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Review

Toward Best Management Practices for Ecological Corridors

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Abstract: Ecological corridors are one of the best, and possibly only viable, management tools to maintain biodiversity at large scales and to allow species, and ecological processes, to track climate change. This document has been assembled as a summary of the best available information about managing these systems. Our aim with this paper is to provide managers with a convenient guidance document and tool to assist in applying scientific management principles to management of corridors. We do not cover issues related to corridor design or political buy in, but focus on how a corridor should be managed once it has been established. The first part of our paper outlines the history and value of ecological corridors. We next describe our methodologies for developing this guidance document. We then summarize the information about the impacts of linear features on corridors and strategies for dealing with them—specifically, we focus on the effects of roads, canals, security fences, and transmission lines. Following the description of effects, we provide a summary of the best practices for managing the impacts of linear barriers. Globally, many corridors are established in the flood plains of stream and rivers and occur in riparian areas associated with surface waters. Therefore, we next provide guidance on how to manage corridors that occur in riparian areas. We then segue into corridors and the urban/suburban environment, and summarize strategies for dealing with urban development within corridors. The final major anthropic land use that may affect corridor management is cultivation and grazing agriculture. We end this review by identifying gaps in knowledge pertaining to how best to manage corridors.

Keywords: ecological corridors; conservation corridors; wildlife; management; conservation biology; urban/agro-ecology

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1. Introduction

An ecological corridor or linkage is a swath of natural land, or stepping stones of natural land, that is conserved to enhance the ability of plants and wildlife to move among larger habitat patches [1–7]. The term linkage is commonly used to refer to a connectivity area with multiple strands, whereas the term corridor suggests a single conduit. In this paper, we use both terms interchangeably except when one is clearly more appropriate. Previous reviews have summarized design of connectivity areas [4,8–10], and strategies to encourage local land use, transportation, and open space planning agencies to adopt connectivity conservation plans [11]. In this paper, we will not cover issues related to design and agency buy in, but will focus on how a corridor should be managed once a design has been implemented. Each linkage design is simply a hypothesis that conserved swaths of natural or semi-natural land will promote wildlife and plant movement at a sufficient level to allow plants and wildlife to maintain genetic and population vigor, recolonize connected habitat blocks after local extinction, and shift ranges in response to climate change [5,12]. It will take decades to collect strong evidence to test these hypotheses [6,13], and we suspect the answers will be "it depends on how the linkage was managed." Our goal in this paper is to recommend management practices that will most likely result in successful corridors.

In deriving our recommendations, we draw upon studies of animal behavior, gene flow, and ecological response to human alterations of the landscape.

The history of conservation linkages is rooted in the Theory of Island Biogeography [13], which first noted that there was a linear relationship between the number and diversity of species on the islands of Hispaniola and island size and proximity to the mainland. Diamond [14] applied this species–area relationship to nature reserve areas on terrestrial landscapes, hypothesizing that corridors connecting otherwise isolated nature reserves in terrestrial landscapes would help conserve biodiversity. As confirmatory experiments and observations accumulated [15], over 300 plans to conserve land for ecological corridors have been developed and at least partially implemented around the world (Keeley et al. 2019). However, there has been little guidance on how those corridors should be managed, hence the reason for this compendium on best practices in corridor management.

Conserving a linkage is rarely as simple as acquiring title or easement to the land and prohibiting further land transformation. For example, 100% of 27 linkage designs in Arizona [15,16] and California's south coast [17] are crossed by linear barriers such as highways, canals, and international borders that must be mitigated. Similarly, most linkage designs include areas used for livestock grazing, water extraction, agriculture, rural residences, and timber harvest, and all are used for human recreation. Linkages typically have a high edge to area ratio, often due to islands of urban land in between or within the linkage (e.g., Figure 1). Despite these modifications and edge effects, these land uses must be realized and managed to sustain connectivity [18].

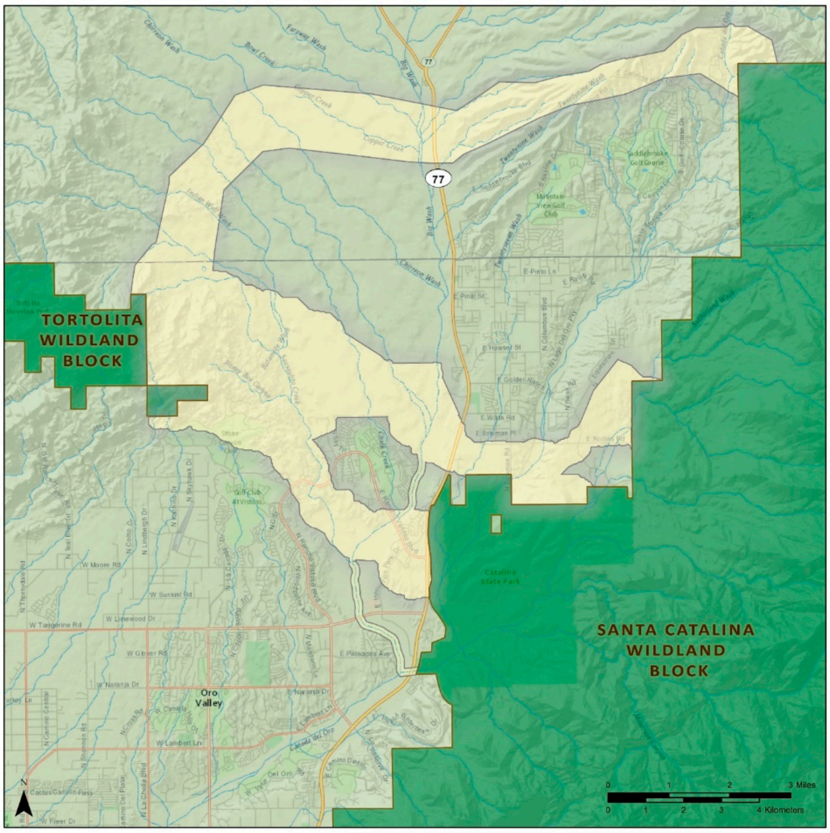

Figure 1. Three stranded corridors (light tan areas) between the Tortolita Mountains and the Santa Catalina Mountains protected areas (dark green areas). This linkage will maintain connectivity between the protected wildland blocks while rapid urbanization north of Tucson, Arizona occurs; virtually all of the gentle terrain between the two mountain ranges is open to residential and urban development, which will abut all strands of the corridor within 30–40 years, given current expansion rates. The design was made to meet the needs of nine focal species. The narrow north–south corridor bands provide riparian connectivity. Like almost every corridor, a highway crosses this one.

In this paper, we summarize management practices that, based on scientific evidence, are likely to conserve or enhance movement and gene flow for plants and animals inhabiting designated ecological corridors (Table 1). We organize our recommendations around four themes, namely mitigation of human-created linear barriers such as roads and canals (Section 3); management of streams, rivers, and riparian areas (Section 4); management of urban, suburban, and industrial land uses in or near corridors (Section 5); and management of agricultural lands in or near corridors (Section 6). Our primary objective is to provide managers, planners, and landowners with the best information available (Sections 3–7). Our second objective is to highlight issues for which additional empirical evidence is needed to inform corridor management (Section 7).

Table 1. Summary of best management practices for conservation linkage management.

