Exploration of potential road ecology strategies and supporting research in AlUla, Saudi Arabia

Final Report

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16. Abstract

This report documents the results of an exploratory visit to AlUla. Specifically, this report 1. Formulates potential road ecology strategies for Sharaan and the surrounding protected areas, 2. Suggests research that can support these strategies, 3. Suggests measures and supporting research for specific livestock and wildlife issues, and 4. Discusses specific maintenance concerns.

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1 Introduction

1.1 Background

The Royal Commission for AlUla (RCU) was established in July 2017 to protect archaeological sites, to protect and restore natural resources - including native wildlife species-, and to enhance economic development of the area. The region now has several protected areas, reserve extensions and proposed protected areas (Figure 1).

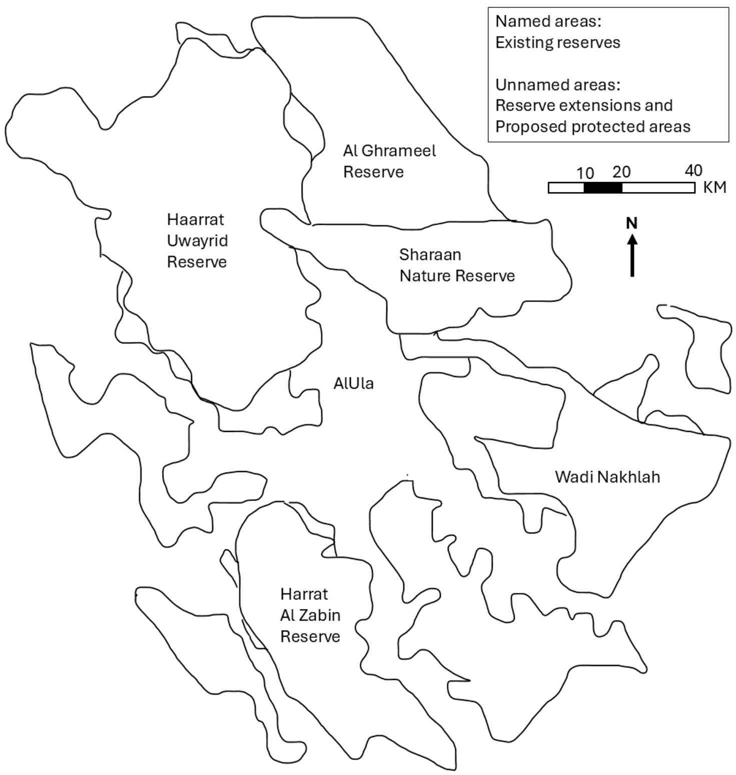

Figure 1: Map of the protected areas in and around AlUla.

1.2 Goal and objectives

The goal for road ecology implementation in the area around AlUla is to enhance road safety for humans through reducing existing or potential future collisions with large wild mammals, large livestock species, and large feral species, and to enhance connectivity across roads for large wild mammals, and potentially also smaller wildlife species.

The objective of this report is to document the results of an exploratory visit to AlUla. Specifically, this report:

- Formulates potential road ecology strategies for Sharaan and the surrounding protected areas.
- Suggests research that can support these strategies.
- Suggests measures and supporting research for specific livestock and wildlife issues.
- Discusses specific maintenance concerns.

1.3 Measures included

While the mitigation hierarchy includes three steps, - avoidance, mitigation, and compensation -, this report assumes that the current roads continue to exist at their current routes (Cuperus et al., 1999). Therefore, this report restricts itself to mitigation measures, in this case measures that are aimed at reducing collisions with large wild mammal species, large livestock species, and large feral species, and at providing safe crossing opportunities for large wild mammal species. Because of this focus, this report is restricted to wildlife fences in combination with crossing structures (i.e., underpasses and overpasses), at least for large wild mammals (Huijser et al., 2021). For livestock species, this report also includes animal detection systems as the movements of livestock species, even those that are free-roaming, are or should at least somewhat be, controlled by humans (Huijser et al., 2021). Other mitigation measures, including wildlife warning signs, do not address all of the objectives, or are not sufficiently effective (Huijser et al., 2015; 2021) (Figure 2).

Figure 2: Wildlife warning sign for gazelles, Hwy 375, AlUla, Medina Province, Saudi Arabia. Note that standard or enhanced wildlife warning signs such as these do not reduce collisions with large animals.

1.3.1 Wildlife crossing structures and fences

Fences in combination with wildlife crossing structures are the most robust and effective mitigation measure package to both reduce collisions with large and small animal species and maintain or improve connectivity for wildlife. However, it is important to be aware of the different functions of fences versus the function of crossing structures and how that relates to the “departure point” of a mitigation project.

If human safety and direct road mortality of a species are the primary concern, then:

- Road sections with a high concentration of collisions and dead animals are identified and prioritized (e.g. Panowicz et al., 2020). The target species may be large common mammals if human safety is the primary concern (e.g. Huijser et al., 2008). If reducing unnatural mortality for rare species is the concern, the target species can be of any body size (e.g., Kramer-Schadt et al., 2004; Huijser et al., 2008; Boyle et al., 2021).
- From a human safety perspective, it is logical to identify and prioritize road sections that currently have a concentration of collisions with large animal species. However, from a biological conservation perspective, direct road mortality may have already caused population depletion. This means that the greatest threat to population persistence due to direct road

mortality may not always be along the road sections that currently have the highest concentration of dead individuals of the target species (Teixeira et al., 2017).
- Fences or other barrier types are the primary measure, as the primary purpose of fences along roads is to keep animals off the highway and reduce animal-vehicle collisions (Huijser et al. 2016).
- Since fences alone would result in an absolute, or near-absolute, barrier for the target species, fences are typically combined with safe crossing opportunities for wildlife, especially wildlife crossing structures (i.e. underpasses and overpasses) (Moore et al., 2021).
- The secondary function of the wildlife fences is to guide or funnel wildlife species to these
- crossing structures (Dodd et al., 2007; Gagnon et al., 2010).

