

Trade-offs between utility-scale solar development and ungulates on western rangelands

Hall Sawyer^{1*}, Nicole M Korfanta², Matthew J Kauffman^{3,4}, Benjamin S Robb⁴, Andrew C Telander¹, and Todd Mattson⁵

Utility-scale solar energy (USSE) has become an efficient and cost-effective form of renewable energy, with an expanding footprint into rangelands that provide important habitat for many wild ungulate populations. Using global positioning system data collected before and after construction, we documented the potential impacts of USSE on pronghorn (*Antilocapra americana*), including direct habitat loss, indirect habitat loss, and barrier effects to both resident and migratory population segments. Our case study highlights the challenges that USSE poses to ungulate conservation, including (1) impermeable security fencing that blocks access to and reduces connectivity between formerly available habitats, and (2) the lack of guidelines for minimizing USSE impacts on ungulates. Improved siting and ungulate-specific best management practices would help to minimize habitat loss and retain landscape connectivity. Ungulate biodiversity and ecosystem services (for example, services provided by long-distance migratory species) in arid rangelands are important considerations when balancing the global benefits of renewable energy with local wildlife impacts.

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Renewable energy can help mitigate global climate change but can also cause localized environmental impacts (Moore-O'Leary *et al.* 2017), including habitat loss and fragmentation (Lovich and Ennen 2011). The growing demand for renewable energy in the US is propelled by renewable portfolio standards (Barbose 2019) and wide-ranging policies that support transitioning to a “green economy” (Gasparatos *et al.* 2017). Solar energy comprises an increasing proportion of the growing US renewable energy market and is predicted to provide 40% of the US electric supply by 2035 (US Department of Energy 2021).

As compared to other renewables, solar energy has the lowest life-cycle greenhouse-gas emissions (Hernandez *et al.* 2015b), and in some cases can have high land-use efficiency (that is, amount of energy generated by area) (Hernandez *et al.* 2014). Yet the impacts associated with utility-scale solar energy (USSE; ≥ 1 megawatt [MW]) are evident in the amount of land these installations require, and can be exacerbated in arid landscapes where plant and wildlife communities are especially sensitive to disturbance (Grodsky and Hernandez 2020). With the exception of several avian (Kosciuch *et al.* 2020) and sensitive (Agha *et al.* 2020) species, the potential impacts of solar development on wildlife, and specifically ungulates, are largely undocumented (Lovich and Ennen 2013). As USSE installations expand in size and distribution, understanding the potential effects on ungulates is needed to inform siting and layout design, and to weigh the

broader trade-offs of mitigating climate change against impacts on local wildlife and ecosystem services.

Pronghorn (*Antilocapra americana*) occupy the open plains and arid rangelands of the Intermountain West, an area heavily impacted by fossil-fuel extraction in recent decades (Jones *et al.* 2015). Such habitats are now also hotspots for USSE because of their excellent solar energy potential (Lovich and Ennen 2011) and proximity to states with renewable energy portfolio standards (Barbose 2019). Pronghorn appear especially vulnerable to USSE impacts because they prefer flat, open habitats ideal for solar development. Furthermore, as a wide-ranging species, pronghorn are more susceptible to linear barriers (such as roads and fences) and fragmentation effects than other ungulates (Jones *et al.* 2019; Xu *et al.* 2021).

Unlike other forms of energy development (eg wind or natural gas) that remain permeable to ungulates (Sawyer *et al.* 2013), safety regulations require USSE perimeters be surrounded by 2-m-tall, chain-link fencing (NFPA 2017), making habitat within solar projects inaccessible to pronghorn and other ungulates. In addition to habitat loss, USSE may also alter or block ungulate movements or migrations, depending on site location, size, and layout design. Given the rapid expansion of USSE, it is critical to understand the consequences of habitat loss and identify ways to make USSE more permeable to wide-ranging ungulates to inform stakeholder decisions regarding project siting and design.