Section 3. Recommendations for Human-Created Linear Barriers Crossing Corridors

1. Avoid building roads, canals, or railroad tracks in linkages and avoid having these infrastructures bisect linkages whenever possible.
2. When roads are unavoidable, use speed abatements to reduce traffic speed within and adjacent to corridors.
3. Use seasonal road closures during critical wildlife life history periods.
4. Reduce or eliminate artificial lighting.
5. Provide a variety of safe crossing structures over or under roads, railways or canals, and whenever possible maintain natural vegetation in the structure.
6. Ensure the protective fencing prevents wildlife from accessing the road/railway or canal interior while simultaneously funneling wildlife to a safe crossing structure.
7. Maintain high-quality natural areas on either end of crossing structures.
8. Aside from protective fencing along roads, rails and canals, ensure that all other fencing within the ecological corridor is wildlife friendly and clearly marked with safe deterring markers.
9. Provide safe drinking water sites near canals/aqueducts to avoid wildlife seeking to access water in unsafe canals/aqueducts.

Section 4. Recommendations for Streams and Riparian Zones

1. Maintain dams and impoundments to ensure that they are functioning properly.
2. Manage the release of water from the impoundment to mimic the natural water cycle of the stream, and to prevent scouring floods.
3. Ensure that water levels below the impoundment are maintained at a level that supports natural vegetation growth.
4. Provide riparian zone buffers.
5. Actively remove invasive species using chemical or mechanical means as necessary.

Section 5. Recommendations for Urban and Suburban Development in Corridors

1. Whenever possible, avoid urban development within the linkage design.
2. Minimize the road infrastructure associated with urban development within or adjacent to the linkage.
3. Strive to maintain residential parcel sizes >20 ha.
4. Use signage and education to explain the value of the linkage and encourage good stewardship by visitors
5. Minimize artificial lighting.
6. Discourage wildlife feeding on trash or other practices that attract animals to unsafe areas or disrupt natural communities.
7. Encourage a leave-no-trace ethic associated with recreational use of the linkage.
8. Reduce use of fertilizers and pesticides on urban lawns.
9. Encourage good pet ownership to reduce domestic animal damages to wildlife within the linkage.

Section 6. Recommendations for Agricultural Development Within Corridors

1. Encourage limited use of herbicides, pesticides, and rodenticides.
2. Use controlled burns or mechanical methods to remove debris from the corridor.
3. Use conservation easements or other incentives to promote appropriate practices on land adjacent to the linkage.
4. Use available government programs to help restore and manage natural vegetation within the linkage.
5. Encourage good ranching husbandry practices to reduce livestock depredations, and consider payment programs to compensate producers for livestock losses from wildlife.
6. Reduce or eliminate grazing within or adjacent to the linkage.

Table 1. *Cont.*

Section 7. Knowledge Gaps, Summary, and Conclusions
1. Do synurbanized wildlife alter human x wildlife x domestic animal x landscape interactions and to negatively affect linkage functionality? 2. How wide do corridors need to be for a given length to ensure functionality? 3. What human activities within or adjacent to the linkage are compatible with linkage functionality? 4. What, if any, time lags occur between human activities and the effects of those activities on linkage function? 5. What state and national level polices best promote successful linkage designs?

2. Methods

We searched for relevant literature (books, peer-reviewed articles, white papers, linkage designs, and theses) using Cambridge Scientific Abstracts, ISI Web of Science, and Google Scholar, searching various combinations of keywords related to roads, canals, railroads, fences, border security, rivers, streams, riparian areas, urbanization, artificial night lighting, livestock grazing, and agriculture in combination with keywords related to biodiversity, conservation, linkages, and corridors. Citations in these documents yielded additional literature. We last searched for literature on 17 April 2020.

We used this literature to recommend management practices for human-created linear barriers, streams and riparian areas, and farms in and near corridors, to conserve connectivity and ecosystem processes. The most effective recommendation would be to "remove all roads, canals, and human land uses, and retain and restore all streams and riparian areas in the corridor." Because such a recommendation is impractical, we took a precautionary "*no regrets*" approach by making recommendations that least restrict human land use and are likely to conserve connectivity, while assuming relatively high estimates of the impacts of human land alterations on wildlife movement. We avoided the alternative strategy of making recommendations that would succeed only under the lowest estimates of such impacts.

3. Recommendations for Human-Created Linear Barriers Crossing Corridors

Linear structures such as highways [19], canals [20,21], and utility lines can impede corridor utility if they cross a corridor and are not mitigated. These structures cause fragmentation primarily through behavioral avoidance and mortality. Linear barriers can break large habitat areas into small, isolated habit patches which support few individuals; these small populations lose genetic diversity and are at greater risk of local extinction [22,23]. Although fragmentation effects are most severe for wide roads with heavy high-speed traffic, some mammals avoid crossing two-lane roads with <100 slow-moving vehicles/day [24], and some birds may avoid crossing electric transmission lines [25]. These linear features impede movement of animals, and movement of plants that depend on animals to transport their propagules. Here we consider roads (with special measures regarding highways), canals, fences, border security barriers, and transmission lines. We assume that our recommendations on highways also apply to railroads.

3.1. Influence of Roads

High vehicle traffic in potential linkage areas increases the mortality and repellent effect of the road system [26–35], resulting in roads causing considerable loss and fragmentation of habitat. For example, the U.S. has approximately 6.5 million km of roads, covering approximately 1% of the nation's land surface [25]. However, the spatial extent of road impacts is much larger due to mortality on highways, barrier effects that fragment habitat, accumulation of road salts and other pollutants, and animal avoidance of road noise and vibrations.

Road mortality (road kill) occurs when animals die in collisions with vehicles. These collisions kill between 89 million and 340 million birds annually on US roads [31], and may contribute to global declines of insect populations [27]. In one desert ecosystem, at least 22.5 snakes were killed by vehicles per road kilometer per year [28], but no reliable, large-scale roadkill estimates exist for amphibians, reptiles, and small mammals. The best information regarding impacts of roads comes from studies of large mammals. Roadkill can have severe impacts on wide-ranging animals that occur in low population densities, such as the cougar in southern California [29–31], the Florida panther [32], the ocelot in south Texas [27], and the Iberian lynx [34].

Roads can also significantly affect animal communication. Road noise and vibration interfere with the ability of reptiles, birds, and mammals to communicate, detect prey, or avoid predators [36]. The intensity of these impacts is related to traffic volume and speed [37]. For example, some reptiles (which "hear" ground-transmitted vibrations through their jaw [38,39]) are repelled even from low-speed 2-lane roads, resulting in reduced species richness [40].

In addition, wildlife fencing along roads (meant to reduce wildlife road collisions), increase the barrier effects of roads and result in greater fragmentation impacts associated with roads. Road surfaces act as heat traps, which may attract certain reptiles species seeking basking sites [29]. Roads often increase the spread of exotic plants, promote erosion, create barriers to fish, and pollute water sources with roadway chemicals [25,41,42]. Vehicles can deposit 300 to 800 exotic seeds per square meter per year to roadside areas, often from several kilometers away [43]. Highway lighting causes some animals to avoid areas near roads [44]. Together, these road effects cause animals to avoid crossing roads (thus increasing fragmentation), increase animal mortality (indirect roadkill), and reduce access to otherwise usable habitat.