If habitat connectivity for wildlife is the primary concern, then:
- Road sections where habitat connectivity needs to be maintained or restored are identified and prioritized. This may be based on the connectivity needs (genetic, demographic) for individual species (the "target species"), a wide suite of species or species groups, seasonal migration of certain species (e.g., for ungulates), dispersal to allow for colonization or recolonization of areas nearby or further away, or ecosystem processes in general (biotic and abiotic parameters), including those associated with climate change (e.g. Kramer-Schadt et al., 2004; Clevenger & Huijser, 2011; Sawaya et al., 2013; 2014; Lister et al., 2015; Sawyer et al., 2016; Jarvis et al., 2018).
- While it seems logical to identify and prioritize road sections that currently have observations of animals living or moving close to the road and observations of animals crossing the road (both unsuccessfully and successfully), the greatest population level conservation benefit of reducing the barrier effect of a road may not be where most animals are currently. From the perspective of biological conservation at the population level, areas where most animals are now may have high population viability, potentially despite being isolated because of the barrier effect of transportation infrastructure. In such cases, reducing the barrier effect does not necessarily lead to an increase in population viability. Instead, the greatest population level benefits of reducing the barrier effect can be where small and isolated populations can be made more viable by providing safe crossing opportunities. This may even include road sections that currently isolate unoccupied habitat patches, and that bisect planned habitat corridors rather than existing ones. In other words, crossing structures may also be required or can also be beneficial for population persistence in areas where the target species has low abundance or where it is currently entirely absent.
- Wildlife crossing structures are the primary measure, as the purpose of wildlife crossing structures is to provide safe crossing opportunities.
- Crossing structures alone do not necessarily reduce collisions (Rytwinski et al., 2016). Therefore, wildlife crossing structures are typically combined with wildlife fences.
- An added benefit of connecting crossing structures to wildlife fences is that it guides or funnels wildlife to the crossing structures and that this increases the use of the structures (Dodd et al., 2007; Gagnon et al., 2010).

In this context, it is also important to be aware of the limitations of existing crossing structures that were not built for wildlife versus designated wildlife crossing structures. While designated wildlife crossing structures should be located where connectivity for wildlife is needed most, existing structures that were not built for wildlife are not necessarily located where connectivity for wildlife is needed most. Nor are such existing crossing structures necessarily of the right type (e.g. overpass vs. underpass) or dimensions given the target species, and there are typically limits to potential modifications to existing structures to improve the suitability for the target species.

In conclusion, fences and wildlife crossing structures are almost always implemented together, regardless of whether the primary objective is to reduce animal-vehicle collisions or to reduce the barrier effect of roads and traffic for wildlife. However, the road sections where the measures are implemented are very much dependent on the primary objectives or departure points, and they may include road sections where the target species is not hit or no longer hit, and where the target species may have low population density or where it is currently not present at all.

1.3.2 Animal detection systems

Animal detection systems use electronic sensors installed along the roadside to detect large animals (e.g., deer size and larger) that approach the road. After the animal is detected, signs are activated to warn drivers (Huijser et al., 2015). These signs are very specific in time and place. The effectiveness of animal detection systems is variable, but they can reduce large mammal-vehicle collisions with large mammals by 33-97% provided that the sensors detect the target species reliably (Huijser et al., 2021). In general, animal detection systems are more successful for large bodied species which could include livestock species, though they have primarily been studied for large wild mammals such as deer, elk, and moose.

Specifics:

- Animal detection systems can reduce collisions with large mammal species, but they do not reduce the barrier effect of roads and traffic. Therefore, depending on the goals and objectives of the project, an animal detection system may or may not be appropriate.
- Follow a step-wise approach when considering the implementation of an animal detection system (Huijser et al., 2015).
- Animal detection systems should only be considered on 2-lane roads (Cramer & McGinty, 2018), perhaps with a traffic volume of a few thousand vehicles per day at a maximum to limit the risk of rear-end collisions as a result of sudden braking in response to activated warning signs (Huijser et al., 2015).
- Consider combining the detection and warning system with advisory or mandatory reductions in speed limit (Huijser et al., 2015; 2017).
- Animal detection systems should still be considered experimental, and implementation should be regarded as a high-risk project as many projects fail because of technological, management, financial, or maintenance issues (Huijser et al., 2015; 2021).
- If implemented, animal detection systems should be located near large mammal-vehicle collision hotspots or used as a fence-end treatment to reduce the probability of moving the collision hotspot to the fence-end.
- Note that the study that found that the inclusion of an animal-detection system resulted in a 97% reduction in collisions with large wild mammals used the animal-detection system as a fence-end treatment, not as a stand-alone mitigation measure (Gagnon et al., 2019).

2 Road ecology strategies for wildlife in protected areas and supporting research

2.1 Current situation

This chapter describes several potential road ecology strategies for the wildlife species and the protected areas in AlUla. Furthermore, this chapter formulates research that can support these strategies. The Ar Rukkab section of Sharaan is currently fully fenced (Figure 3). This fence is likely a near absolute barrier for large mammals (Figure 4, Figure 5). The Madakheel section of Sharaan, west of Hwy 375, is fenced along Hwy 375 but it is not fenced towards the west where it connects to Haarrat Uwayrid Reserve. Livestock species (i.e., "camel" or dromedary (*Camelus dromedarius*), domesticated goats (*Capra hircus*), domesticated sheep (*Ovis aries*)) and feral species (i.e., donkeys (*Equus asinus)* and dogs *(Canis lupus familiaris)*) have been (near) excluded or eradicated from the Ar Rukkab section of Sharaan. Over the last few years, the following native species, now about 1,000 individuals in total, were reintroduced in the Ar Rukkab section of Sharaan (Personal comment Abid Mehmood; Tommaso Savini; Niti Sukumal):

- Arabian sand gazelle or reem (*Gazella marica*) (Vulnerable (IUCN, 2024)).
- Mountain gazelle or true gazelle or Palestine mountain gazelle or idmi (*Gazella gazella*) (Endangered (IUCN, 2024).
- Arabian oryx or white oryx (*Oryx leucoryx*) (Vulnerable (IUCN, 2024)).
- Nubian ibex (*Capra nubiana*) (Vulnerable (IUCN, 2024)).

Other species that may be reintroduced in the future include (Personal comment Abid Mehmood; Tommaso Savini; Niti Sukumal):

- North African ostrich or red-necked ostrich or Barbary ostrich (*Struthio camelus camelus*) (Least concern (IUCN, 2024)). This subspecies is the closest to the extinct Arabian ostrich or Syrian ostrich or Middle Eastern ostrich (*Struthio camelus syriacus*).
- Arabian leopard (*Panthera pardus nimr*) (Critically endangered (IUCN, 2024)).

