	+/–	– –	+ + +	+ + +
	Animal mounted training collars	+	+	– – –	+	+ + +	– – –	–	– – –
	Real-time virtual fencing	+ + +	+ + +	– –	?	+ + +	?	– –	+ +
	Remote monitoring of permeable barriers	+ + +	+ +	?	?	+ + +	?	– –	?

et al., 2011). While sensory deterrent cues can be easily applied, their effectiveness typically is short-lived and they often require repeated application (Walter *et al*., 2011). Furthermore, where repellents are repeatedly applied, there is risk of acclimatization by individuals over time (Darrow & Shivik, 2009; Kimball *et al.,* 2009). To increase their effectiveness, sensory deterrent cues can be used in combination to deter wildlife from utilizing an area (Walter *et al*., 2011), or linked with real-time tracking collars placed on individual animals to warn and condition animals when they approach or cross a virtual barrier (Lee *et al*., 2009).

Biological virtual fencing

The intentional planting or placement of species to control the movement of another species is an increasingly common and cost-effective type of virtual fencing. Guard dogs have a long history of use as roaming barriers to predators that could harm domesticated livestock (Gehring, VerCauteren & Cellar, 2011). More spatially fixed biological barriers are increasingly being used for wildlife management. For example, in Zimbabwe, the planting of chili pepper, *Capsicum annuum*, plants has been shown to reduce the risk of mammalian herbivores crossing into agricultural areas and causing crop damage (Parker & Osborn, 2006). Similarly, the presence of African honeybees, *Apis mellifera scutellata*, and even the presence of old hives or sound of buzzing, can be effective at controlling African elephant movements and limiting crop-raiding (King, Douglas-Hamilton & Vollrath, 2011). For small mammals, planted or uncropped grasses can form biological barriers that are effective at limiting dispersal (Terrall, 2006; Eddy, 2011). However, these types of biophysical barriers further blur the line between traditional and virtual fences, because they likely have consequences for the impacted species similar to those of traditional fences. In general, the use of these types of biological virtual fences is cost effective and could enjoy wide public support (King *et al*., 2011), yet there are few rigorous assessments of their effectiveness. Furthermore, managers planning to release species intended as barriers into new areas outside of the historic range should always be wary of their potential to become invasive (Ricciardi & Simberloff, 2009).

Conversely, rather than forming a barrier to movement, biological attractant cues can be used to minimize movement beyond boundaries. For example, the placement of limiting habitat features such as water (Loarie *et al*., 2009) or food plots (Phipps *et al*., 2013) can be used to focus the use of species within protected areas. In this sense, the virtual fence is actually viewed as a biogeographic phenomenon where probability of use of an area by an animal is expected to decline as distance from a centrally placed key resource increases.

Animal-mounted training collars

Animal-mounted training collars have a long history of use in domesticated animals (e.g. dogs and livestock), and more recently been extended to control the movement behavior of wildlife (Hawley *et al*., 2009; Rossler *et al*., 2012). These proximity-based alarms typically take one of two forms: they either alert on-the-ground visual or auditory alarms, termed radio-activated guards (Breck *et al*., 2002), or the collar itself provides an electric shock or auditory cue to the animal when it crosses an invisible, predefined barrier (Rossler *et al*., 2012). The use of training collars provides time-specific hazing stimuli that limit the potential for habituation (Breck *et al*., 2002), and potentially provides longer-term aversive conditioning or training (Umstatter, 2011). However, with the exception of grey wolves, *Canis lupus* (Hawley *et al*., 2009, 2013; Rossler *et al*., 2012), the deployment of animal-mounted training collars is only slowly being adopted for use in wildlife management due to product costs, technological limitations and the logistical difficulty of capturing wildlife (Shivik, 2006). Furthermore, the use of electric shock raises significant animal welfare issues (Lee *et al*., 2009), and such collars are illegal in parts of the United Kingdom and Australia (Blackwell *et al.*, 2012).