We used global positioning system (GPS) data collected from 30 pronghorn before and after the first USSE constructed in the US state of Wyoming to evaluate habitat loss and barrier effects to resident and migratory animals. Our study provided a unique opportunity to quantify impacts from USSE by comparing high-use areas before and after construction. We also used fine-scale movement data to estimate

¹Western Ecosystems Technology Inc, Laramie, WY (*hsawyer@west-inc.com); ²Haub School of Environment and Natural Resources, University of Wyoming, Laramie, WY; ³US Geological Survey, Laramie, WY; ⁴Wyoming Cooperative Fish and Wildlife Research Unit, University of Wyoming, Laramie, WY; ⁵Western Ecosystems Technology Inc, Golden Valley, MN

the extent of barrier effects and we discuss the potential ramifications to resident and migratory ungulates. We use this case study to highlight planning and policy considerations needed to inform USSE siting, layout designs, and the broader trade-offs between reducing global emissions and creating localized impacts on ungulates in western rangelands.

Methods

Study area

Our study area was located in southwestern Wyoming (41.628°N, -109.683°W), adjacent to Highway 372 (Figure 1). With flat and rolling topography, this region is characterized by high-elevation (1920–2030 m above sea level) sagebrush (*Artemisia* spp) communities. High irradiance values, relatively low snowfall, and existing electricity transmission infrastructure make the region attractive for solar development (BLM 2018). The Sweetwater Solar Facility, the first USSE (80 MW) in Wyoming,

was built during the autumn of 2018 on native rangelands managed by the US Bureau of Land Management (BLM). In response to concerns from the Wyoming Game and Fish Department (WGFD) about the facility's proposed square layout potentially blocking pronghorn migration and diverting animals onto Highway 372 (BLM 2018), the developer modified the southwest corner to an angled layout (WebFigure 1) to accommodate pronghorn movements on flat terrain around the west side of the facility (BLM 2018). Following construction in October 2018, the 2.3-km² facility was enclosed with a 2-m-tall chain-link fence topped with three-strand barbed wire.

The project sits in an area designated as crucial pronghorn winter range by the WGFD. The study area south to Interstate 80 supports hundreds of resident pronghorn year-round and hundreds more during the winter, when migratory animals return from their respective summer ranges. In severe winters, the area is also used by >1000 pronghorn from the Opal herd that normally spend winters 20–40 km northwest of the USSE.