Other mammal species that are or may currently be present in the area include (Personal comment Tommaso Savini; Niti Sukumal):

- Sand cat (*Felis margarita*) (Least concern (IUCN, 2024)).
- Caracal (*Caracal caracal*) (Least concern (IUCN, 2024)).
- Gray wolf (*Canis lupus*) (Least concern (IUCN, 2024)).
- Striped hyena (*Hyaena hyaena*) (Near threatened (IUCN, 2024)).
- Indian crested porcupine (*Hystrix indica*) (Least concern (IUCN, 2024)).
- Rock hyrax (*Procavia capensis*) (Least concern (IUCN, 2024)).
- Desert hedgehog (*Paraechinus aethiopicus*) (Least concern (IUCN, 2024)).

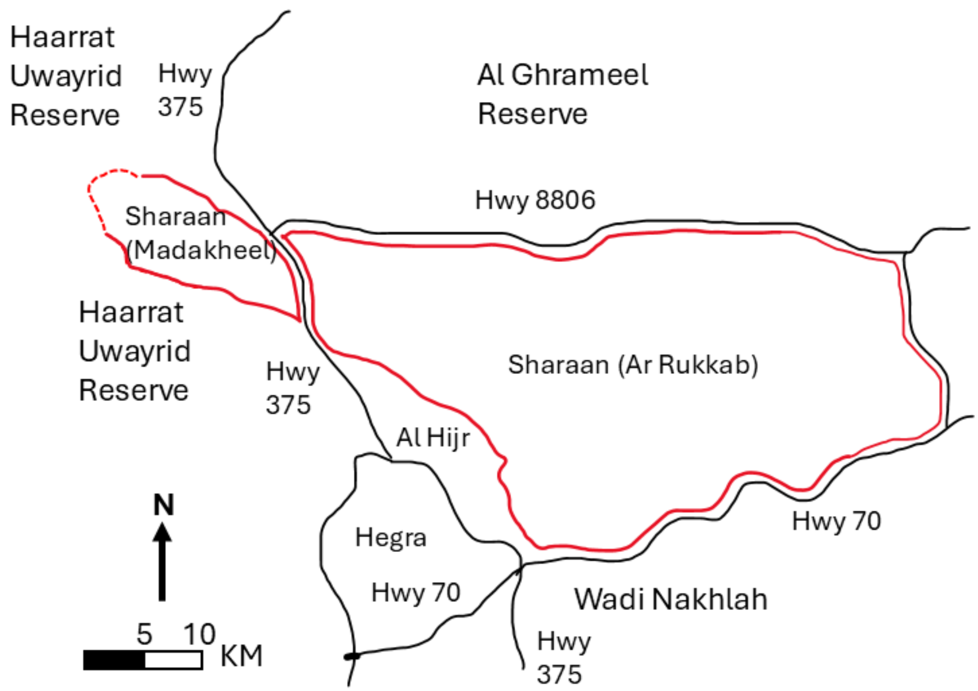

Figure 3: Conceptual map of Sharaan (fence in red), and its surrounding roads (black lines) and protected areas. Note that the western boundary of Madakheel is not fenced (dotted line).

Figure 4: Wildlife fence along Hwy 8806 (to the left) and Sharaan (to the right), AlUla, Saudi Arabia.

Figure 5: Arabian sand gazelle or reem (Gazella marica) in Sharaan, along the wildlife fence along Hwy 8806, AlUla, Saudi Arabia.

Before formulating a policy that deviates from the current situation, the following research needs may be considered.

Research and policy needs:

1. Document the traffic volume on the different road sections. Allow for traffic volume to be estimated by the hour of the day. This provides insight into the level of disturbance for wildlife and the barrier effect that the road and traffic may represent for different wildlife species for the times of the day that they are active.
2. Estimate the future traffic volume for different road sections based on policy and growth projections.
3. Document the posted speed limit on the different road sections. This provides insight into the ability of drivers to see large mammals in the dark in the headlights of their car far enough ahead to come to a complete stop (see Huijser et al. (2017) for stopping distances depending on vehicle speed).
4. Develop a vision for which roads are managed as “through roads” which need to be safe (low probability of hitting large mammals) and efficient (high vehicle speed, including in the dark), versus which roads are managed as “park roads” that also need to be safe but where efficient travel may be less important than experiencing the landscape and the wildlife and minimizing

the environmental impacts. For “park roads” lower design speeds and traffic calming measures may be appropriate (e.g., narrow, curvy, short sight distances, road follows the topography rather than “plowing” through the topography to minimize grades).

5. Document where wildlife species currently are (e.g., inside the fully fenced area of Sharaan, but also outside of Sharaan such as the Nubian ibex population east of Harrat Al Zabin Reserve (see section 3.2).
6. Develop a vision for where the different wildlife species may be in the future (50-75 years into the future) and how they could reach these areas (e.g., reintroduced into the individual areas or dispersal from other areas (e.g., Sharaan could be a “source” area). Having long-term vision is relevant as the life span of concrete wildlife crossing structures is projected at about 75 years.
7. Because almost all large wild mammal species have been extirpated or nearly extirpated, and because the reintroduced large mammals are within the fenced eastern section of Sharaan, there is no or little current road mortality data or wildlife movement data to inform where mitigation measures may be required for large wild mammals (Personal comment Wael Hassan). This means that the location and types of mitigation measures may be largely based on policy, or a vision, for wildlife in relation to wildlife-vehicle collisions and connectivity for wildlife. This is especially needed for Sharaan and the surrounding protected areas. Make this vision explicit regarding fences and wildlife crossing structures, and potentially also animal detection systems. Note that the current masterplan for Sharaan includes:
    - A 3 km wide crossing structure (a land bridge that connects an entire ecosystem rather than a wildlife crossing structure that is targeted at one or more wildlife species only), connecting the eastern (Ar Rukkab) and western section (Madakheel) of Sharaan.
    - Indications of wildlife crossing structures between the Ar Rukkab section of Sharaan and the protected areas to the north and south of Sharaan.

    However, no vision is formulated in the current masterplan regarding potential wildlife fences in the surrounding areas. Yet, crossing structures that connect to the surrounding areas which only have a wildlife fence on the Ar Rukkab section of Sharaan, would not be effective in reducing collisions, and are only partially effective in guiding wildlife to the crossing structures. In other words, wildlife crossing structures without wildlife fences on both sides of the road only partially address some of the objectives.

Because of the unknowns regarding the future presence, distribution, and movements of wildlife across roads, this report identifies three potential scenarios that are discussed in the following sections.

2.2 Scenario 1: Sharaan stays fenced, and surrounding protected areas will also be fully fenced

In this scenario, Sharaan stays fenced and the surrounding protected areas will also be fully fenced (Figure 6). Reintroduction of native species will continue in Sharaan and may also be initiated in the surrounding protected areas. Feral species and livestock species are near eradicated or excluded from all the fenced areas to increase the carrying capacity for wild ungulates, to minimize unnatural predation of wild ungulates, and to reduce the risk of disease transmission from domesticated or feral species to wild species.