Real-time virtual fencing

The use of real-time tracking technology in combination with automated computer systems has a relatively recent history in both wild and domesticated animal management. In their simplest form, RTVFs can be viewed as rapid communication between people when wildlife cross management barriers, such as through the use of cellular phones (Graham, Adams & Kahiro, 2012). More complex, automated animal-mounted tracking systems have also been developed and improved over the past 15 years (Umstatter, 2011). In domesticated animal management, automated RTVFs typically involve the integration of Global Positioning System (GPS) tracking with irritating cues such as electric shock or auditory signals (Lee *et al*., 2009) to actively dissuade animals from leaving or entering a particular area. RTVFs present a number of benefits including the ability to do away with traditional wire or electric fencing that can be expensive to install and maintain and potentially harm wildlife and livestock, as well as allowing for more efficient management (Umstatter, 2011). For example, by redefining virtual barriers for livestock, managers can both monitor and control livestock movements to avoid overgrazing and degrading range condition (Butler *et al*., 2006). However, despite these benefits, RTVFs are not widely used in domesticated livestock operations due to technological limitations and high product costs, slow acceptance by livestock producers and animal welfare issues associated with aversive conditioning (Umstatter, 2011). By contrast, in wildlife management, RTVFs typically do not involve irritating cues, but rather alert managers as to when animals cross a boundary, which results in management action to alter the individual's location (Box 1).

Box 1: Use of real-time virtual fences to manage elephant populations in South Africa

In central and southern Africa, virtual fences have been used in elephant management to temporarily place a buffer around areas where risk of human–wildlife conflict is greatest. In iSimangaliso Wetland Park, cellular phone based transmission of GPS locational data from collars is processed by a central computer, which logs elephant locations in real-time and uses computer software (http://www.yrless.co.za/animals/animalsGI.html) to track when animals leave predetermined polygons (Fig. 1). Once the animal is detected beyond the boundary, a task force is dispatched to haze the individual back into the reserve or go through the expensive and time-consuming process of capturing and relocating the individual or family group. Similarly, when elephants leave Ithala Game Reserve and cross a river near human settlements, managers receive a cellular phone text message notifying them of where and when the transgression occurred, and of the identity of the elephants involved, so that appropriate management actions can be taken (Slotow, 2012). This system allows for the management of risk across a wide geographic area without having to fence-off access to the river for elephants, and the host of other species impacted by such a fence. Furthermore, virtual fence polygons can be easily modified so that alarm messages are sent to alert managers during specific time periods when elephants are near areas where humans are actively working on a given day (Slotow, 2012), and can be restricted to send alerts only when specific problem animals have crossed or are in proximity to a virtual fence.

There is also potential that virtual fences can be integrated with our rapidly advancing understanding of elephant movement behavior to predict areas of potential human-elephant conflict. Within reserves, it is important to limit human access to elephant refugia and corridors to mitigate disturbance to elephants and reduce the likelihood of aggressive encounters with humans (Jachowski *et al*., 2012). Thus, managers could establish virtual fence polygons surrounding key refugia and corridors that alert managers when human access to those areas should be limited. Furthermore, predictive models are being developed to proactively mitigate human-elephant conflict prior to crossing a virtual fence (http://www.savetheelephants.org/research-reader/items/elephant-geofencing.html). In addition, the organization 'Save the Elephants' is developing an alert network that extends beyond managers to include private landowners outside protected areas, who can register their lands so as to be warned when elephants have crossed or approaching a virtual barrier near their land, potentially limiting crop raiding.