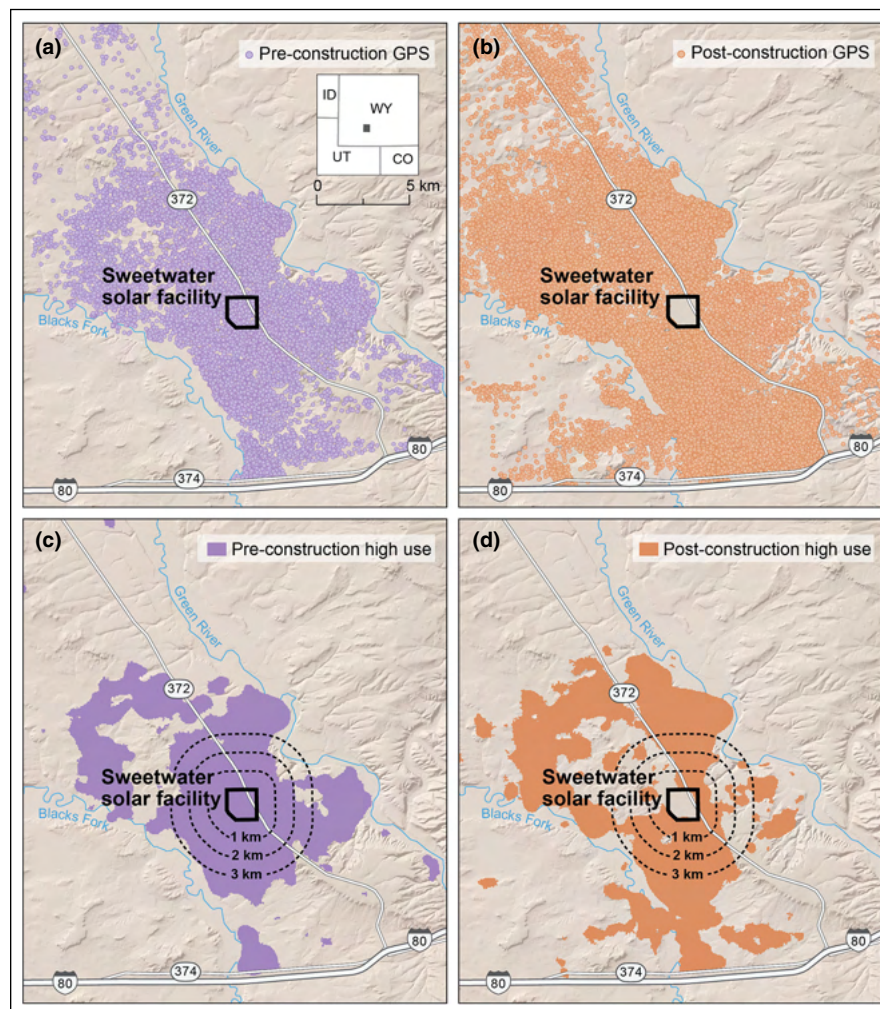


Figure 1. Global positioning system (GPS) locations of resident pronghorn (*Antilocapra americana*; $n = 11$) (a) before and (b) after construction of the Sweetwater Solar Facility, a utility-scale solar energy (USSE) project in southwestern Wyoming. High-use range of resident pronghorn (c) before (01 May–30 Sep 2018) and (d) after (01 May–30 Sep 2019 and 2020) the USSE facility was built.

Data collection

We used helicopter net-gunning to capture 20 adult female pronghorn in February 2018 and an additional three females in November 2018. We fitted each pronghorn with a GPS collar programmed to collect locations every 2 hours through October 2020. Overall, we collected 198,278 locations from 23 individuals, of which 70% ($n = 16$) were non-migratory and 30% ($n = 7$) were migratory. As part of a separate study, we also captured seven pronghorn in March 2017 from the larger Opal herd. Our capture coincided with one of the periodic migrations of this herd through the study area, allowing us to document their migratory movements relative to the USSE site during the spring of 2017, approximately 18 months prior to construction.

Habitat loss and barrier effects

We used several complementary maps and metrics to quantify habitat loss. First, we mapped pre-construction (01 Apr–30 Sep 2018) GPS locations ($n = 25,881$) to visually compare with post-construction (01 Nov 2018–30 Oct 2020) locations ($n = 67,967$). We restricted this analysis to resident animals that had at least one location in, or moved through, the project area prior to USSE construction ($n = 10$). We then used Brownian bridge movement models (Horne *et al.* 2007) to estimate utilization distributions (UDs) from GPS location data. We

calculated UD_s for each individual and then averaged across individuals to estimate pre- and post-construction population-level UD_s (Sawyer *et al.* 2009). We restricted the post-construction UD analyses from 2019 and 2020 to the same date range as pre-construction (01 Apr–30 Sep) to facilitate comparison. We then used the 30% contour of the UD_s (that is, the highest 30% of UD values) to identify high-use areas relative to the USSE before and after construction. To identify potential changes in habitat use adjacent to the USSE, we compared the amount of high-use areas within 1-km, 2-km, and 3-km buffers around the USSE before and after construction. We limited our buffer analysis to 3 km because barrier effects were unlikely to extend farther, and pronghorn movements were restricted by a railroad 3 km to the west and the Green River 3 km to the east. We also used Brownian bridge movement models to estimate the average high-use winter (01 Dec–15 Mar) and summer (01 Jun–01 Sep) range size of all pronghorn from the study area ($n = 23$). On the basis of the average winter and summer range sizes, we then calculated what proportion of each the USSE habitat loss of 2.3 km² represented.