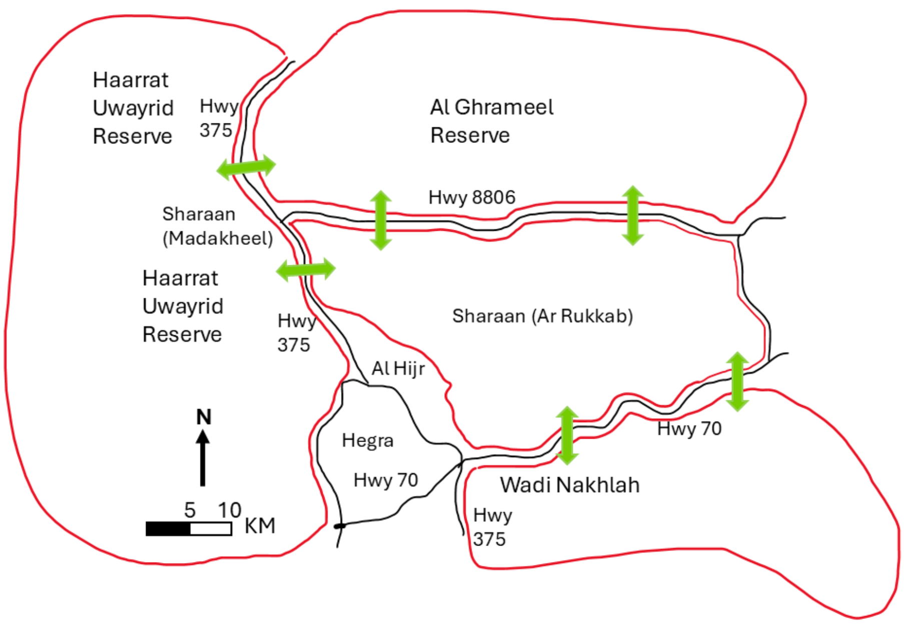

Figure 6: Based on scenario 1, a conceptual map of Sharaan and surrounding protected areas that are all fully fenced (in red), the roads that bisect the protected areas (black lines), and wildlife crossing structures (green arrows).

In this context, connecting the fenced protected areas through safe crossing opportunities for wildlife would result in one larger, better-connected population, or at least a meta population, with reduced risk of extirpation. Wildlife would be able to move across all protected areas in response to varying resources, e.g. because of high temporal and spatial variability in precipitation and associated vegetation growth.

The fences that would keep the animals off the road would already be in place. This means that, unless the existing fence is found to be unsatisfactory, the fence design is settled upon already. Note that a 2.5 m high fence is estimated to be a substantial barrier to Arabian sand gazelle, mountain gazelle, and Nubian ibex, whereas a much lower fence (e.g., 1.0-1.5 m) would be required for Arabian oryx (Personal comment Abid Mehmood). Appropriately spaced wildlife crossing structures (i.e., overpasses and underpasses) of the right type and dimensions given the target species would still have to be constructed. The fences could then be connected to these structures. See Huijser et al. (2022a) for planning, design and construction considerations.

Research needs:

1. **What are the target species for which connectivity needs to be provided?**

The target species likely include:

- Arabian sand gazelle or reem (*Gazella marica*).
- Mountain gazelle or true gazelle or Palestine mountain gazelle or idmi (*Gazella gazella*).
- Arabian oryx or white oryx (*Oryx leucoryx*).
- Nubian ibex (*Capra nubiana*).

And possibly also:

- North African ostrich or red-necked ostrich or Barbary ostrich (*Struthio camelus camelus*).
- Arabian leopard (*Panthera pardus nimr*).

As the lifespan of concrete structures is around 75 years (Huijser et al., 2009; 2022b), it is important to include species that are anticipated to be present over the next 50-75 years, rather than to only base this on the species that are currently present. Alternatively, rather than selecting a range of target species, a more ambitious ecosystem approach could be chosen where the ambition level goes beyond individual species or species groups; it could even include abiotic processes (Huijser et al., 2022a).

2. **Given the habitat use of the target species, given the areas where the target species are present, given the spatial configuration of habitat types of the protected areas, where does connectivity need to be provided?**

The habitat use of the target species and the areas where they are present can be obtained from release records, ongoing sightings in the field, and potentially also through locations of individual animals that carry a GPS collar. For example, Arabian sand gazelles and Arabian oryx predominantly use open flats, mountain gazelles can also be at slightly higher elevation with steep rocky outcrops, and Nubian ibex are associated with rocky outcrops (Personal comment Abid Mehmood). While the connectivity locations across roads can at least partially be based on policy, population viability analyses can also help decide on the number and location of safe crossing opportunities, especially in the context of scarce resources that are highly variable in time and space. GPS collars can also identify activity patters over the course of the day or night. This may be relevant as some species (e.g. gazelles) may be predominantly active during the day and cannot be expected to take advantage of lower traffic volumes at night when crossing highways at-grade (Personal comment Abid Mehmood). In addition, some species (e.g., gazelles) may avoid roads altogether (Personal comment Abid Mehmood).

3. **Given the target species, what type and dimensions of crossing structures need to be provided?**

The knowledge of the type and dimensions of crossing structures that would be suitable for the target species is likely not existent or very limited. A literature review of similar species in arid and open habitat (deserts, grasslands) elsewhere in the world can help identify the types and dimensions of crossing structures that would likely be suitable for the target species. However, species of flat open landscapes (e.g., Arabian sand gazelle, Arabian oryx) typically require large overpasses (e.g., 50-70 m wide) or underpasses (e.g., dozens or hundreds of m wide, 5-6 m high) with long sight distances for ungulates that need to see predators at long distances (e.g., Sawyer et al., 2016; Personal comment Abid

Mehmood) (Figure 7, Figure 8). Small structures, especially those that also have solid dividing walls that limit sight distances for animals, are typically not suitable for large mammals of open flat landscapes (Figure 9). Species associated with rocky ridges (e.g., Nubian ibex) may require overpasses (e.g., 50-70 m wide) connecting to that specific habitat (Gagnon et al., 2022) (Figure 10).

Figure 7: Long bridge over a desert wash, Hwy 328, south of Alula near Magattyah, Medina Province, Saudi Arabia.

