Exploring Scientific Approaches to Developing Habitat Connectivity Mitigation

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INTRODUCTION

One of the greatest threats currently facing biodiversity is habitat loss and fragmentation. Changes in land use are expected to be the largest driver of declines in terrestrial biodiversity, with an impact greater than climate change (Sala et al. 2000). As new areas are developed, transportation projects and the construction of roads and highways can have significant impacts on wildlife populations by further disrupting natural movement and migration patterns. These patterns are likely to be exacerbated by climate change and range-shifting species, emphasizing the importance of developing connectivity enhancements. Wildlife crossings, particularly those that incorporate best practices like directional fencing, can have substantial impacts for not only wildlife populations and habitat connectivity, but also for driver safety, by preserving and enhancing connectivity corridors. As climate change continues, connectivity will become increasingly important as species undergo range shifts and redistributions.

Planning for and implementing wildlife crossings is becoming more common, and recent legislation has recognized the importance of wildlife crossings, as well as providing funding to transportation agencies to incentivize development. However, there remains significant barriers to implementation including the high costs, relative novelty, and ecological complexity (McGuire et al. 2020), as well as complicated and often opaque regulatory environments. Mitigation credit agreements (MCAs) for connectivity through the California Department of Fish and Wildlife (CDFW) could offer a potential solution for the difficulties associated with implementing wildlife crossings into transportation projects by increasing access to funding and reducing bureaucratic hurdles (Samanns et al. 2020). The program would create credits that can be used as compensatory mitigation to offset development impacts. As of today, there are no common methods that can be used to measure the value of a wildlife crossing or connectivity enhancements. California is currently the only state in which wildlife connectivity mitigation projects can be used to establish mitigation credits. With the passage of SB790, CDFW can develop a credits-for-connectivity program that can serve as a template for other state and federal agencies. CDFW's guidance would provide great benefit to transportation planners and other interested parties if it were to provide guidance on standardizing metrics and crediting valuation. In addition, clarity around when this mitigation is required by state and federal agencies in California would be valuable to practitioners.

A proposed wildlife crossing structure at Highway 17 can serve as a case study for exploring scientific approaches for developing connectivity mitigation credits. Highway 17 connects the San Francisco Bay area to the Monterey Bay region and is travelled by more than 65,000 vehicles each day and approximately 24 million vehicles a year (Santa Cruz County Regional Transportation Commission 2021). The density of vehicles and characteristics of the road, such as sharp turns and concrete medians, create hazards for wildlife and people, and the highway fragments thousands of acres of protected land as it passes through the Santa Cruz mountains. With construction slated to begin in 2025, the Highway 17 crossing project led by the Midpeninsula Regional Open Space District (Midpen) will restore connectivity for wildlife by linking more than 30,000 acres of protected public lands with a wildlife undercrossing, while a separate pedestrian bridge will connect more than 50 miles of regional hiking trails (Midpeninsula Regional Open Space District 2020). The wildlife crossing would increase habitat connectivity for important regional species, including the mountain lion, California red-legged frog, American badger and Western pond turtle (ICF 2019). Criteria for the wildlife crossing included proximity to an identified wildlife corridor, habitat connectivity, topography, and reduced human exposure.

The estimated costs of the two crossings and directional fencing are expected to range from $31.1 to $39.8 million. Midpen is exploring an MCA with CDFW under the Santa Clara County Regional Conservation Investment Strategy (RCIS) to offset potential ecological impacts of the project, with excess mitigation credits used to help fund construction of the crossings. Mitigation credits would also provide funding for long-term maintenance of the crossings and fencing.