To estimate the extent of barrier effects, we determined the proportion of resident and migratory animals whose movements were affected by the USSE. We identified individual animals as affected by barrier effects if their pre-construction movements (represented by lines connecting GPS locations) were inside of the area or within 500 m of where the USSE installation was subsequently constructed and fenced. The 500-m buffer was based on average step length (454 ± 12 m, mean $\pm$ standard error [SE]) and intended to account for uncertainty in movement between successive GPS locations.

Results

Analysis of the UD_s revealed that the USSE was constructed within a high-use seasonal range of resident pronghorn (Figure 1). Following construction, pronghorn were unable to access habitat within the USSE, losing 2.3 km² of year-round habitat. Pre-construction, high-use areas totaled 110.5 km², including 11.7 km², 26.6 km², and 43.9 km² within the 1-km, 2-km, and 3-km buffers, respectively. Post-construction, high-use areas totaled 106.8 km², including 7.0 km², 15.8 km², and 27.3 km² within the 1-km, 2-km,

and 3-km buffers, respectively. Overall, the amount of high-use areas adjacent to the USSE was reduced by 40% within 1–2 km and by 34% within 3 km following construction (Figure 1). Reduced use was most apparent northwest and southeast of the USSE installation (Figure 1). The average high-use pronghorn summer range size was 18.78 ± 2.41 km² (mean $\pm$ SE), whereas the average high-use winter range was 22.05 ± 2.15 km². The 2.3-km² loss of habitat due to the USSE represented 12% of the average summer range and 10% of the average winter range.

Prior to construction, 69% ($n = 11$) of resident pronghorn used the USSE site and were subsequently forced to alter their year-round movements to accommodate the USSE (Table 1). Only 31% ($n = 5$) of resident pronghorn did not overlap with the USSE and were presumably unaffected by barrier effects. Within the migratory segment, 86% of pronghorn ($n = 6$) moved through the USSE before construction and could no longer migrate through that specific area after construction (Table 1). Most of these migratory movements were to summer ranges approximately 30 km northwest, but some extended up to 225 km (Figure 2). Of the migratory pronghorn sampled from the larger Opal herd that periodically migrates southeasterly and northwesterly through the study area, 57% ($n = 4$) migrated through the USSE site before its construction (Table 1; Figure 3).

Discussion

Solar energy offers an efficient and cost-effective source of renewable energy that plays a growing role in reducing global atmospheric carbon emissions (Moore-O'Leary *et al.* 2017). However, with USSE expansion into western rangelands comes a new set of challenges for managing and conserving ungulates. Other forms of energy development (eg natural gas, wind, oil) typically remain permeable to ungulates (Sawyer *et al.* 2013), and their impacts can often be minimized by consolidating infrastructure and reclaiming disturbed sites (Northrup and Wittemyer 2013). In contrast, habitat within USSE is completely lost because the required security fencing is impermeable to large mammals. Our case study demonstrates that the first USSE constructed in Wyoming was sited on important seasonal pronghorn range that resulted in habitat loss inside and possibly adjacent to the project,

Table 1. Summary of solar development habitat loss and barrier effects to resident and migratory pronghorn (*Antilocapra americana*) in southwestern Wyoming, 2018–2020

Herd segment	Proportion of animals affected	Habitat loss	Barrier effect
Residents	69%	Year-round habitat	Daily and seasonal movements
Local migrants	86%	Migratory habitat	Annual spring and autumn migratory movements
Opal herd migrants	57%	Migratory habitat	Periodic migratory movements