3.2. *Influence of Canals on Connectivity and Ecosystems*

Canals are typically a nearly-complete barrier to wildlife movement because they are often bordered by tall chain-link fences, have nearly vertical concrete sides, and are filled with swiftly-moving water that is often >2 m deep and >10 m wide. Such a configuration is almost certainly a complete barrier for all or almost all reptiles, non-flying mammals, and non-flying invertebrates (Figure 2).

Figure 2. Canal in the Mojave Desert of California showing wildlife-proof protective fencing along the edges. Photo taken from a road across the canal.

Canals can cause linear discontinuities in natural land cover, and also kill some animals, such as small animals that can pass through chain-link fences to drown in the canal. Where fences are absent or breached, large mammals such as desert mule deer, bighorn sheep, and pronghorn drown in canals [45].

3.3. Influence of Border Security Structures on Connectivity and Ecosystems

Security measures at national borders include roads, fences, walls, bright outdoor lighting, vegetation clearing, and increased human activity. In some cases, the eventual abandonment of these measures may improve wildlife habitat and connectivity over the long term, such as the EU Greenbelt that now exists along the former Iron Curtain [46], and the demilitarized zone between North and South Korea. These promote connectivity because semi-natural conditions flourished in the 1 to 25 km wide "*no man's lands*" between border fences [46]. In other instances, such as along parts of the U.S.–Mexico border and India–Pakistan border, fences impede movement for some species resulting in population subdivision [47–49].

3.4. Influence of Other Transmission Lines and Livestock Fences on Connectivity

Collision and electrocution with electrical transmission lines and entanglement in livestock fences are significant sources of mortality for some species [50,51], even for short distribution lines [32]. By providing perches for raptors, powerlines and fences likely cause local decreases in some raptor prey, although rigorous studies of population impacts are lacking. Moreover, powerlines in rural areas typically maintain a clear right of way 30–60 m wide, with width increasing with voltage, to reduce risk of fire. This can enhance the perceived or actual barrier effect of the powerlines. Wind turbines and the associated infrastructure with wind parks may also have an impact on wildlife corridor efficacy due to avoidance behavior by some wildlife species [52].

Fences are barriers that can enhance the fragmentation impacts of the road, or cause direct mortality when wildlife are ensnared trying to cross the fence [19]. Although strips of natural vegetation along fencerows can enhance connectivity for some species [53], livestock and property boundary fences impede movement of many species [54].

3.5. Avoid Building Roads in Corridors

Clearly, the best way to avoid the barrier effect of roads is to avoid building roads in wildlife corridors. An unmitigated major road crossing a corridor might render it unusable for some species [55]. Small roads that do not create significant barriers, can degrade habitat as road density increases. For example, Mladenoff et al. [56] suggested that road densities >0.6 km/km^2 render landscapes inhospitable to wolves, and suggested that road avoidance behavior has removed >10.9 million ha of potential elk habitat in the U.S. [57].

3.6. Minimize Artificial Lighting on Roads That Pass through the Linkage Design

It is a best practice to avoid artificial lighting, because artificial lighting has been shown to disrupt natural daily, seasonal, and lunar light cycles as experienced by a diversity of organisms, leading to altered cues for the timings of many biological activities [58]. If lighting is deemed necessary in an area, the following guidelines will limit impact on wildlife: (i) dim lighting (reducing the intensity of artificial lighting to optimize the balance between what is required for human activities and deterioration of the natural nighttime environment); (ii) part-night lighting (switching off lighting when use is low/motion activated lighting); (iii) change the spectra of the lighting (avoid blue light emissions); (iv) minimize light trespass (improving the design and use of light sources so as to direct artificial light where it is actually required and to prevent it from being directed elsewhere [59]).

3.7. Reduce Vehicle Speeds on Roads in Corridors

As vehicle speed decreases, roads pose less of a barrier to wildlife movement and areas near roads are less avoided by wildlife [25], in part due to less noise and vibration [40]. For many animals, speed has a greater effect on mortality and avoidance than traffic volume [19]. Vehicle speed and collisions with wildlife can be reduced by making roads narrower, using traffic-calming devices (curves, bumps), and installing more road signs (speed limit signs, wildlife crossing signs) per unit of road length [57]. If periods of high vehicle traffic coincide with peak periods of animal activity (e.g., large mammal migrations), lowering speed limits during peak activity, installing temporary road signs that warn drivers of animal activity, or installing speed bumps in key sites will alert drivers to be more cautious and careful driving through these areas [60]. To the extent that it is socially or politically practical, the size and types of vehicles allowed to utilize roads within a corridor should be limited, and seasonal road closures during critical breeding and dispersal periods should also be considered [3,7,19].

3.8. Raise the Highway Bed above the Surrounding Terrain to Minimize Road Kill and Direct Animals toward Crossing Structures

Clevenger et al. [60] found that vertebrates were 93% less susceptible to road kills on sections of both 2-lane and 4-lane highways raised on embankments, compared to segments at the natural grade of the surrounding terrain. Raised sections of road can funnel animals toward crossing structures. Raised road beds require less maintenance than wildlife fencing.

3.9. Design Highway and Canal Crossing Structures Specifically to Provide for Animal Movement

There are two general classes of wildlife crossing structures: *overpasses* (sometimes also referred to as green bridges or faunal passes) and *underpasses*. Wildlife overpasses (sometimes also referred to as green bridges or faunal passes), bridges, culverts, and pipes. While many of these structures were not originally constructed with ecological connectivity in mind, many species benefit from them [25,61]. Clevenger and Huijser [62] provide detailed recommendations on planning, placement, and design of crossing structures. In Banff National Park, Alberta, grizzly bears, wolves, and ungulates (bighorn sheep, deer, elk, and moose) prefer overpasses to underpasses, while species such as mountain lions and black bear prefer underpasses [63]. Here we describe important considerations for managers developing both types of structures.

Wildlife overpasses are typically 30 to 50 m wide, but can be as wide as 200 m. Wildlife underpasses include viaducts, bridges, culverts, and pipes, and are often designed to allow water to flow beneath highways. A bridge is a road supported on piers or abutments above a watercourse or ravine, whereas a culvert is a round or rectangular tube under a road. The most important difference is that the streambed under a bridge is mostly native rock and soil, instead of concrete or corrugated metal as in culverts, and the area under the bridge is large enough that a semblance of a natural stream channel and riparian vegetation typically returns a few years after construction, even when rip-rap or other scour protection is installed to protect bridge piers or abutments. In contrast, vegetation does not grow inside a culvert, and hydrology and stream morphology are permanently altered, not only within the culvert, but for some distance upstream and downstream from it.

Most ungulates will not use culverts, but readily pass under tall bridges with long spans [64,65]. Because most small mammals, amphibians, reptiles, and insects need vegetative cover for security, bridged under-crossings should extend to uplands beyond the scour zone of the stream, and should allow enough light for vegetation to grow underneath. In the Netherlands, rows of stumps or branches under crossing structures have increased connectivity for smaller species crossing under bridges on floodplains [25]. Because traffic noise within an under-crossing discourages use by ungulates [66], new designs should minimize vehicle noise in underpasses. Ungulates prefer under-crossings with a high openness ratio (height x width divided by length) and sloped earthen sides (instead of vertical concrete sides) [67].