BACKGROUND

There are more than 4 million miles of roads in the United States, but their impacts extend well beyond their footprint. Roads cover approximately 1% of US lands but affect close to 20% – an area larger than the entire state of Alaska (Forman 2000). The most visible ways in which wildlife are affected is through direct mortality, in which individuals are hit by vehicles and killed while trying to cross. While risk of mortality varies between species, no taxa is unaffected. Large, mobile mammals, such as deer or bobcats, are likely to cross many roads due to their large ranges and are therefore highly susceptible to being stuck and killed by a vehicle (Rytwinski and Fahrig 2012). However, smaller animals are just as susceptible. Small mammals and birds are often attracted to roads due to high abundances of resources or fewer predators (Rytwinski and Fahrig 2012). Roadkill or the presence of small mammals in the shoulder present an additional risk to birds of prey as they hunt (Boves and Belthoff 2012). Amphibians and reptiles can be especially vulnerable, as they are typically slow moving and can be drawn to roads for thermoregulation (Glista et al. 2008). For birds and herptiles, road mortality is often tied directly to life history, with mortality increasing during breeding and nesting seasons (Garrah et al. 2015). Breeding populations are increasingly isolated due to fragmentation from roads and infrastructure, increasing the likelihood of long-term impacts to populations.

Mortality risks increase in areas of high road density where animals must make frequent crossings, and road strikes can have long-term effects on the health of a population, as animals killed or injured by a vehicle are often healthier than those removed from the population via predation (Bujoczek et al. 2011). In the Los Angeles metro area, for example, 52% of coyotes and 40% of bobcats were documented crossing roads, representing a significant risk to population sizes (Riley et al. 2006). While population abundances are not always affected by individual collisions, even single mortality events can be concerning for endangered or threatened species (Jackson SD 2000). For example, the Florida panther is the most threatened population of mountain lions in the United States, and 35% of annual deaths are attributed to vehicle collisions (Taylor et al. 2002). In the US, road mortality is a major threat to survival for 21 federally listed endangered or threatened species, including desert bighorn sheep, San Joaquin kit foxes, desert tortoises, and tiger salamanders in California. (Huijser et al. 2008). The land surrounding the proposed site of a crossing structure on Highway 17 contains several species that are listed either federally or under the California Endangered Species Act (CESA), including mountain lions, western pond turtles, California giant salamanders, Santa Cruz Black salamanders, and California red legged frog.

Roads can also lead to reduced population sizes through habitat fragmentation. In addition to directly replacing wildlife habitat, roads can indirectly affect wildlife by reducing the quality of nearby habitats through disturbances such as noise, light, and pollution, including the introduction of salts and heavy metals (Spellerberg 1998, Snell-Rood et al. 2014). Roads also present a barrier to movement, which reduces the accessibility of habitats and other resources (Fahrig and Rytwinski 2009, Beebee 2013). This disproportionately affects species that move frequently or across large areas, or species that move between habitats as part of their reproductive strategies such as amphibians (Carr and Fahrig 2001). As populations become more isolated, a loss of genetic diversity can further endanger wildlife and can make it more difficult to reestablish populations. For example, populations of mountain lions (also known as cougars or pumas) in southern California are small and isolated, geographically separated by a network of roads and highways. To breed, mountain lions in this region must traverse areas of high traffic and high speed, namely interstates I-10 and I-15, and as a result have a mortality rate of 56% (Gustafson et al. 2017). Without movement between populations, mountain lions in the area have lost genetic diversity, threatening the long-term viability of these populations and increasing the risk of extirpation in southern California (Shilling and Waetjen 2023).

Between one and two million collisions with large mammals occur each year in the United States (Huijser et al. 2008), with an estimated one million vertebrate mortalities per day (Forman and Alexander 1998). These numbers only include reported collisions (estimated to be between 4-10 times lower than actual collisions), meaning impacts to wildlife are likely significantly higher than can be determined with existing data. The high number of collisions present a challenge not only to protecting wildlife, but also to motorist safety. Approximately 5% of car accidents are caused by collisions with wildlife (Samanns et al. 2020). This can lead to significant costs for drivers and society, related to vehicle damage, emergency response, and treatment and recovery for injuries. Costs related to reported collisions are estimated to be between $1.1 and 2.2 billion in 2016-2020 (Shilling et al. 2021).