Technological advancements in GPS tracking devices have allowed for great advances in wildlife conservation, making the implementation of RTVF an increasingly realistic management strategy. There are at least 18 companies that produce satellite or cellular phone-based GPS collars for wildlife (Millspaugh *et al*., 2012), at least four of which have the capacity to be integrated into a RTVF system. Also known by telemetry companies as 'Geofencing' (http://www.lotek.com/geofencing.htm), technological and logistical limitations (see below) and low market demand restrict wide-scale use of virtual fencing (C. Kochanny, Lotek Wireless, pers. comm.). The first documented evaluation of

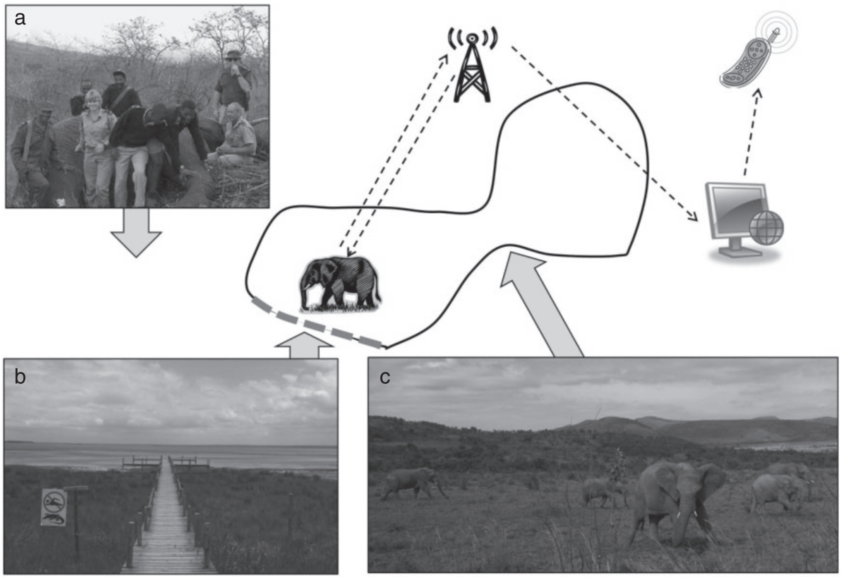

Figure 1 Diagram of real-time virtual fence system used for African elephants. A collar on an adult female member of each family group relays real-time coordinates of elephant locations via cellular phone network (GSM) to a master computer at 30 min intervals. When the elephant comes into close proximity or crosses a virtual boundary programmed into the computer, a text message is sent to the reserve managers. If the elephant has crossed the reserve boundary, a crew is sent to harass the animal back into the reserve or capture the animal for transportation (a). Virtual fences are particularly useful along water boundaries of reserves where fencing is difficult to establish due to changing water levels and the need to allow other animals access to water (b). Virtual fences can also be established within reserves to identify when elephants are utilizing corridors (c), and where and when human access should be restricted to avoid human-elephant conflict (Photograph a courtesy of Chantal Dixon, University of KwaZulu-Natal).

RTVFs on wildlife occurred on African elephants in Kenya (Box 1). More recently, the use of RTVFs has been expanded to the management of elephant populations in South Africa (Slotow, 2012; Fig. 1), suggesting there could be wider applicability of the product for use on other species and systems to mitigate human–wildlife conflict.

Conservation benefits of virtual fencing

Enhancing protected area management

Compared to traditional fences, virtual fences can allow for boundaries to be modified temporally and spatially based on specific conservation concerns. Protected area planning typically involves the delineation of hard boundaries often based on political or cadastral borders that, at their most extreme, are reinforced with traditional fences (Licht, Slotow & Millspaugh, 2008; Licht *et al*., 2010). Using virtual fences, it may be possible to move beyond hard and fixed boundaries to vary management based on individual landowner objectives and natural animal movement patterns (Slotow, 2012). Furthermore, within protected areas, virtual fences can be responsive, and more easily put in place for specific areas of management concern. For example, if managers are concerned by herbivore overuse of a small area, virtual fences could temporarily be put into place to discourage access and reduce the risk of habitat degradation (Lagendijk *et al*., 2011). Thus, because they can be altered over relatively short spatial and temporal scales, virtual fences provide a responsive and non-permanent tool for controlling animal movements to enhance protected area management (Box 1).