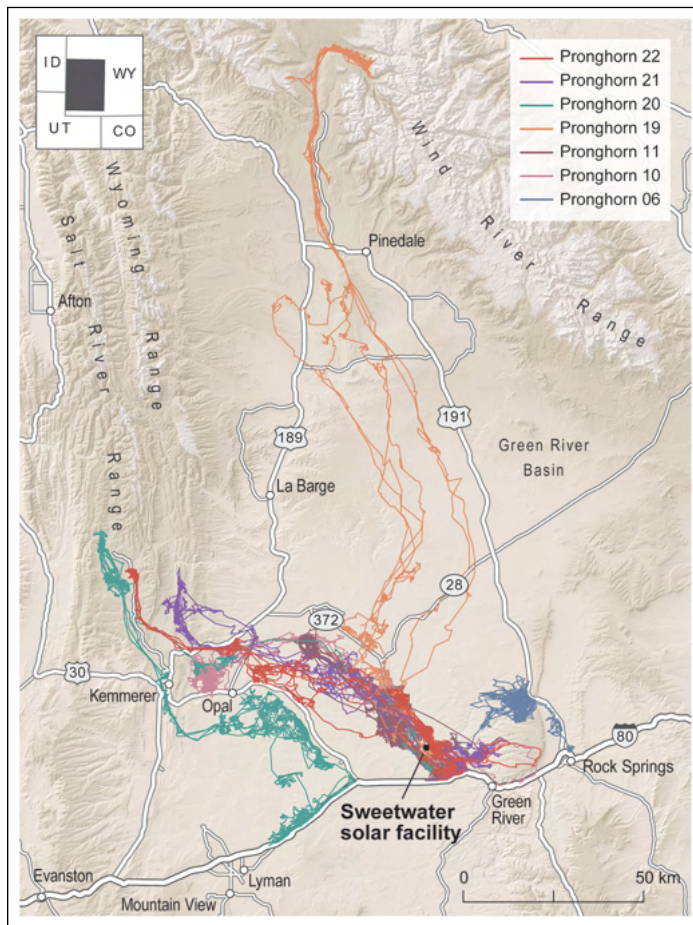


Figure 2. Year-round (2018–2020) movements of migratory pronghorn ($n = 7$) captured in or near the Sweetwater Solar Facility. Most (86%) of these animals migrated through the site's footprint prior to its construction. Pronghorn #19 migrated 225 km to summer range each year: in 2018, 2019, and 2020.

and introduced barrier effects to both resident and migratory herd segments – distinct impacts that other ungulate populations may be exposed to as solar development expands.

Pronghorn directly lost 2.3 km² of high-use habitat, an area equivalent to 10% and 12% the size of the average pronghorn winter and summer core ranges, respectively. Furthermore, the proportion of high-use habitat up to 2 km beyond the USSE declined by 40% following construction. This degree of indirect habitat loss was unexpected because of the relatively low levels of human disturbance (eg traffic, noise, lights) associated with the USSE. Nonetheless, our GPS data collected from the same animals and date ranges before and after construction revealed reduced levels of use to the northwest and southeast of the USSE. We recognize that – relative to other ungulates – pronghorn can be more plastic with respect to movement and site fidelity (Morrison *et al.* 2021), and thus pronghorn possibly shifted habitat use patterns in subsequent years due to factors unrelated to the USSE. However, because no obvious environmental or land-use change occurred following construction of the facility,

we speculate that the indirect habitat loss was related to barrier effects or behavioral responses that modified pronghorn movements beyond the USSE boundary. Indirect habitat loss from avoidance behavior is well documented for ungulates living near conventional forms of energy development (Sawyer *et al.* 2017), including pronghorn (Sawyer *et al.* 2019). Our results suggest that indirect habitat loss associated with USSE may also occur and additional study is warranted.

Although relatively small, the 80-MW Sweetwater USSE was sited where it impacted 69% of resident and 86% of migratory pronghorn, adding to the cumulative effects of existing highways, gravel pits, trona mines (mineral from which soda ash is refined), railroads, and other anthropogenic disturbances. Resident pronghorn lost year-round habitat and had to modify their movements accordingly, and migratory pronghorn could no longer move through the USSE during migration, affecting migrations that extended up to 225 km away. The biological cost of barrier effects on ungulate movements is unclear but is of broad conservation concern and growing research interest (Xu *et al.* 2021). Likewise, more than half the pronghorn we sampled from the Opal herd also lost migratory habitat. Anecdotal evidence suggests that these animals, which only move through the area periodically, currently lack the knowledge or perceptual range to move around the west side of the project area and instead follow the USSE fence east to Highway 372. During one of the Opal herd migration events, several hundred pronghorn encountered the north boundary of the USSE and subsequently moved onto Highway 372, on which they traveled south for several miles (<https://bit.ly/3L7CHA5>). The WGFD opened several right-of-way fence gates and attempted to haze the animals off the highway. Although collisions with vehicles were averted, it was dangerous for both motorists and pronghorn, and several pronghorn that became entangled in fences died. Snow trails indicated that several hundred other pronghorn had indeed moved around the west side of the USSE as intended with the angled-fence layout design. However, given the strong propensity for pronghorn to move parallel to the highway, agencies and industry made the post-hoc decision to create a 50-m-wide corridor between the solar panels and highway right-of-way fencing for the 1.5-km length of the USSE, although at the time of publication this modification had yet to be completed.