Reducing the number of impacts is important for both motorist safety and wildlife conservation, and wildlife crossing structures and directional fencing play an important role. For example, when a new portion of United States Highway 64 was constructed in Washington County, North Carolina in the early 2000s, the four-lane highway traversed a predominantly agricultural and forested region. Wildlife underpasses and fencing were incorporated into the project design due to high abundances of white-tailed deer, black bears, and endangered red wolves (Jones et al. 2010). At the sites where wildlife crossings existed, there were 58% fewer wildlife-vehicle collisions than at adjacent areas of the highway (McCollister and van Manen 2010). These benefits are further reflected in savings, with crossing infrastructure in Washington state yielding an annual benefit of between $235 to $443 thousand each due to reduced collisions (Sugiarto 2023). Wildlife crossings, particularly those that incorporate best practices like directional fencing, can have substantial impacts for not only wildlife populations and habitat connectivity, but also for driver safety.

Planning for and implementing wildlife crossings is becoming more common. Longstanding regulatory programs within the United States that consider these issues include the National Environmental Policy Act (NEPA). Since NEPA went into effect in 1970, planners have been required to avoid or minimize impacts of infrastructure projects on wildlife populations of concern and to provide appropriate mitigation if impacts cannot be avoided. Wildlife connectivity mitigation can also be required under the Endangered Species Act (ESA) due to potential incidental take, where a transportation project impedes the movement of a threatened or endangered species. Road mortality has been identified as a major threat for 21 federally listed species, which could benefit from the development of wildlife crossings (Bissonette and Cramer 2008, Huijser et al. 2008). The Clean Water Act focuses more on ecosystems than on species but requires similar impact avoidance and mitigation measures to protect wetlands and the associated species that live and reproduce within them. Because many species use wetlands and riparian systems during their lifecycles, ensuring access to these habitats is an important aspect of habitat connectivity.

Several new legislative efforts are also considering these issues. The Bipartisan Infrastructure Law (The Infrastructure Investment and Jobs Act), which became law in November 2021, allocated federal funding for transportation projects and research that increase connectivity and decrease wildlife vehicle collisions. The new law not only recognizes the importance of wildlife crossings, but also provides funding to transportation agencies to incentivize development. Additionally, multiple states have enacted policies around wildlife crossings. Sixteen states have seen executive orders issued or legislation proposed related to habitat connectivity or wildlife migration, representing bipartisan support for this issue (Breuer et al. 2022).

Despite the benefits of connectivity projects, such as wildlife-crossing structures, there are some significant barriers to implementation. The high cost, relative novelty, and ecological complexity of these projects can hinder adoption (McGuire et al. 2020). Additionally, the regulatory requirements can be complex and unclear. The lack of mandates from regulators in certain states on when connectivity is required or the involved permitting process required can hinder projects or lead to delays or additional costs. There are also relatively few cost-benefit analyses, which is a further challenge to balancing ecological impacts with costs (Taylor and Goldingay 2010). Furthermore, project proponents may find it challenging to agree upon success metrics for connectivity projects (Hardy et al. 2003). Constructing wildlife-crossings and other connectivity structures also often requires multi-stakeholder partnerships to leverage funding, as most state transportation departments do not have dedicated funding for wildlife connectivity mitigation (Samanns et al. 2020). The high costs can be further complicated by misalignment of funding schedules (McGuire et al. 2020).

In addition to sharing funding, multiple agencies are often required to collaborate on connectivity projects as they can cross jurisdictional boundaries and require the expertise of multiple agencies. This type of collaboration is vital to a project's success but can prove challenging (Beckmann et al. 2010). Interviews with international practitioners advancing connectivity projects found some core challenges to be planning around uncertain funding for implementation and securing funds for scientific monitoring as well as network and relationship management, such as structuring the network, building relationships, and managing conflict (Brawn 2018).