Integrating monitoring, research and management

Virtual fence management is readily suited to experimental manipulations that can be tested and refined in an adaptive management framework (Williams, 2011). Optimal management strategies can be developed for a specific population or protected area through experimentation with aversive conditioning by means of biological, sensory or proximity-based virtual fences, individually or in combination (Shivik, 2006). Through RTVFs in particular, managers can gain detailed monitoring records of animal movement that are well suited to adaptive management programs, and that can enable improved protected area management (Box 1). In addition to managing terrestrial wildlife within protected areas, conservation of larger-scale processes like migration of terrestrial and avian species could also be enhanced through the use of remotely monitored virtual fence systems, by allowing managers to monitor, identify and prioritize conservation actions at fine spatial and temporal scales along migratory routes (Box 2).

Box 2: Use of real-time virtual fences to conserve long-distance movements and migratory behavior

Protecting large, landscape-scale movement of wildlife populations is one of the most pressing conservation concerns (Milner-Gulland, Fryxell & Sinclair, 2011). For avian species in particular, there is increasing concern over the impact of wind farm development (Fig. 2) along migratory routes (Arnett *et al.*, 2011; de Lucas *et al.*, 2012; Piorkowski *et al.*, 2012). While individuals of many avian species are too small to sustain current real-time animal tracking technology, many large raptors are of sufficient size. However, to date, use of GPS satellite tracking has only been used in retrospective analyses of movement pathways, perch sites and roosts (García-Ripollés, López-López & Urios, 2011; Cogan *et al.*, 2012), or in predictive models of impacts to species (Katzner *et al.*, 2012). While these approaches inform management decisions about the placement of wind turbines, the use of real-time virtual fencing could be used to develop more flexible, or adaptive, management plans. For example, using real-time satellite tracking of California condors (*Gymnogyps californianus*), managers could be informed when condors are approaching and likely to fly through an area containing wind energy turbines, allowing managers to slow or shut down turbine blades and limit collision risk to this extremely rare species.

Figure 2 Wind energy turbines, like those pictured here in Judith Gap, Montana, can be 79.9 m tall with blades 38.4 m in length. At this size, the tips of blades can travel at up to 379.8 km h^{-1}. Often clustered to form 'wind farms,' these structures cause collision risk for a variety of avian species (Piorkowski *et al.*, 2012).

Social-psychological benefits

There are many social-psychological benefits of virtual fences that are likely to attract and reconnect people with wildlife. Firstly, a key social-psychological benefit is that there is no need for traditional fences and the visual and emotional problems that accompany them (Kotchemidova, 2008). Secondly, similar to use of traditional fencing in mitigating human conflict with large herbivores and predators (Hayward *et al.*, 2007), virtual fences could be used to restore and conserve these frequently threatened or controversial species within protected areas (Slotow, 2012). In addition to ecological benefits, the presence of these species could increase tourism and public support for conservation (Hayward *et al.*, 2007). For RTVF systems in particular, the availability of real-time animal locations can facilitate human-wildlife interactions, providing managed viewing opportunities as well as helping to mitigate potentially dangerous interactions (Slotow, 2012).

Challenges, limitations and technological needs for virtual fencing

Behavioral challenges

A key element of virtual fence efficiency is the training of individual animals (and in some cases social groups) to understand and obey boundaries without the need for repeated management action or aversive training (Umstatter, 2011). In domesticated livestock operations where virtual fencing is practiced, livestock training is important for reducing the need to aversively condition animals over the long term (Anderson, 2007; Umstatter, 2011). While there is evidence that wild animals can adjust their movements over time as they learn boundaries (Druce, Pretorius & Slotow, 2008), the ability to apply effective virtual fences is likely species-specific and depends on behavioral considerations, such as dispersal ability, longevity and social structure (Anderson, 2007). Species that have tight social structures, such as elephants, are ideal for virtual fence designs because a single satellite transmitting collar on the matriarch or a high-ranking female represents the larger family group's movements (Jachowski, Slotow & Millspaugh, 2012). Similarly, most primate species live in groups and could benefit from virtual fencing technologies where they are considered urban or agricultural pests that are otherwise most commonly controlled by lethal means (Wallace & Hill, 2012). By contrast, species with less structured social hierarchies and that produce many offspring and live only a brief period of time are less suitable to manage with virtual fences due to difficulty in capturing, tracking and training many individuals over a relatively short time period. Thus, virtual fence management is best suited to slowly reproducing, long-lived and group-living species with overlapping generations.