Our case study reveals clear impacts of the USSE on resident and migratory pronghorn, raising the question of whether this project could have been sited or designed to better accommodate pronghorn. Ideally, USSE projects are sited in disturbed areas (“brownfields”) or agricultural fields where environmental impacts are largely avoided (Cameron *et al.* 2012; Hernandez *et al.* 2015a,b) and, in some instances, improved with native plant restoration to benefit soils, water quality, pollinators, small mammals, and birds (Semeraro *et al.* 2018; Sinha *et al.* 2018). However, brownfield site

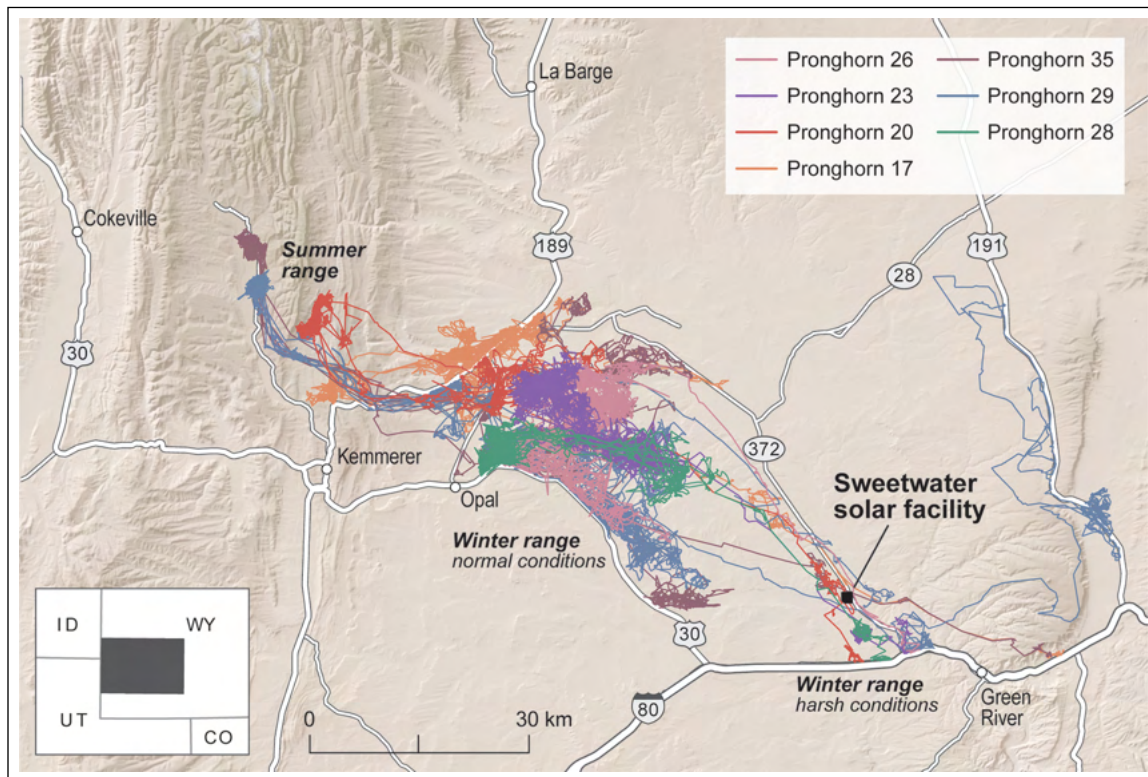


Figure 3. Year-round (2017–2019) movements of migratory pronghorn captured from the Opal herd, which migrates through the study area periodically in response to harsh winter conditions. Several thousand pronghorn utilize winter ranges 10–30 km north of the project area. Most (57%) of these animals migrated through the site of the Sweetwater Solar Facility prior to its construction.