Finally, incorporating wildlife crossing structures and connectivity enhancements into transportation projects can be difficult within existing systems, which are not set up for mitigating impacts to wildlife connectivity. Conservation banks are a common tool that project proponents can use to mitigate impacts to wetlands, endangered or threatened species, and their habitats. In exchange for permanently protecting or restoring natural lands, banks can sell or transfer habitat credits needed to satisfy mitigation requirements and compensate for environmental impacts of projects. However, while mitigation banks are an important conservation and mitigation tool, there are several limitations. Credits are for in-kind mitigation (for the same species or habitat) within a geographic area, but because banks are by nature off-site mitigation, there is not necessarily equivalency between impact losses and offset gains (Carreras Gamarra and Toombs 2017, Grimm 2022). Additionally, credits are typically calculated based on acreage ratios, which cannot account for ecological complexity. Most significiantly, conservation banks do not always contribute to enhancing regional connectivity as it is not the primary consideration in selecting banking sites (Bunn et al. 2014). For projects that hinder species' movements, conservation banks are unlikely to offset the connectivity impacts.

MITIGATION CREDIT AGREEMENTS

Mitigation credit agreements (MCAs) offer a potential solution to the difficulties associated with implementing wildlife crossings and enhancing connectivity. MCAs can be used to satisfy compensatory mitigation requirements by valuing and implementing mitigation projects, namely connectivity enhancements, ahead of transportation projects and their associated impacts. Advanced mitigation strategies are most effective when they are coordinated at the state or regional level, and MCAs can serve several functions including simplifying the regulatory process, providing an alternative to piecemeal mitigation for individual projects, and contributing to ecosystem or regional conservation efforts (Sciara 2017, Samanns et al. 2020). In California, MCAs are developed within an approved Regional Conservation Investment Strategy (RCIS). The RCIS program, overseen by CDFW, is a voluntary and non-regulatory assessment that serves as a regional conservation planning tool to identify conservation priorities, assist in land use planning efforts, minimize environmental impacts, and reduce mitigation costs using the best available scientific evidence (CDFW 2023). Any person or entity can enter an MCA, with mitigation credits created through implementing the identified conservation actions in an RCIS. Credits can be used for compensatory mitigation for impacts under the California Environmental Quality Act (CEQA), the California Endangered Species Act (CESA), and the Lake and Streambed Alteration Program.

In September 2021, California passed Senate Bill No. 790, which authorizes CDFW to issue mitigation credits to transportation projects that incorporate wildlife crossings. The bill, which went into effect October 8, 2021, directs CDFW to develop guidelines and considerations for issuing credits, which could be used to fulfill compensatory mitigation requirements established by regulatory agencies. The following year, Assembly Bill No. 2344, The Safe Roads and Wildlife Protection Act, was passed. Building on the framework established by SB 790, AB 2344 requires the California Department of Transportation (Caltrans) to identify connectivity needs on state highways. The bill also establishes the Transportation Wildlife Connectivity Remediation Program, administered by Caltrans in consultation with CDFW, to fund projects that facilitate wildlife movement and enhance driver safety.

The first project to generate wildlife connectivity mitigation credits in the United States was the Laurel Curve project, which is located on Highway 17 in Santa Cruz County, CA. In this location, the highway is built over a natural drainage ditch adjacent to 460 acres protected by a conservation easement from the Land Trust of Santa Cruz County. The site is also located within the Sugarloaf Mountain – Montara Mountain Essential Connectivity Area and Santa Cruz Mountains – Gabilan Range Linkage Design, making it an ideal location for a wildlife crossing (Spencer et al. 2010, Penrod et al. 2013). This location of the highway has long been considered dangerous as a high number of wildlife-vehicle collisions occur here due to four lanes of traffic, concrete medians, high vehicle density, and lack of existing crossings. The placement of the crossing at Laurel Curve was determined based on years of research, and construction began in February 2022. The crossing will allow animals to pass beneath the highway using a 13-foot-high and 85-foot-long bridge.