Technological limitations

While all virtual fence techniques require some further refinement on a species-by-species or case-by-case basis, both proximity-based and real-time tracking collars in particular face a number of technological obstacles prior to their wide-scale use. Despite the use and continued development of satellite and cellular phone-based tracking systems in wildlife biology over the past 25 years, and recent technological advances and proposals for GPS transmitters as small as 5 g in the next few years (Pennisi, 2011), only recently have proximity-based and RTVF concepts been used by conservation managers in restoring and conserving wildlife. Most sensors that provide continuous tracking needed for RTVFs require large batteries or those that can recharge (Millspaugh *et al*., 2012). Therefore, the first criterion to consider is the size of the individual that can be monitored without the attached sensor having a negative physiological, behavioral or demographic effect (Moll *et al*., 2009).

Provided the appropriate technology exists for a specific species of concern, RTVFs still face data acquisition and management limitations shared by other global positioning systems (Tomkiewicz *et al*., 2010). Use of satellite-based real-time tracking systems often requires paying the cost of data acquisition from telemetry companies (although this cost is reduced when using cellular phone-based systems or systems that allow managers to alter the interval at which locational fixes are collected). Once data are acquired, RTVF systems require the development of reliable and accessible data management and analysis tools capable of relating spatial locations to predefined virtual boundaries either through the use of a telemetry company, or the use of a computer base station with Geographic Information System mapping capabilities (Box 1). Finally, because RTVF systems provide only a warning message to managers, they must be paired with increased on-the-ground management action.

Social-psychological concerns

While there are clear social-psychological conservation benefits to establishing virtual fencing, there are drawbacks compared to traditional fencing (Table 2). The most marked distinction is that traditional fencing not only serves as a physical barrier, but as a visible and culturally recognized barrier between humans and wildlife (Lindsey *et al*., 2012). For potentially controversial and dangerous species, such a barrier is critical to maintaining public support for conservation within protected areas (Licht *et al*., 2008, 2010). Therefore, any attempt to remove traditional fencing, or to manage species without traditional fencing in favor of virtual fences, would need to be preceded by extensive public outreach and the development of a response management plan with explicit guidelines on when, where and how virtual barriers will be enforced (Slotow, 2012). Conversely, traditional fencing helps psychologically or physically to keep people out of sensitive protected areas or away from species of conservation concern (Hayward & Kerley, 2009; Lindsey *et al.,* 2012). Thus, replacement of traditional fences with virtual ones could have unintended negative effects that should be considered, and requires education campaigns to inform the public of the effectiveness of virtual fences and the consequences of not having a traditional physical barrier on the ground.

In addition to social-psychological concerns for protected areas, it is important to consider the costs and benefits to animal welfare associated with virtual fencing. While virtual fences alleviate concerns about the ability of target and non-target species to move 'freely' (Slotow, 2012), there are welfare issues associated with attaching collars or otherwise marking animals (Hayward *et al*., 2012). The placing of collars containing proximity detectors or tracking devices on animals also has social implications for how we view wildlife as distinct from domesticated animals (Benson, 2010). Attaching equipment to wildlife and tracking their movements requires managers to further blur the line between the hands-on approach taken with domestic livestock and the traditional hands-off approach to managing 'natural' or 'self-sustaining populations' of wildlife as currently practiced by the National Park Service in the United States and other organizations worldwide (Licht *et al*., 2008). Furthermore, tourists may complain about 'visual pollution' of having collars on animals they are photographing. However, while attachment of satellite transmitters to animals likely elicits a feeling in the public that some of the uncertainty inherent in 'wild' animal behavior is removed, this loss has to be weighed against the considerable 'visual pollution' created by traditional fencing (Hayward & Kerley, 2009, p. 7).