Figure 8: Supporting pillars, rather than supporting walls, allow for greater sight distance for wildlife under the bridge, Hwy 328, south of Alula near Magattyah, Medina Province, Saudi Arabia.

Figure 9: Double box culvert with solid dividing wall limiting sight distance for wildlife, Hwy 328, south of Alula near Magattyah, Medina Province, Saudi Arabia.

Figure 10: Wildlife overpass primarily designed for desert bighorn sheep, I-11, near Boulder City, Nevada, USA. Note that the bighorn sheep depicted on the overpass communicate the purpose of the overpass and that the design and color of the structure fit into the landscape better than a standard bridge design.

4. **Explore the potential of lines of rock or cairns in the landscape to help guide wildlife to the safe crossing opportunities.**

Lines of rock or cairns have been used for millennia by people hunting ungulates in open landscapes including tundra's, grasslands and deserts (see review in Huijser et al., 2013). Ungulates tend to follow these man-made features, potentially increasing the use of safe crossing opportunities. This very old technique to influence wildlife movements could potentially have a modern application in the context of increasing wildlife use of crossing structures (See Huijser et a. (2013) for a conceptual drawing).

5. **After implementation, investigate the effectiveness of the mitigation measures in reducing collisions and providing connectivity for wildlife.**

Note that is no or almost no "before" data on road mortality for wild large mammals as large wild mammals have been extirpated or have been nearly extirpated, and the reintroduced large wild mammals are largely within the fenced section of Sharaan (Ar Rukkab section). This means that historic data are a poor reference for the effectiveness of the measures in terms of reducing collisions. Instead, the "after" road mortality data can be evaluated against "maximum allowable numbers of roadkilled animals" that would be based on policy. Before data on wildlife movement data are also absent. The effectiveness of the wildlife crossing structures can be evaluated using wildlife movement in the surrounding (protected) area as a reference (see e.g., Andis et al., 2017). In addition, the acceptance ratio of animals that approach the crossing structures can be calculated to estimate the suitability of the crossing structure types and dimensions. Furthermore, the effectiveness can be evaluated through population viability analyses (e.g, Ottburg & van der Grift, 2019; Soanes et al., 2024).

2.3 Scenario 2: Sharaan stays fenced, and surrounding protected areas will be partially fenced

In this scenario, Sharaan stays fenced and the surrounding protected areas will only be partially fenced (Figure 11). Note that this situation already exists for the Madakheel section of Sharaan (see Figure 3). Reintroduction of native species will continue in Sharaan and may also be initiated in the surrounding protected areas. Feral species and livestock species are near eradicated or excluded from all the fenced areas to increase the carrying capacity for wild ungulates, to minimize unnatural predation of the wild ungulates, and to reduce the risk of disease transmission from domesticated or feral species to wild species.

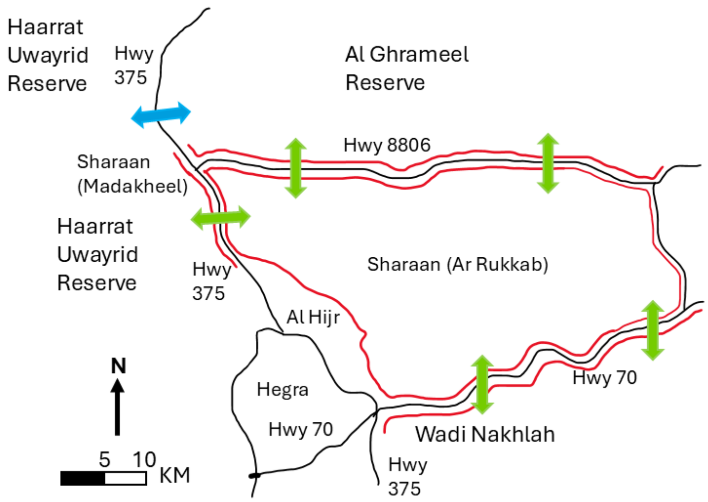

Figure 11: Based on scenario 2, a conceptual map of Sharaan (fully fenced, in red) and surrounding protected areas (partially fenced, in red), the roads that bisect the protected areas (black lines), wildlife crossing structures (green arrows), and at-grade crossing opportunities for wildlife (blue arrows).

This scenario is similar to scenario 1, but there would be "open" wildlife populations for the areas surrounding Sharaan. Note that the length of the fences affects the effectiveness in terms of collision reduction. For 80-100% reduction in collisions with large wild mammals, at least 5 km of road length needs to be fenced (Huijser et al., 2016). Shorter fenced areas suffer from reduced effectiveness because of collisions near the fence ends in the fenced road sections (Huijser et al., 2016), let alone a potential concentration of collisions just beyond the fence-ends (e.g. Huijser & Begley, 2022). However, the fenced sections should extend beyond the suitable habitat of the species, and it is generally strongly recommended to fence both sides of a highway, which means that the road sections along the neighboring protected areas should be fenced for the entire distance that they share their boundary with Sharaan.

For road sections that are not fenced on either side of a road, at-grade animal detection systems could be considered. Note that animal detection systems do not reduce the barrier effect of the road, are high-risk projects, and should only be considered at low traffic volume (Huijser et al., 2015).

Research needs:

- Similar to the previous section. However, should livestock or feral species still be present in the areas surrounding Sharaan, it is important to investigate if barriers can be installed on wildlife crossing structures that would:
    - Block entry into Sharaan for large livestock species or feral species.
    - Still allow native wild large mammals to move through or across wildlife crossing structures in both directions.
- Identify road sections where potential direct road mortality of large wild mammals, or large livestock species or feral species may need to be addressed or reduced, potentially through animal detection systems.

2.4 Scenario 3: Sharaan stays fenced, and surrounding protected areas will not be fenced

In this scenario, Sharaan stays fenced and the surrounding protected areas will not be fenced and may continue to have livestock and feral species (Figure 12). Note that the Madakheel section of Sharaan is already fenced along the highway, but that the border is open to the west where it is adjacent to Haarrat Uwayrid Reserve (Figure 12). Reintroduction of native species will continue in Sharaan and Sharaan may act as a source for the surrounding areas once minimum population sizes have been reached for the reintroduced species. Depending on the population size of livestock species and feral species in the surrounding areas, these surrounding areas may either develop established populations of the reintroduced species in time, or they will act as a sink without having met the requirements for a viable population.