Despite their disadvantages, well-designed and located culverts can mitigate the effects of busy roads for small- and medium-sized mammals [61,68], including mice, shrews, foxes, rabbits, armadillos, river otters, opossums, raccoons, ground squirrels, skunks, coyotes, bobcats, mountain lions, black bear, long-tailed weasel, amphibians, lizards, snakes, and frogs [64,65,69,70]. In locations where the floor of a culvert is persistently covered with water, a concrete ledge above water level can provide terrestrial species with a dry path through the structure [71]. It is important for the lower end of the culvert to be flush with the surrounding terrain. Many culverts are built with a concrete pour off of 8–12 inches, and others develop a pour-off lip due to scouring action of water. A sheer pour off of several inches makes it unlikely that many small mammals, snakes, and amphibians will find or use the culvert. Culverts intended to promote wildlife passage should have both upstream and downstream openings flush with the surrounding terrain and native land cover.

The best crossing structure for a canal is to bury segments of the canal below ground. For narrow canals, such as those irrigating fields, it may be cheaper to cover the canal with metal or concrete slabs, and cover these plates with soil and vegetation. To prevent damage from natural floods, many canals often include a buried siphon to convey water under a natural watercourse; these siphon gaps create opportunities for wildlife to cross the canal. Siphons intended for wildlife use should create a passageway at least 40–50 m wide that has natural vegetation and follows the natural grade of the surrounding landscape.

3.10. Build Multiple Types of Crossing Structures Spanning Highways and Canals to Provide Connectivity for All Species, Preferably with Appropriate Structures No More Than One Home Range Width Apart

Viaducts (bridges that span an entire valley), long railroad or highway tunnels, and long canal siphons can support movement by all wildlife species in an area. For sections of linear barriers where such structures cannot be built, it may be necessary to build different types of structures to accommodate all species [61,63,68,72,73], including wildlife overpasses for ungulates, underpasses such as large box culverts for bears and felids [74], and pipe culverts from 0.3 to 1 m in diameter for small mammals [61,68].

Because most reptiles, small mammals, and amphibians have small home ranges, Clevenger et al. [61] recommend culverts at intervals of 150–300 m. For ungulates and other large mammals, Mata et al. [74] and Clevenger and Wierzchowski [75] suggest that bridges or wildlife overpasses should be located no more than 1.5 km apart. Although these spacing guidelines are ideal, we believe they can be relaxed in areas where the more widely-spaced structures connect to large intact habitats on both sides of the linear barrier in such a way that genetic and demographic connectivity can be maintained.

3.11. Maintain Suitable Habitat on Both Sides of Highway and Canal Crossing Structures

Suitable habitat should occur on both sides of the crossing structure [64,76,77]. This applies to both *local* and *landscape* scales. At the local scale, vegetative cover should be present near entrances to give animals security, and to reduce negative effects of lighting and noise [61,68,72]. At the landscape scale, for key focal species, it may be important to manage vegetation, land use, and human behavior to ensure that individuals from nearby population centers can reach the structure [63].

Whenever possible, suitable habitat should occur *within* the crossing structure. This can best be achieved by having a bridge high enough to allow enough light for vegetation to grow under the bridge, and by making sure that the bridge spans upland habitat that is not regularly scoured by floods. Where this is not possible, rows of stumps or branches under large-span bridges can provide cover for smaller animals such as reptiles, amphibians, rodents, and invertebrates; regular visits are needed to replace artificial cover removed by floods. Within culverts, mammals and reptiles prefer earthen to concrete or metal floors.

In the southwestern US, most box culverts smaller than 2.4 × 2.4 m have large accumulations of branches, Russian thistle, sand, or garbage (Beier, personal observation). Structures should be monitored for, and cleared of, obstructions such as detritus or silt that impede movement of small mammals, carnivores, and reptiles [67,69].

Clevenger and Waltho [63] suggest that human use of crossing structures should be restricted and foot trails relocated away from structures intended for wildlife movement. However, a large crossing structure (viaduct or long, high bridge) may be able to accommodate both recreational and wildlife use. Furthermore, if recreational users are educated to maintain utility of the structure for wildlife, they can be allies in conserving wildlife corridors. At a minimum, nighttime human use of crossing structures should be restricted.

3.12. Use Fencing along Highways and Canals to Keep Animals off the Roadway and Funnel Them toward Crossing Structures

Fencing should never block entrances to crossing structures, and instead should direct animals toward crossing structures [66,69]. In one study, such funnel fencing reduced roadkill by 93.5% and increased the number of species using the culvert from 28 to 42 [70]. Fences, guard rails, and embankments at least 2 m high discourage animals from getting on roads [21,77,78]. For animals that cross such fencing, one-way escape ramps can prevent animals from being trapped on a road [25].

3.13. Provide Alternative Water Sources near Canals and Escape Structures along Unfenced Canals

To discourage wildlife from attempting to drink water from a canal, some water should be diverted to catchments where wildlife can drink without risk of drowning [45]. Cable-and-float directors in conjunction with stairs or ramps can allow ungulates and other species to escape. Rautenstrauch and Krausman [45] found that desert mule deer could swim an average distance of 947 m before escaping via escape structures, and recommended escape structures $\leq$2 km apart, with at least one structure upstream from hazards such as a siphon entrance.

3.14. Use Wildlife-Friendly Fencing

Highway fences should prevent wildlife from entering highways, as noted above. However, for fences used to mark grazing allotments, mark property lines, or keep livestock off rural roads, planners should: use wildlife-friendly fencing, raise the lower wire to allow wildlife to pass under the fence, and use flashing or other wildlife-friendly markings on the top wire to alert wildlife to the fences presence and dimensions [51]. Do not use flashing, fladry, or other wildlife markings on the lower wire of the fence, as this may be perceived by some species, in particular carnivores, as a barrier [79].

4. Recommendations for Streams and Riparian Zones in Corridors

Streams form natural corridors connecting most protected wildlands, provide travel paths required by many aquatic species, and are strongly preferred by most terrestrial wildlife species [80]. As such, perennial and ephemeral streams have strong positive influences on connectivity. The only potential negative impact is that a major river cutting across the main axis of the corridor could be a linear barrier for animals that cannot fly or swim across it.

In this section, we focus solely on streams that run along the long axis of a wildlife corridor and we give less attention to aspects of stream ecology, restoration, and conservation unrelated to connectivity. For example, we oppose actions that would dewater a stream, making it a less attractive wildlife travel route, but we do not advise against actions such as discharge of treated wastewater that extend the annual flow period of ephemeral streams, as long as it does not harm corridor function by; for example, creating perennial flow that allows invasive frogs to displace native amphibians.