The project resulted in 92 credits, with 46 credits released at the end of each phase. The number of credits was determined by calculating the "road permeability improvement reach dimensions," which is the length of highway for which wildlife passage would be improved with the implementation of a crossing. This consisted of identifying the nearest available crossings or the next potential barriers. Caltrans identified no other structures in a 36.8-acre area that would allow for crossings, and credits were determined by equating 10 credits per acre of this stretch of highway for a total of 368 credits. Caltrans contributed $3.115 million to the project, which was equivalent to 25% of the project and 92 credits, resulting in a price of $33,819 per credit. However, because these credits were established solely based on the area of the wildlife crossing, they do not directly measure ecological benefits.

, California is currently the only state to develop wildlife connectivity mitigation credits, however, there are no common metrics used to quantify the value of mitigation efforts or the number of credits that they could generate (Samanns et al. 2020). This is despite an increasing number of programs and policies that recognize the importance of habitat connectivity and wildlife crossings. CDFW's guidance would provide great benefit to transportation planners and other interested parties if it were to provide guidance and standardization on metrics and crediting valuation. In addition, clarity around when this mitigation is required by state and federal agencies in California would be valuable to practitioners.

ECOLOGICAL METRICS AND METHODS OF VALUING WILDLIFE CONNECTIVITY

There are currently no standardized metrics or methods for calculating credits for wildlife connectivity projects in the United States (Kagan et al. 2014). Crediting and debiting methodologies differ widely with little to no analysis on evaluating the different approaches abilities to accurately assess habitat function or condition (Wilkinson et al. 2017). Acreage ratios are often used in mitigation banks to determine value based on the number of acres impacted, with credits issued for acres that are protected or restored in other areas. However, acreage as a quantification method may not be scientifically robust, as it does not account for ecological or functional gain from a project, but rather makes assumptions about the gain or loss. For example, credits for the Laurel Curve project in Santa Cruz County, California were calculated based on the footprint of the highway reach (36.8 acres) divided into 0.1-acre credits—since California mitigation banks often sell credits in this increment. This project assumed that increased permeability of a larger highway footprint would equate to greater benefits to focal species, which may not be necessarily true. Although the methods are straightforward and repeatable, acreage valuations are unlikely to capture a project's true ecological benefits

Because connectivity projects are meant to enhance population viability for focal species and can provide cascading ecological benefits, scientifically robust metrics that relate to the ecological gain of the project are ideal and are supported by planners and environmental managers (Bennett et al. 2017, Samanns et al. 2020). Regardless of the metrics and methods used, efficacy depends on scientific robustness, transparency, and usability (Wilkinson et al. 2017, Chiavacci and Pindilli 2020). Methods that are difficult to use or understand may not be adopted by practitioners, while methods without a scientific foundation are likely to result in fewer ecological gains (Gonçalves et al. 2015). In addition, metrics should account for function, condition, and landscape context (Wilkinson et al. 2017). Incorporating functional metrics and using habitat quantification tools or modeling approaches can result in a more ecologically relevant crediting framework than traditional acreage assessments.

Function-Based Metrics and Habitat Quality Tools

Function-based metrics assess the value of wildlife connectivity or ecological processes, such as amount of suitable habitat or patterns of wildlife movement (Samanns et al. 2020). For function-based metrics like genetic connectivity, connectivity projects can be monitored at various levels of biological organization (Clevenger 2005). These are: (1) genetic connectivity—movement within populations and genetic interchange, which is low cost, short-term, and could be documented by predominantly adult male movement across road barriers; (2) demographic connectivity—genetic connectivity among populations, which is moderate-to-high cost, more long-term, and could be documented by young females that survive and reproduce; and (3) functional connectivity—genetic and demographic connectivity among populations, which is also moderate-to-high cost and long-term and could include dispersal from maternal ranges, movement in response to environmental change and disturbance, and the long-term maintenance of metapopulations and ecosystem processes as documented by dispersal of young females that survive and reproduce (Clevenger 2005, Samanns et al. 2020). An important consideration, however, is that elusive carnivores and other large mammals may not be suitable focal species for a population-level impact metric due to sample size limitations (Clevenger 2005).