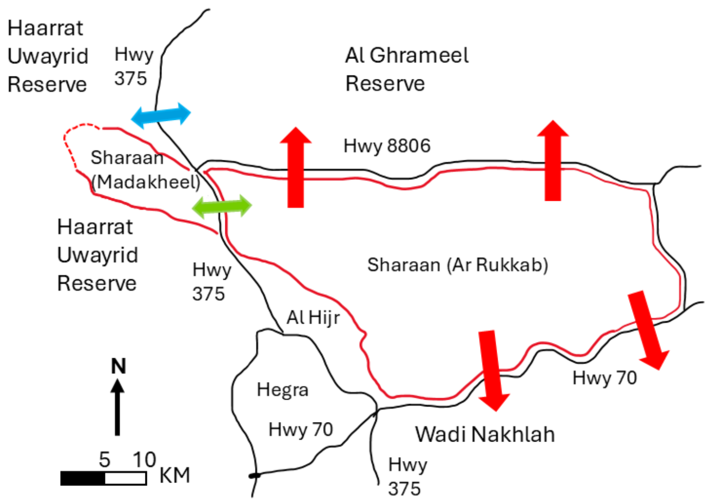

Figure 12: Based on scenario 3, a conceptual map of Sharaan (Ar Rukkab is fully fenced, in red lines)) and surrounding protected areas (Madakheel is partially fenced, in dotted red line; other protected areas are not fenced), the roads that bisect the protected areas (black lines), crossing structures for wildlife (green arrows), at-grade crossing opportunities for wildlife (blue arrows), and one way exits for wildlife out of Sharaan and associated at-grade crossing opportunities for wildlife (red arrows).

Because the Makadheel section of Sharaan is already fenced along the highway, a wildlife crossing structure is appropriate here. However, as Makadheel is open towards the west where it borders Haarrat Uwayrid, livestock species and feral species could enter the Ar Rukkab section of Sharaan which is undesirable. Therefore, the possibility of livestock and feral species barrier may need to be explored at the west side of the crossing structure. For road sections that are not fenced on either side of a road, at-grade animal detection systems could be considered. Note that animal detection systems do not reduce the barrier effect of the road, are high-risk projects, and should only be considered at low traffic volume (Huijser et al., 2015). For the road sections that only have a fence on the Sharaan side (Ar Rukkab) of the roads, wildlife crossing structures would not meet their full potential. Instead, one way exits for wildlife could be explored. These one-way exits should allow native wildlife species to exit Sharaan but keep domesticated species or feral species out of Sharaan.

Research needs:

- Same as the previous section.
- Explore the potential for livestock species (e.g., camels) barriers on the west side of the potential future wildlife crossing structure between Madakheel and the Ar Rukkab section of Sharaan. The objective is to allow wild ungulates to leave the Ar Rukkab section but to deny livestock species and feral species access to Ar Rukkab. Experiments with wildlife-jump outs for captive large wild ungulates and for livestock and feral species could be considered (e.g. test designs that are like those tested by Huijser & Getty, 2023a). These designs could be integrated on the approach of a wildlife crossing structure.
- Explore the potential for livestock species (e.g., camels) barriers on north and south side of the Ar Rukkab section of Sharaan. The objective is to allow wild ungulates to leave the Ar Rukkab section but to deny livestock and feral species access to Ar Rukkab. Experiments with wildlife-jump outs for captive large wild ungulates and for livestock and feral species could be considered (e.g. test designs that are like those tested by Huijser & Getty, 2023a).

3 Specific domesticated species and wildlife issues

3.1 Domesticated species-vehicle collisions

Livestock species (i.e., "camels" or dromedary (*Camelus dromedarius*), domesticated goats (*Capra hircus*), domesticated sheep (*Ovis aries*)) and feral species (i.e., donkeys (*Equus asinus)* and dogs *(Canis lupus familiaris*)) are free-ranging through the area (Figure 13). Livestock vehicle collisions result in vehicle damage, represent a risk to human safety, and cause losses to the owner of the livestock. The impacts of collisions with feral species are similar, except that there is no owner of the animal and thus no economic impact to an owner. Whereas the movement of feral species is not controlled by humans, the movements of livestock species - even if they are free-roaming - are or should be at least somewhat controlled by humans (Huijser et al., 2021).

Figure 13: Feral donkey (Equus asinus), Hwy 375, AlUla, Medina Province, Saudi Arabia.

Free-range livestock grazing is a long-time economic and cultural activity in Saudi Arabia. It included measures to protect against overgrazing, e.g., through the *hema* system (Ghanem & Eighmy, 1984). Free-range livestock grazing is likely to continue, though not everywhere (e.g., not in Sharaan), and potentially better organized and enforced (Figure 14, Figure 15). Measures to reduce collisions with both livestock species and feral species could be warranted, both for human safety and animal welfare reasons. Standard or enhanced animal warning signs are not effective in reducing collisions (Figure 16) (Huijser et al., 2015). Only signs that are specific in time and location with the warning message - e.g., animal detection systems – can be effective in reducing collisions (Huijser et al., 2015). Measures aimed at providing safe crossing opportunities for feral species depend on the long-term objective for feral species. If the objective is to eradicate feral species, then no safe crossing opportunities would be required for those species. The appropriateness of measures aimed at providing safe crossing opportunities for livestock species depend on if and where livestock grazing would be permitted over the next 50-75 years, and if and how much their movements are controlled by humans. Regardless, at-grade crossings, potentially in combination with livestock fences, may be most appropriate and cost-effective for livestock (Huijser et al., 2021). At-grade crossing opportunities can be made safer through having the livestock owners act as traffic guards or having the animals cross where animal detection systems are present, either as a stand-alone mitigation measure or at a gap in a livestock fence (Huijser et al., 2015).

Figure 14: Posted regulations for Algharameel Nature Reserve, including no grazing Hwy 8806, AlUla, Saudi Arabia. Note that the dromedaries are present in the area anyway.

Figure 15: Dromedary (Camelus dromedarius) grazing, north of Hwy 8806, Algharameel Nature Reserve, AlUla, Medina Province, Saudi Arabia.

Figure 16: Animal warning sign, Warning! Camel crossing area ahead, Hwy 8806, AlUla, Saudi Arabia. Note that these types of animal warning signs are not effective in reducing collisions.