availability varies regionally, brownfields may not be located close to transmission lines or other necessary infrastructure, and brownfields can have unique permitting challenges. Our study area contained no alternate sites that were previously disturbed and available for surface occupancy, and therefore any new development would disrupt native sagebrush grasslands and incur greater environmental costs. Our project relied on federal (National Environmental Policy Act), state (eg industrial siting process), and local (eg county commission) planning to minimize environmental impacts. We suggest these multiple planning levels would benefit from a unified strategy for siting and designing USSE installations to accommodate ungulates.

Regardless of the regulatory framework that a particular project undertakes, planning would benefit from greater access to wildlife movement and distribution data. Widespread use of GPS collars, through programs like those associated with the US Department of the Interior Secretarial Order 3362, has made ungulate migration routes and key seasonal ranges widely available. For example, the US Geological Survey is now collaborating with state wildlife agencies to collate and provide access to ungulate migration and winter range data for the western US (Kauffman *et al.* 2020). Armed with these types of data, solar developers and regulators could improve USSE siting and design layouts to minimize impacts to ungulates. Another challenge for managers is the short duration of USSE construction; unlike other energy

development projects, which often take years to construct, USSE projects can be built within several months, making it difficult to collect sufficient ecological baseline data. Here, agencies and developers were proactive in implementing a pronghorn study immediately after project approval, yet that allowed us only 6 months of baseline data collection prior to construction, a limitation that may have masked or missed important patterns in seasonal use. Given how quickly USSE projects can be constructed, we suggest that state and federal agencies preemptively monitor ungulate movement and distribution in regions where solar development is anticipated.

Although habitat loss due to USSE installations may be unavoidable, thoughtful layout designs that accommodate animal movements can minimize barrier effects and retain the landscape connectivity needed for migratory ungulates. Depending on the size of the USSE, this may require one or more corridors through the project, possibly by splitting the USSE into multiple smaller units to allow ungulate movement in between. Unlike oil and gas development projects, in which managers often consolidate infrastructure (eg drilling multiple wells from a single pad) to minimize impacts (Northrup and Wittemyer 2013), solar arrays may need to be dispersed to accommodate ungulate movements. To date, there are no best management practices (BMPs) or standard corridor widths available to developers and regulators to inform layout design; consequently, we encourage experimentation with fence angles and corridor widths (even if they are relatively small

[eg <50 m]), associated monitoring (eg GPS collars, trail cameras), and consolidation of information to help establish corridor guidelines and BMPs.

The global environmental benefits of renewable energy come at a cost of localized impacts that include loss of habitat, movement options, and possibly ecosystem services associated with affected species (including long-distance migrants). Although it can be argued that impacts to local wildlife from renewable energy are necessary to reduce the far greater risks to global biodiversity incurred from climate change (Allison *et al.* 2014), it is also clear that improved coordination and consideration of local and regional plans to protect wildlife could reduce the local impacts of green energy and climate policies (Jackson 2011). As increasing effort is put into reconciling trade-offs and minimizing local impacts (Santangeli *et al.* 2016; Gasparatos *et al.* 2017), we emphasize the need to consider ungulates – both migratory and resident populations – in future planning and design of USSE facilities. Arid western rangelands are generally not considered biodiversity hotspots, but the unique biological value of these ecosystems is critically important (Durant *et al.* 2012), and they support some of the longest ungulate migrations in the world (Middleton *et al.* 2020).

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Data Availability Statement

Utilization distributions and migration route data are available on the Dryad Digital Repository website (<https://doi.org/10.5061/dryad.djh9w0w14>).

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