4.1. Support Native Riparian Ecosystems along Streams

Minimize risk of scouring floods, reduce erosion, and support native riparian plants over invasive plant species. To preserve the ability of streams to promote animal movement along a corridor, we recommend five actions. First, maintain settling basins within the flood plains of dams to ensure they are present and functioning properly, and these should be required in upstream urban areas along tributaries to the riparian corridor so as to minimize risk of unnatural floods that would otherwise scour riparian vegetation in the corridor [81]. Flooding impacts stream morphometry in ways that make stream beds and adjacent land inhospitable to many wildlife species [82]. Second, use native vegetation to stabilize banks of riparian corridors to reduce erosion, and reduce siltation from adjacent agricultural or urban areas [83]. Third, in an intermittent reach with native amphibians, releases of treated wastewater should not create perennial flows that might disrupt the ability of the stream to support native wildlife. For example, in many streams of the western US, modified flow regimes have resulted in bullfrogs displacing native amphibians [84,85]. Fourth, manage flow regimes to favor native over invasive species. For example, in the western US, most spring soils favor native riparian trees over invasive tamarisk [86]. Fifth, manage groundwater pumping near the riparian corridor to maintain native riparian vegetation and natural duration of stream flow [86].

4.2. Create and Protect Buffer Regions of Natural Habitat Beyond the Riparian Zone

Buffer strips can protect and improve water quality, provide habitat and connectivity for many species, improve quality of life for human neighbors, and increase nearby property values [87–90]. Recommended buffer widths to sustain riparian plant and animal communities vary from 30 to 500 m [87,91–93]. At a minimum, buffers should contain the stream channel and the terrestrial landscape affected by flooding and elevated water tables. Wider buffers are needed to protect edge sensitive species; for example, Ficetola et al. [92] suggest that buffers for amphibians should protect 400 m wide swaths of suitable vegetation, that roads be minimized, and stream connectivity maximized within 1 km of the main channel. Thus, to support dispersal, gene flow, and meta-population stability of riparian zone wildlife and plants, we recommend delineating a buffer that extends a minimum of 200 m beyond the annual high-water mark on each side of the channel.

4.3. Maintain Biotic/Abiotic Interactions

Riparian zones contain a diverse array of species and environmental processes as a result of variable flood regimes, geographically unique channel processes, altitudinal and climate shifts, and drainage influences on the fluvial corridor [81]. As a result, riparian zones each support a unique community adapted to a particular riparian zone [94,95]. Many regulated rivers and streams are characterized by an inundated upstream region and a downstream reach with an unnaturally regulated flow. Such systems modify the riparian zone, increase salinity, and are ultimately more prone to invasion by exotic species [96]. For example, in Kansas, channelization reduced water flow along the Cimarron River and has led to the collapse of local plant biodiversity as a result of *Tamarix* species invasion [97]. Within the arid southwestern United States, riparian systems evolved with grazing and browsing pressure from deer and pronghorn antelope, which are highly mobile grazers and browsers. High-intensity livestock grazing by cattle poses a very different grazing pressure than native grazers and is a major stressor for riparian systems in hot southwest deserts [98]. Thus, livestock should be excluded from stressed or degraded riparian areas, and hydrologic management should strive to mimic natural flow regimes as best as possible.

4.4. Eradicate or Control Invasive Riparian Plants

Some invasive species in riparian corridors create significant ecological problems, such as tamarisk in the western US, which depletes soil water, displaces native species, increases sedimentation, and increases flood damage [99]. Additional work is needed to determine the extent to which such disruption reduces habitat connectivity for species that depend on displaced native riparian species. Removing stressors and reestablishing natural flow regimes can help restore riparian communities, but physical control of some persistent exotics is necessary ([83,98], but see [100]).

4.5. Enforce Existing Regulations

Finally, we recommend aggressive enforcement of existing regulations. Within the United States, the Clean Water Act of 1972, as amended in 2009, restricts dumping of soil, agricultural waste, and trash in streams and restricts the intensity of farming, mining, and building along streams and on floodplains. Adequate enforcement of these existing policies would go a long way toward improving riparian zone and stream habitat quality along corridors. In areas of the world where such policies do not exist, the enactment of policies that restrict the dumping of soil, human waste, and trash in streams, as well as policies which restrict the intensity of farming, mining, and building allowed along streams and on floodplains should be sought [101].

5. Recommendations for Urban and Suburban Development in Corridors

Today >80% of the world's population lives in urban and suburban settings [102,103]. Urbanization includes high-density and low-density residential areas, as well as factories, gravel mines, and shopping centers. In addition, many urban corridors are being designed and implemented after build out has occurred using least cost modeling to identify and link existing green infrastructure throughout the urban setting [104]. For example, the city of Shenzhen in Guandong, China used this approach to identify and protect a 9.53 km^2 ecological network embedded in a city of 10.37 million people [105]. While such approaches are beneficial, care needs to be taken when assessing the efficacy of such approaches, as centuries of urbanization can result in the urban green spaces being populated with urban adapted species and lead to a false sense of corridor success. In such instances, the goal of the corridor and selection of a suite of focal species should be carefully considered and articulated prior to corridor development.

Urbanization within a corridor stimulates development of a network of local roads. Rural subdivisions require more road length per dwelling unit than more compact residential areas. Increased vehicle traffic in potential linkage areas increase the mortality and repellent effect of the local road system [27,30,36]. For example, even low-speed 2-lane roads can have a severe repellent effect on reptiles and amphibians that "hear" ground-transmitted vibrations through their jaw [38,39].

Another way urbanization impacts corridors is through the removal and fragmentation of natural vegetation. CBI (2005) evaluated four measures of habitat fragmentation in rural San Diego County, namely, percent natural habitat, mean patch size of natural vegetation, percent core areas (natural vegetation > 30 m from non-natural land cover), and mean core area/habitat patch at seven housing density levels (Figure 3) [106,107]. Fragmentation effects were negligible in areas with $\leq$1 dwelling/80 acres, and severe in areas with $\geq$1 dwelling/40 acres [108]. Similarly, "ranchette" development (40 acre lots) in Colorado harbored eight non-native plants not found on nearby ranchlands or parklands of the same elevation and soil type [104]. The negative effects of urbanization were evident at housing densities as low as one dwelling unit per 40–50 acres. Wagner [109] observed similar effects of urban sprawl on wildlife in Texas. In Arizona, some species of birds [110] and lizards [111] were absent as housing density increased. Similar patterns were observed for birds and butterflies in California [112–114], birds in Washington state [114], mammals and forest birds in Colorado [115], and migratory birds in Ontario [116]. In general, housing densities below the 1 unit/>70 acres threshold had little impact on birds and small mammals.

Urban and rural development leads to increased numbers of dogs, cats, and other pets that act as subsidized predators, killing millions of wild animals each year [117,118]. Domestic dogs were detected at 65% and 35% of sampling locations respectively on ranchette developments in Colorado compared to <3% of sampling locations on working ranches and parks [119]. Subsidized suburban/urban native predators such as raccoons, foxes, coyotes, and crows, may exploit garbage and other human artifacts to reach unnaturally high density with negative impacts on native prey [118–120] and disease spread [104].