Research needs:

- Consider continuing to collect data on the location of roadkilled animals, especially livestock species and feral species. These data can be used to identify locations that may need to be prioritized from the perspective of improving human safety and reducing roadkilled livestock species and feral species. The data may also be used, as an indirect indicator of effectiveness, to evaluate the effect of a sterilization program of feral dogs (Personal comment Holly Marshall). Since large wild mammal species are almost all fenced, current roadkill data is only informing wildlife-based mitigation in select areas (see e.g., section 3.2) (Personal comment Tommaso Savini; Niti Sukumal).
- Consider initiating data collection on the location of life animals, especially livestock species and feral species, along highways. These data can also be used to identify locations that may need to be prioritized from the perspective of improving human safety and reducing roadkilled livestock species and feral species. The data may also be used, as an indirect indicator of effectiveness, to evaluate the effect of a sterilization program of feral dogs (Personal comment Holly Marshall). Furthermore, in areas where wildlife is present, the observations may indicate where safe wildlife crossing opportunities may need to be considered, regardless of whether road mortality has been observed.
- Consider using an app (on cell phones) that can be used to allow for easy data entry of dead and life observations of animals, potentially tracking search and reporting effort for different road sections. The latter is important if the data is used to identify and prioritize road sections for potential mitigation measures which depends on consistent search and reporting effort. The data can be stored with controlled access in a centralized local database (Ament et al., 2018; 2019; 2021).
- Consider implementing a carcass removal program to reduce secondary collisions, e.g., with scavengers) (Personal comment Tommaso Savini; Niti Sukumal) and to potentially improve visitor experience.
- Consider selecting a road section for the implementation of an animal detection system, either as a stand-alone measure or at a gap in a livestock fence. This could start as a demonstration project with input from the local community, including livestock herders. Consider a staged implementation where the reliability of the system is investigated before the warning signs are unveiled (Huijser et al., 2015). If an animal detection system is installed in combination with a livestock fence, consider electrified barriers embedded in the roadway that encourage the animals to cross the road without wandering in between the fences, both at a fence gap and at fence-ends (Huijser & Getty, 2023b).

3.2 Nubian ibex connectivity

There are reports of Nubian ibex potentially crossing a highway that cuts through where a mountain range (Personal comment Emma Gallagher). The location is Hwy 328, between Masader and Jadedah, AlUla, Medina Province, Saudi Arabia. The rocky slopes provide habitat for the Nubian ibex. Given the likely habitat use of the Nubian ibex, an overpass, potentially integrated with existing rocky slopes would likely be most suited to allow for safe crossing opportunities for this species (Figure 17). However, while there are road cuts on the west side of the highway, there are none on the eastside; here there is a desert wash that runs parallel to the road (Figure 18). This means that an artificial rock structure may be required on the east side of the highway. Here, the structure would have to have substantial protection from erosion associated with the desert wash (Figure 18). Note that there is a culvert just north (upstream) of the potential mitigation site (Figure 19). The potential overpass would have to be connected to fences on both sides of the highway for the entire length that the highway cuts through suitable habitat (i.e., the mountain range with its steep rocky slopes) plus an adjacent buffer zone (potentially about 6 km long). Additional crossing structures, including for other species with different habitat requirements, may also need to be considered.

Figure 17: Potential mitigation site for Nubian ibex (Capra nubiana), Hwy 328 between Masader and Jadedah, AlUla, Medina Province, Saudi Arabia. The rocky slope on the right could be integrated into a wildlife overpass.

Figure 18: Potential mitigation site for Nubian ibex (Capra nubiana), Hwy 328 between Masader and Jadedah, AlUla, Medina Province, Saudi Arabia. The rocky slope on the right could be integrated into a wildlife overpass. An artificial rock structure could be considered between the desert wash (far left) and the road (far right). This artificial rock structure could be integrated into a wildlife overpass. Substantial erosion protection would have to be put in place where the structure is adjacent to the desert wash.

Figure 19: Culvert just north (upstream) from the potential mitigation site for Nubian ibex (Capra nubiana), Hwy 328 between Masader and Jadedah, AlUla, Medina Province, Saudi Arabia. The rocky slope on the right could be integrated into a wildlife overpass.

4 Maintenance issues

4.1 Flooding, erosion, and sedimentation impacting wildlife fence

While deserts ecosystems are generally dry, they can also flood and have substantial surface flow. Because desert soil is often highly erodible, the surface flow can carry large sediment loads. Obstacles, including the wildlife fence around Sharaan, can catch sediments resulting in extensive damage (Figure 20). There are no simple solutions for these types of sedimentation and erosion processes. However, experiments with “floating fences” could be initiated (see e.g. Huijser & Fairbank, 2023).

Research needs:

- Identify road sections where surface flow is affecting the wildlife fence around Sharaan.
- Investigate designs, test designs with “floating fences” or other approaches to reduce fence damage because of surface flow and erosion and sedimentation (see e.g. Huijser & Fairbank, 2023).

Maintenance needs:

- Based on the review and tests, conduct fence repairs where needed.

Figure 20: Surface flow and sedimentation damaged the wildlife fence around Sharaan, along Hwy 8806, Alula, Medina Province, Saudi Arabia.

4.2 Erosion at the outflow of a culvert is a barrier to small animal species

Surface flow can be blocked by a road as highways typically sit on embankments. Culverts can relief the water pressure and reduce the likelihood that the roadbed will be saturated and fail because of a blow-out (Figure 21) (Huijser & Walder, 2021). However, the culverts still result in water being concentrated resulting in higher water velocity inside and at the outflow of the culverts. The outflow of culverts is especially susceptible to erosion (Figure 22). Erosion processes can result in a barrier for small species that approach the culvert. The best approach is to increase the culvert size and increase the number of culverts to the point where the waterflow no longer causes substantial erosion. Riprap at the outflow can also reduce erosion, but if culverts are to be used by small species (e.g., reptile species), then the riprap can form a barrier, and potentially even be a death trap (Huijser & Fairbank, 2023).

Research needs:

- Review, and test designs that reduce the erosion processes at the outflow of culverts (see e.g., Huijser & Fairbank, 2023).

Maintenance needs:

- As long as the erosion does not threaten the integrity of the culvert structure or the roadbed, there is no urgent maintenance need.
- As long as the road is not fenced on both sides for small species (e.g., reptiles, small mammals) the erosion at the outflow of culverts is not resulting in an absolute barrier of the road corridor for those species groups. However, extreme road avoidance, i.e., not wanting to cross the pavement at-grade, could result in a substantial barrier effect of the road corridor already, which would make it more urgent to address barriers at the outflow of culverts, as well as the number, location, dimensions, and other characteristics of culverts that may not only need to be based on hydrology, but also on connectivity needs for small animal species.

Figure 21: Inflow of a culvert to address surface flow, along Hwy 8806, AlUla, Medina Province, Saudi Arabia.