Conclusions and future directions

Given that most species of wildlife occur in an increasingly human-dominated landscape, proactive, or at least responsive, conservation and management plans need to be put in place to ensure their persistence. For management of terrestrial species, the construction of traditional fences can be an effective solution to localized problems, particularly when management resources are limited and there is high risk of human–wildlife conflict (Hayward & Kerley, 2009). However, despite the creation of a physical barrier, all fencing is temporary, requiring regular maintenance and support from surrounding human communities to enforce such boundaries over the long term (Hayward & Kerley, 2009). In contrast to traditional fences, all virtual fence techniques present key benefits associated with integrating monitoring, research and management action that could enhance wildlife population and protected area management (Table 2). Furthermore, because virtual fences are inherently temporary and adaptable, their use requires managers, land owners and the broader public to think more deeply and pragmatically about wildlife boundaries and management. Thus, while in some cases wildlife conservation must involve physical barriers, virtual fencing is likely to be a more socially responsible and forward-thinking technique for management of wildlife within and around protected areas.

The two areas of greatest promise and in need of further research are the simultaneous use of multiple virtual fence techniques, and the use of real-time technology to monitor permeable barriers. For some species, the use of virtual fencing techniques that involve multiple sensory deterrent cues (Walter *et al*., 2011) or linking those cues with real-time tracking collars (Lee *et al*., 2009) can be used to improve the ability of virtual fences to deter wildlife movement. However, in some instances, sensory deterrent cues are only effective when implemented individually (Davies *et al*., 2011). Therefore, future research is needed to identify optimal strategies for implementing virtual fencing programs that use either individual cues or multiple cues specific to a particular site or suite of species.

The implementation of RTVFs and remote monitoring of permeable barriers in particular, represents the potential for a new 'virtual management' era in wildlife conservation, where it is possible to initiate management actions promptly in response to real-time data. With these techniques, conservation managers have a new tool that has a number of ecological, social and management benefits over traditional barrier fences (Table 2). However, the application of these new techniques has been limited to a few parks and reserves (Box 1). We still have a limited understanding of the long-term feasibility of these methods, as well as potential species-specific behavioral challenges that they face (Table 2). Furthermore, it remains to be seen how the public perceives, and if they are likely to support, these virtual management techniques.

Conservation practitioners need to carefully consider the costs and benefits of any fencing approach when attempting to address management concerns (Tables 1 and 2), taking into account species- and site-specific factors. Both traditional and virtual fence approaches come with considerable costs, but the nature of those costs varies between techniques (Table 2). Traditional fences have significant costs associated with ease of creation and maintenance, impacts on non-target species and public opinion; but are relatively easy to enforce and comparatively long-lived in comparison to virtual fences. By contrast, virtual fences are often easy to initiate and reduce negative impacts on non-target species, but require extensive maintenance or intervention to maintain (Table 2). Collectively, while considerable technological, logistical and social obstacles remain to be addressed, the use of virtual fences is likely to increase in popularity and become a realistic strategy for managing and restoring wildlife.

Acknowledgments

We are grateful to C. Kochanny and J. Roth for insights into the current state of real-time animal tracking. We acknowledge the contribution to our thinking from the management teams of iSimangaliso Wetland Park, Ithala Game Reserve, Tembe Elephant Park and Phinda Private Game Reserve, in development of ideas about virtual and permeable fencing. Martin and Sophie Haupt from Africa Wildlife Tracking helped develop their virtual fence systems. We thank the University of KwaZulu-Natal, University of Missouri, and Virginia Polytechnic Institute and State University for their support. We are grateful to D. Atwill of Columbia, Missouri, USA, for introductions leading to collaborative research between the Universities of Missouri and KwaZulu-Natal.

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