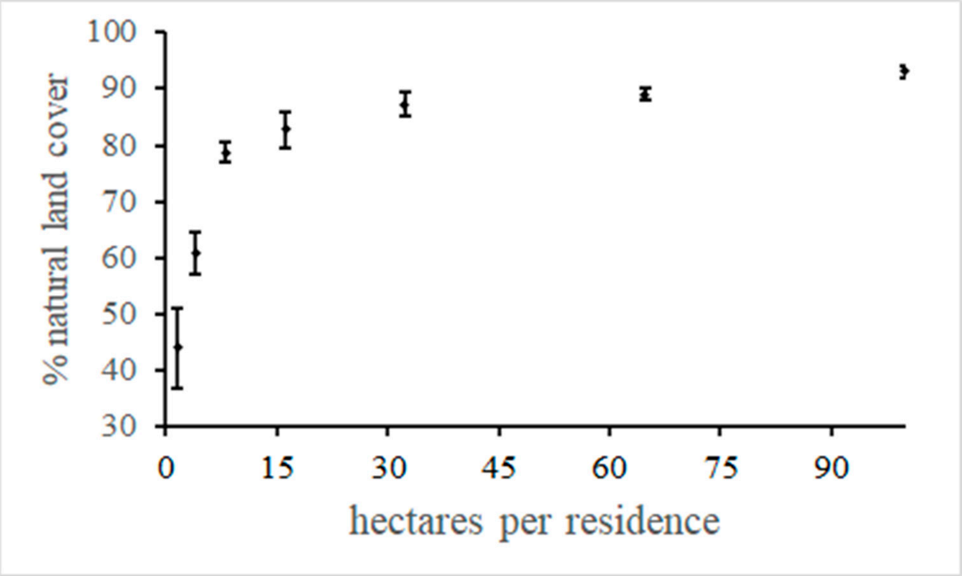

Figure 3. Percent natural land cover in relation to residential housing density in rural San Diego County, California, USA. The study excluded cells with orchards and farms to focus solely on the impact of single-family residences [121].

Urbanization can lead to increased numbers of wild predators removed for killing pets or hobby animals. Although exurban development may bring little increase in the number of depredation incidents per unit area, each incident is more likely to lead to death of predators because humans are emotionally attached to pets and prompt to notice loss or injury [122,123]. Orlando [123] found that pumas strongly avoided parcels less than 8 ha, preferred parcels greater than 16 ha, and experienced high mortality and conflict with hobby livestock owners on parcels of 16–32 ha.

Urban development along streams or other traditional wildlife movement corridors may divert wildlife from traditional paths, leading to increased human wildlife conflicts [102]. For example, black bears in Bozeman, Montana frequently follow stream drainages into town each spring, where they apparently become lost and confused, feed on residential trash, and are subject to lethal control actions [124,125]. Humans living in or adjacent to corridors may use rodenticides, which kill not only target species (e.g., domestic rats) but also secondary scavengers and predators (e.g., raccoons and coyotes that feed on poisoned rats) and tertiary carnivores such as mountain lions which feed on raccoons and coyotes [126].

Urbanization is associated with artificial night lighting, which can impair the ability of nocturnal animals to navigate through a corridor [127] and has been implicated in decline of reptile populations [128]. Finally, human-produced noise associated with development may disturb or repel some animals and present a barrier to movement [129–131].

Synurbanization is the process by which wildlife become acclimated to human presence and activity on the landscape, and can result in wildlife populations that inhabit urbanized landscapes having distinct behaviors, life histories, and physiology from conspecifics inhabiting agricultural or natural landscapes [102]. For example, anthropogenic noise can change the frequency and amplitude of bird songs [39], the timing of social courtship displays [132], diet [133–135], number of offspring or number of breeding attempts per year/season [133], density and social structure [102], and dispersal distance and movement propensity [136]. Consequently, synurbanized wildlife may behave differently than conspecifics living in wild or agricultural landscapes [102,137].

5.1. Avoid and Minimize Urbanization in or Adjacent to Corridors

Unlike road barriers (which can be modified with fencing and crossing structures), urbanization creates barriers to movement which cannot easily be removed or restored.

If possible, planners should keep residential lot sizes in corridors above 20 ha per residence, ban artificial night lighting, keep vehicle speeds low by limiting lane width and incorporating curves, and specify what plant species are allowed and prohibited. Local governments or homeowners' associations are typically reluctant to require a homeowner to retain natural fire-prone vegetation, remove artificial night lighting, or tolerate wild predators that kill companion animals [138]. Therefore, precluding urbanization is the best way to manage urban impacts in a wildlife linkage. However, most corridors are designed after urbanization and suburban sprawl has begun, such that humans reside in the corridor before it is designated. Further, virtually all corridors will be bordered by urban and residential areas as human footprint expands. Therefore, local jurisdictions striving to conserve corridors will have to engage local residents as cooperative stewards.

5.2. Encourage People Residing in or Adjacent to the Linkage to Be Proud Stewards

Specifically, residents should be encouraged to landscape with natural vegetation, minimize water runoff into streams, manage fire risk with minimal alteration of natural vegetation, keep pets indoors or in enclosures (especially at night), accept depredation on domestic animals as part of the price of a rural lifestyle, avoid all use of rodenticides, use herbicides and insecticides carefully, and direct outdoor lighting toward houses and walkways (and away from the linkage area). These activities can be implemented by builders of planned communities, homeowners' associations, local jurisdictions, conservation NGOs, and owners of conserved lands in the corridor. When the local land permitting agency considers a proposal for new urban development in the linkage area, the agency should stipulate appropriate conditions. Even if some clauses are not rigorously enforced, such stipulations promote awareness of how to live in harmony with wildlife movement.

In most situations, it is impossible and politically undesirable to prohibit nearby residents from enjoying the natural areas in the corridor. Instead, the number of access points should be limited to trailheads where signage can engage and educate people entering the corridor. Signage should provide a link to a website where people can learn more about the value of wildlife corridors and how they can engage in good corridor stewardship practices. The signage and website should be part of a public education campaign that allows people living in and visiting the linkage to educate each other about living with wildlife and the importance of maintaining ecological connectivity [102].

5.3. Encourage Small Building Footprints on Large Parcels with a Minimal Road Network

Where development is permitted within the linkage design, minimize impacts by keeping the footprint of the building small and limit roadways, with fewer than 1 residence per 20 ha and requirements to maintain native vegetation on most of each residential lot. The Santa Lucia Preserve, an 8300 ha residential development in central California USA, provides an example of such a development (https://slconservancy.org/). Most of the preserve consists of wildlands permanently protected and managed for biodiversity, and funded by homeowners. The 350 privately-owned parcels for residences average 12 ha in size, of which 10 ha is natural open land and 2 ha is designated as homeland, which is the only place that fences, outdoor lighting, off-leash pets, and non-native vegetation can occur. The homelands have a well-crafted strict plant palette (no invasive exotic plants), strict lighting codes, and other rules that create a setting in which wildlife including large carnivores and rare species thrive with even less human disturbance than on neighboring publicly-owned wildlands.

5.4. Regulate Access by Recreational Users

Beier et al. [4] recommend that each strand of the linkage design be wider than 1 km so that it can accommodate a well-designed trail system without compromising the usefulness of the linkage for wildlife. The trail network should be laid out so that most of the corridor is relatively undisturbed by humans. People should be encouraged to stay on trails, keep dogs on leashes, and discouraged from collecting reptiles and harassing wildlife. Off-road motorized vehicles should be prohibited within the linkage.

5.5. Discourage Residents and Visitors from Feeding Wildlife

Feeding wildlife can encourage undesirable human–wildlife interaction and a cycle of dependency [139]. For example, bears that supplement their diets with, or depend upon, human garbage generally are not as healthy as their wild counterparts, and small mammal densities are artificially inflated when their resources are supplemented by trash [140]. Feeding is not only deliberately offering food to animals, but also the accidental provision of food via discarded food and wildlife accessible trash containers. Trash receptacles at trailheads should be wildlife-proof, and trailhead signs should encourage leave-no-trace practices and inform recreational users that they are responsible for bringing out whatever they bring in.