Wildlife crossings can have cascading effects, impacting more than just a focal species, therefore an ecosystem approach to valuing wildlife crossing projects could also be considered. One example of function-based metrics that quantify ecosystem health can be found in the General Crediting Protocol 2.0 developed by the Willamette Partnership (2017). For example, their wetlands assessment protocol assessed 16 wetland functions and values provided by different Oregon wetlands, which were combined into an index of wetland function and multiplied by the wetland acres enhanced, restored, or created to determine credits in units of functional acres (Willamette Partnership 2017). Quantifying the value and diversity of habitat connectivity in this way can account for greater ecosystem functioning than crediting acreage alone. The Willamette credit calculator also accounts for connectivity by giving more weight to sites that are closer to other large uninterrupted patches of the focal habitat type, such as prairie patches (Willamette Partnership 2017). It is important to locate crossings between tracts of intact protected land or with a connection to other high-quality protected lands as carrying capacity increases with increasing protected habitat quality and area (Hodgson et al. 2009). For most species, habitat quality and area are more certain to increase population size than habitat aggregation, unless isolation is the main species constraint (Hodgson et al. 2009).

Because habitat availability is the baseline consideration for where animals will cross, it is important that the land on either side of a potential wildlife-crossing structure is high value, undegraded land. There are also ecosystems or habitats that should be given special consideration, such as wetlands and riparian zones as most wildlife requires access to water. Riparian zones also offer important habitat for wildlife and are critical for wildlife movement (Jensen et al. 2022). Despite comprising a small portion of the landscape, riparian habitats often harbor a disproportionate number of species (Fischer and Fischenich

2000, Catterall et al. 2007). Riparian corridors offer opportunities for movement in undisturbed habitats but are especially important in areas that have been developed as they often are the only remaining link between patches of habitat (Catterall et al. 2007). Protecting these linkages increases the diversity and robustness of populations that may otherwise be isolated.

Habitat quantification tools (HQTS) are an alternative method for crediting, which allows for the incorporation of the relative quality of an area into credit values to reflect ecological benefits. HQTs can also have more ecological relevance than acreage crediting ratios alone, as they involve assessing both the quantity and quality of habitat. HQTs use a formula to calculate credits and debits in functional acres, with credits determined by the difference in existing and post-project conditions. To determine functional acres, the habitat quality is multiplied by the number of acres. A significant benefit of HQTs for a selected species or habitat is that it provides transparency and standardization in the credit quantification process (Pindilli and Casey 2015).

For example, the crediting methodology proposed for Giant Garter Snake habitat in the Mid-Sacramento Valley RCIS region illustrates a potential methodology for assessing habitat quality. Developed by the Environmental Defense Fund, HQTs consider a particular species' habitat needs across its life (e.g., breeding habitat, foraging habitat, shelter habitat), and the condition is assessed at the site, region, and landscape level. The assessed quality is divided into three bins: 1) Unsuitable—there currently is not enough or only low value habitat available that will not support the species throughout its lifecycle, 2) Suitable—the available habitat will support most life stages or activities, and 3) Premium—sites with high foraging opportunities, limited disturbance, and high-quality habitat that will support the species throughout its lifecycle (Environmental Defense Fund 2021). The assessment also incorporated the habitat preference of the species by valuing aquatic features (e.g., wetlands and agricultural canals) at a different rate than adjacent agricultural rice fields, which ensures continued use and management of aquatic features and are therefore necessary for the persistence of the species (Reyes et al. 2017).