Figure 22: Erosion at the outflow of a culvert to address surface flow, along Hwy 8806, AlUla, Medina Province, Saudi Arabia. Note the drop at the concrete which forms a barrier to small animal species. The erosion also is in the process of forming a channel.

4.3 Failing culvert and potential danger of road washing out

A culvert along highway 328 between Masader and Jadedah, is at risk of causing a road blow-out. The culvert seems to have been installed to reduce road flooding, and a channel has been dug on both the inflow and outflow of the culvert. However, the channel has been dug in a very large desert wash (Figure 23). This means that the culvert is extremely undersized compared to the waterflow of the larger desert wash. In addition, the outflow channel goes upslope rather than downslope, resulting in increased sedimentation inside the culvert, and likely also inside the human made channel (Figure 24). At the time of inspection, the culvert (3 adjacent culverts) was largely blocked by sediments (Figure 25, Figure 26). This means that water flow through the culvert is almost non-existent, and moreover, the human-made channel concentrates water at the inflow and can cause saturation of the roadbed. If enough pressure builds, the saturated roadbed could blow-out, resulting in road failure.

Short term action could be to fill the human-made channels (and bury the culverts). While this does not reduce the flooding of the road, it does reduce the possibility of a road blow-out at the culvert. To reduce road flooding, the road should ideally not be in the desert wash. Alternatively, a very large bridge structure (perhaps several kilometers long) could keep the road from flooding.

Maintenance needs:

- Investigate the risk of road blow-out at the culvert with the human-made channels.
- Potentially fill in the channels to reduce the immediate risk of road failure. This may be required before the next major rainfall.
- Investigate alternative measures to reduce road flooding, including rerouting the road out of the desert wash, or constructing a very long bridge (multiple kilometers) where the road is in the desert wash.

Figure 23: Desert wash at the site of a plugged culvert south (downstream) of potential mitigation site for Nubian ibex (Capra nubiana), Hwy 328 between Masader and Jadedah, AlUla, Medina Province, Saudi Arabia.

Figure 24: Human made channel in a desert wash at the outflow of a plugged culvert, Hwy 328 between Masader and Jadedah, AlUla, Medina Province, Saudi Arabia.

Figure 25: Plugged culvert south (downstream) of potential mitigation site for Nubian ibex (Capra nubiana), Hwy 328 between Masader and Jadedah, AlUla, Medina Province, Saudi Arabia.

Figure 26: Plugged culvert south (downstream) of potential mitigation site for Nubian ibex (Capra nubiana), Hwy 328 between Masader and Jadedah, AlUla, Medina Province, Saudi Arabia.

4.4 Dirt road impacting a wetland

A dirt road near Fort Nazar, Kaybar, Medina Province, Saudi Arabia, cuts through a wetland associated with an oasis and date palm plantation (Figure 27). Most of the road length through the wetland is on an embankment, but there is a section of the road that is lowered, resembling a ford (Figure 28, Figure 29). The embankment results in water being held upstream for longer, and the ford concentrates the water flow. Therefore, there is less water in the wetland on the downstream side of the embankment, and the concentration of water, and the higher velocity of water at the ford, has resulted in an erosion gully downstream of the ford that is about 1 meter below the natural soil level (Figure 30). The gully then acts as a drain, dewatering the wetland on the downstream side of the road.

While rerouting the road away from the wetland would be best (avoidance of impacts), a bridge across the entire wetland would be the second choice. However, given the very low traffic volume and speed, one can also consider removing the embankments in the wetland and making the entire wetland crossing similar to a ford. This would reduce water concentration and reduce water velocity, and therefore be more similar to the natural hydrology of the area. This would then keep the wetland downstream from the road wetter across a wider area with less erosion.

Maintenance needs:

- Confirm the observations regarding the current impact of the road on the wetland.
- If confirmed, consider removing the embankment and making the entire road length through the wetland a ford, potentially with a hardened surface that is only minimally above the natural soil level of the wetland.

Figure 27: Wetland looking upstream from the road towards the oasis, near Fort Nazar, Kaybar, Medina Province, Saudi Arabia.

Figure 28: The dirt road is situated on an embankment for a portion of the wetland, near Fort Nazar, Kaybar, Medina Province, Saudi Arabia.

Figure 29: The road goes off the embankment to a ford across the wetland, looking upstream across the road towards the oasis, near Fort Nazar, Kaybar, Medina Province, Saudi Arabia.

Figure 30: Erosion gully downstream from the ford, near Fort Nazar, Kaybar, Medina Province, Saudi Arabia.

5 Summary recommendations

Potential tasks and considerations regarding road ecology in and around AlUla are summarized in Table 1.

Table 1: Potential tasks and considerations regarding road ecology in and around AlUla.

	Scenarios wildlife species				Domestic species
Tasks and considerations	**Current situation (Basic needs)**	**Areas around Sharaan fully fenced**	**Areas around Sharaan partially fenced**	**Areas around Sharaan not fenced**	**Livestock and feral species**
Traffic volumes					
Posted maximum speed limit					
High level vision through roads vs. park roads					
Current wildlife distribution, potentially start using app for observations					
Vision for future (50-75 years) wildlife distribution / methods for recolonization					
Current livestock and feral species distribution, potentially start using app for observations					
Vision for future (50-75 years) livestock and feral species distribution					
Associated vision for mitigation measures (collision reduction and connectivity)					
Monitor large mammal-vehicle collisions (locations, numbers), potentially with app					
Consider implementing a carcass removal program (reduce collisions with scavengers)					

	Scenarios wildlife species				Domestic species
Tasks and considerations	**Current situation (Basic needs)**	**Areas around Sharaan fully fenced**	**Areas around Sharaan partially fenced**	**Areas around Sharaan not fenced**	**Livestock and feral species**
Target species for collision reduction					
Target species for connectivity					
Identify road sections for collision reduction measures (e.g., based on current distribution, future distribution)					
Identify road sections for connectivity measures (e.g., based on current distribution, future distribution)					
Design specifications for fences for the target species (literature review, own data)					
Design specifications for connectivity measures for the target species (literature review, own data)					
Explore implementation animal detection systems					
Lines or cairns in landscape to funnel ungulate movements to crossing areas (literature review, field tests)					
One-way features at crossing structures (keep livestock and feral species out) (literature review, experiments with captive animals)					
One-way features at fence openings (e.g., jump-outs) (keep livestock and feral species out) (literature review, experiments with captive animals)					
Evaluate effectiveness, if possible, based on Before-After-Control-Impact (BACI) study designs					

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