5.6. Take Special Steps to Protect Species That Might Be Perceived as Undesirable

Venomous snakes, poisonous plants, alligators, and other predators may be perceived as dangerous, but these species may need the linkage, and may be important to maintaining ecological function in the linkage. Managers should use signage and other methods to educate visitors not to harm these species. In some cases, managers may need to protect critical habitat areas at some distance from trails in order to provide core refuges for them.

6. Recommendations for Agricultural Development in Corridors

The two main types of agricultural development are intensive row-crop farming (including orchards) and livestock grazing. Both types of agriculture impact connectivity due to fencing (covered in Section 3). Both activities alter fire regimes by increasing the number of wildfire ignitions, especially those outside the natural burning season [141], suppressing what might otherwise be beneficial fires, and requiring firebreaks and vegetation manipulation, sometimes at considerable distance from human-occupied sites [142,143]. Fire suppression in rangeland ecosystems has led to increased woody encroachment. Conversely, over-burning has resulted in decreased biodiversity, decreased habitat structure, and increased invasibility [144,145]. Many forested ecosystems are fire adapted and have suffered from fire suppression, resulting in increased coarse woody debris accumulation leading to increased fuel loads and increased risk of type-converting fires [146].

Intensive cultivation degrades connectivity by causing loss of native woodlands and grasslands [143] and declines of many wildlife populations [147,148]. Only approximately 50% of agricultural fertilizers are used by crops; the rest runs off into drainage ditches and ground-water [149]. Agricultural herbicides, pesticides, and fertilizers have negatively impacted biodiversity [150], causing reduced hatch rates among birds, increased susceptibility to disease in small mammals, extirpation of lizards and amphibians, hemorrhagic fever in fish, and stream eutrophication [42,150,151]. Buffer strips of natural vegetation between agricultural fields and wildlife-sensitive areas can prevent or reduce agricultural herbicides and fertilizers from reaching sensitive wildlife [152–154]. Such buffers harbor a higher density of predators of agricultural pests (reducing the need for pesticides) and pollinators (reducing the need for fertilizers) [154–157]. No-till farming practices may reduce or eliminate farmers' need to apply fertilizers and pesticides, and the cost savings can compensate for lower yields [150]. No-till farming practices also increase soil carbon sequestration, reducing atmospheric carbon accumulation [158]. When fertilizers and pesticides are required or no-till farming practices are not practical, producers should be encouraged to follow the "4R's" of fertilizer use: right source of nutrients/fertilizers; right rate or density of nutrient application; right timing of fertilizer application to best coincide with crop growth; right place for nutrient/fertilizer application [159].

Wildlife depredation of both livestock and crops may be a major concern for farms and ranches abutting wildlife corridors [160]; in the US, damage to crops may exceed $4.5 billion annually [161]. The economic impact of direct livestock depredation by wildlife is poorly known, but most loss is felt by a few landowners whose herds are repeatedly depredated [158,160,161]. Such losses can erode local support for the corridor. Although financial compensation reduces the economic impact, these payments do little to reduce the animosity felt by farmers and ranchers [162]. Farmers and ranchers prefer to have the knowledge and tools to proactively reduce economic damage from wildlife [163–167].

Horizontal transmission of disease between infected wildlife and domestic livestock is an emerging concern for corridors in agricultural regions for diseases such as bovine tuberculosis, West Nile Virus, and malaria [168,169]. In agricultural landscapes, it is therefore important that the corridor does not become the major vector of disease transmission, which could erode public support for the corridor [170].

6.1. Encourage Farmers to be Good Stewards of the Corridor

Encourage farmers in or adjacent to the linkage to be proud stewards. In some ways, this recommendation is simpler for farmlands than for urbanization (Section 5) because farmers and ranchers are stewards of the land, and correctly view themselves as such. Consequently, engagement can focus on providing farmers and ranchers with information to allow them to become better stewards and minimizing impacts to their livelihoods. Such engagement should be led by familiar partners such as agricultural extension agencies, government forestry, and agricultural entities accustomed to working with farmers and ranchers, and local agricultural community organizations to disseminate information to local landowners about the benefits of good husbandry practices. Outside NGOs should take the time to develop good relationships by, for example, attending annual agricultural fairs and sponsoring competitions with cash prizes and a physical trophy that can be displayed by the farmer or rancher with the most corridor-friendly farming and ranching practices.

6.2. Encourage Farmers to Reduce the Amount of Herbicide, Pesticide, and Fertilizer They Use and Provide Information about No-Till Farming Practices

In particular, farmers should be encouraged to establish semi-natural transition zones between agricultural fields and the corridor, emphasizing the benefits that such buffers may have for their crops [152–154].

6.3. Encourage Controlled Burns or Mechanical Removal of Debris along Corridor and Adjacent Lands That Most Closely Mimic Natural Fire Regimes

In rangeland systems, recommend a patch-burn patch-graze rotational grazing systems for ranchers with lands adjacent to corridors. Along with the patch-burn patch-graze fire regime, season-long cattle stocking at low to moderate stocking densities should be encouraged. The interaction of this level of burning and stocking intensity will most likely be able to maintain adequate grassland habitat heterogeneity necessary to support wildlife [171], without adversely affecting ranchers' profitability [172]. In forested corridors, encourage mechanical removal of coarse woody debris and mechanical stand adjustments to lessen fuel loads, increase stand diversity and otherwise mimic the effects of fire without the risk of catastrophic fire that might disrupt connectivity [173].

6.4. Encourage Conservation Easements or Acquisition of Conservation Land

Recognizing that there may never be enough money to buy easements or land for an entire linkage, encourage innovative cooperative agreements with landowners that may be less expensive [174,175]. Use available government programs (such as the US Farm Bill, and IUCN Ag. Lands Programs) to establish natural land buffers between farmland and the corridor and to expand the size of the corridor. Encourage the use of wildlife-friendly fencing on property and pasture boundaries, and wildlife-proof fencing around gardens and other potential wildlife attractants. Encourage landowners to remove unnecessary fences.

6.5. Use National and Local Agricultural Programs

The United States' Farm Bill [176] includes the Conservation Reserve Program, the Wetlands Reserve Program, the Wildlife Habitat Incentives Program, the Environmental Quality Incentives Program, and the Conservation Securities Program, which provide managers with the ability to enhance connectivity across agricultural gaps in the corridor, establish natural land buffers between cropland and corridor lands along corridor routes to reduce edge effects, and increase the amount of suitable habitat within or adjacent to the corridor to enhance meta-population dynamics [177]. Similar programs are included in the European Union's Natura 2000 initiative and the EU's Common Agricultural Policy [7,178]. These programs provide cost-sharing opportunities, technical assistance, and other financial incentives to restore or enhance habitats, and protect habitats through long-term or permanent conservation easements [176,179]. For example, the US Farm Bill's Wildlife Habitat Incentives Program provides up to 75% cost share for wildlife habitat improvement under contracts lasting five to 15 years (Public law 104–127). Similar CAP policy programs have had similar beneficial effects for wildlife in Europe [67]. In African nations, laws expanding and protecting traditional grazing and nomadic lifestyles of tribal peoples, such as the Masai, have been used to enhance connectivity [180,181]. Additionally, the government of Australia makes an effort to preserve the Stock Route Network, historic cattle-droving routes, that connects a network of protected areas in New South Wales and Queensland [179]. The creation of other similar programs in other nations should be encouraged and supported [182].

6.6. Help Ranchers Reduce Depredation Losses

Provide farmers and ranchers with information on the use of livestock or crop guarding dogs [164,183], scarecrows, the use of fladry or flashing along fence lines [79], and good husbandry practices. Cleaning up livestock carcasses may be the single best practice to reduce wildlife depredation on livestock and domestic companion animals [184]. Managers can provide information on non-lethal predator control [160] and on relevant laws and regulations (*Information available for all U.S. regions is available through the United States Department of Agriculture, Animal and Plant Health Inspection Service. Website: http://www.aphis.usda.gov/wildlife_damage*).

6.7. Concentrate Supplemental Feeding and Water Sites Away from Natural Areas

Many wildlife species will make use of livestock feed and mineral blocks, especially during winter months when forage may be scarce. Wildlife use of livestock feed areas is intensified when such food plots are far from human-use areas and near wildlife utilized resources [185]. In many instances, horizontal disease transmission between wildlife and livestock occurs at shared food plots [186,187]. Therefore, managers should encourage farmers with land within or adjacent to corridors to locate livestock watering facilities, supplemental feeding stations, and salt licks close to farm buildings and away from the corridor.

6.8. Prohibit Farmed Wildlife within or Adjacent to Corridors

The presence of farmed wildlife species such as deer, elk, buffalo, gazelle, kudu, bison, or others increases the likelihood of horizontal disease transfer among livestock and wildlife utilizing the corridor [163]. Further, landowners should be encouraged to vaccinate all domestic companion animals and livestock for distemper and other transmissible diseases.

6.9. Limit the Number of Landowners Whose Property Is Either within or Adjacent to the Corridor

This will limit the number of parties with vested interest in the corridor and make implementing the above management practices easier.

7. Knowledge Gaps, Summary, and Conclusions

In general, the best management practices for corridors can be summed up in the adage *less is more*. The less human activity within or adjacent to a linkage, the better and more successful it will be. Thus, for areas in, or adjacent to, wildlife linkages, our recommendations strive to: (1) minimize the number and intensity of human activities within, (2) maintain or re-create natural processes in linkages, (3) create buffers between linkage lands and human-use areas, and (4) help wildlife cross linear barriers, and (5) encourage recreationists and other people using the corridor to behave as well-informed stewards.

Project proposals that would impact designated wildlife corridors should include detailed environmental analyses of the impacts and benefits of several alternative strategies, should consider an array of mitigation strategies, and should provide opportunities for public review and comment. Following the precautionary principle, proponents of a project that would degrade connectivity should bear the burden of proving that such impacts will be minimal.

We offer this paper as a first attempt to outline good practices for corridors, and we look forward to improvements. We encourage others to improve on our recommendations by conducting research on poorly-understood relationships. One promising approach would be to replace some of our reasonable inferences from observed ecological patterns with more targeted observations or experiments. For example, in Section 5.1, we note that synurbanization can cause wildlife behavior to differ between populations living close to humans and more remote populations. Additional research is needed to determine if these behavioral differences may impede movement and gene flow between populations in corridors and the natural landscape blocks the corridors are intended to connect. Future improvement should strive to include more evidence from areas outside North America and Europe, including pastoral regimes that may differ from the farming and livestock practices on these two continents, and a broader array of legal and cultural settings.

Below, we call attention to several knowledge gaps that, if resolved, would produce better management practices for wildlife corridors.

7.1. What Are Critical Dimensions of Corridors?

Is there an interaction between how wide corridors must be with corridor length or type of human use within or adjacent to corridors? What impact do edge effects have on corridor functionality? Is the edge to area ratio a meaningful metric of corridor function?

7.2. Is There a Critical Threshold in Intensity of Land Use?

Wildlife seem to tolerate certain low-impact land use practices (Burchett and Burchett 2011). For example, converting up to half of a landscape to grain cultivation can benefit some wildlife populations, with steep declines as larger areas are converted [188]. Do these observations apply to most wildlife species, and to use of land for movement as strongly as for occupancy? Is there a non-linear relationship between the intensity of adjacent human land use and wildlife use of a corridor? Thresholds are common in wildlife ecology [189], but to date little to no work has been completed with regards to ecological thresholds and corridors.

7.3. How do Landscape Traits of Corridors Affect Different Species?

Individual species and types of species almost certainly vary in their response to certain corridor traits. For example, forest rodents have limited tolerance to open landscapes, whereas grassland and rangeland rodents readily enter forests [190,191]. For some wide-ranging and edge-tolerant species, roads, grazing, and even limited human development of the corridor will have only minimal impacts on corridor functionality [192]. For other species, even light recreational use creating a narrow hiking path will be sufficient to create a significant and measurable barrier [193]. To date, little work has evaluated the relative effect of species versus landscape attributes on corridor use.

7.4. How Far Away from the Linkage Edge Do We Need to Manage Human Uses?

Our recommendations are vague about human activities “adjacent to” a linkage. What influence do second- or third-order spatial lag effects have on corridor use? The increasing spatial extent of population dynamics synchronization under climate change suggests that managing successful linkages might also include managing areas outside of the linkage as intensively as the linkage itself, but the intensity, types, and spatial extent of these activities is currently unrecognized and unstudied [191].

7.5. How Do Time Lags Affect Corridor Use?

Past land use practices incur extinction debts [194]. Do they impede wildlife use of a newly conserved corridor? The environmental history of a corridor could be critical to understanding how the corridor functions today, whether and how fast a landscape returns to equilibrium. Adaptive landscape models and neutral theory models could be useful in this context [195].

7.6. Which Governance and Management Activities Are Most Acceptable to People Living in or near Corridors and Which Policies Are Beneficial for Corridors?

Corridor establishment and management is an issue of coupled natural–human systems [196]. There are socio-political aspects to developing and managing corridors and human access to natural areas. For example, in the Czech Republic, federal laws prohibit any management legislation that would limit citizen access to forests [197]. Similarly, in New South Wales Australia, human desire to preserve the droving history of the landscape resulted in the preservation of the Stock Route Network, and mandated that those areas be maintained to allow livestock grazing [182]. Lastly, sometimes well-intentioned conservation practices can have unintended interactions. For example, in both China and Kenya, fortress conservation practices of forests created a high-value commodity resource that created market-economy incentives for people to violate conservation laws and utilize the resources to a greater/more intense degree than had been previously observed [196,198–201].

Public perception of the quality and legitimacy of the science supporting corridor development and management is also an important consideration [202]. In some instances, public and political interest will spur the creation of a corridor, but that support will wane later if the goals and reasoning for the corridor and regulations protecting the corridor are ambiguous [203,204]. This requires the balancing of social, ecological, and political factors during the planning stages of the corridor and integration of all major stakeholder perspectives into the corridor management plan. An example of how this was performed well can be seen in the Green River Corridor in the Netherlands [205].

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