Unsuitable habitat types would receive no crediting, while suitable or premium habitats would receive difference credits depending on the habitat type. For aquatic features, premium habitat credits are 1:1 per acre, compared to 1:1.3 for suitable habitat. Because agricultural fields provide less ecological value, premium and suitable habitat credits are 1:3 and 1:5 respectively. For a connectivity project, HQTs could be used to assess the value of the number of acres of home range that are being connected, instead of solely the acres of the project's footprint.

A similar method was used to fund a wildlife undercrossing under Interstate 4, which runs through central Florida from Tampa to Daytona Beach linking the state's east and west coasts. I-4 is a major barrier to wildlife connectivity as it divides the Green Swamp, which has significant ecological and hydrological importance. To promote the movement of both terrestrial and aquatic species across I-4, the Florida Department of Transportation (FDOT) has proposed three undercrossings, with the first located at SR 557 in Polk County. The crossing will link the surrounding area to the 6,093-acre Hilochee Wildlife Management Area – Osprey Unit, which is a critical linkage in the Green Swamp-Hilochee Corridor. By restoring connectivity, the crossings will help link wildlife populations, many of which are facing local extinction due to small populations and low genetic diversity (Hoctor et al. 2000, Larkin et al. 2004).

The crossing is designed to allow large animals like bears and deer to cross beneath the highway, while a channel that runs beneath the bridge supports aquatic connectivity (Florida Department of

Transportation 2020). Because of impacts to the adjacent wetlands, FDOT was able to use mitigation credits for restoration and development of the wildlife crossing. Florida's Uniform Mitigation Assessment Method (UMAM) was used to quantify the potential impacts and the amount of mitigation necessary to offset them. The assessment relies on the assessor's expertise, judgement, and familiarity with a given area or wetland (Reiss and Hernandez 2018). A standardized field protocol exists to limit assessor bias (Bardi et al. 2021).

UMAM evaluates an area through quantitative scoring of a wetland's function or condition, specifically location and landscape support, water environment, and community structure (Bardi et al. 2021). Each category receives a score between 0 and 10, which are combined to give an overall assessment of an area compared to an optimal condition. Additional calculations assess time lag (amount of time required to restore functionality) and risk (the level of uncertainty associated with mitigation efforts) under different mitigation scenarios (Reiss and Hernandez 2018). Impacts are quantified by multiplying the impacted acres by a mitigation delta to determine the mitigation credits or area needed to offset impacts.

For the SR 557 project, the wildlife crossing would directly impact 12.10 acres of wetlands under the US Army Corps jurisdiction with 2.98 acres of secondary impacts, resulting in a functional loss of 6.63 units. The crossing itself would restore 6.25 functional units; the remaining 0.76 units were purchased from a mitigation bank (Shepherd et al. 2023).

Functional metrics have become increasingly common in market-based crediting methodologies (Chiavacci and Pindelli 2019). In addition to the examples provided in Table 1, the United States Geologic Survey (USGS) maintains a comprehensive database of quantification tools used for market-based conservation (Chiavacci et al. 2022).

Table 1. Examples of existing crediting methodologies beyond simple acreage ratio quantification.

Assessment	Organization or Agency	Methodology
Habitat Quantification Tool	Environmental Defense Fund	Functional acres determined by habitat attributes across the full life cycle of a species. Features are measured as percentages of optimal conditions.
Uniform Mitigation Assessment Method	Florida Department of Environmental Protection	Evaluates wetland functions by assessing current condition, hydrologic connection, uniqueness, location, species use, time lag and mitigation risk.
Ecosystem Credit Accounting System	Willamette Partnership	Index of wetland function multiplied by the wetland acres enhanced, restored, or created to determine credits in units of functional acres
Panther Habitat Assessment Methodology	U.S. Fish and Wildlife Service	Habitats are assigned habitat suitability ranks between 0 and 10, with higher values indicating habitats are more likely to be used. Different habitat suitability scores are multiplied by the acreage of that habitat and then summed. This value is then multiplied by a base ratio (amount of

		at-risk habitat within dispersal zones)and a landscape multiplier (location relative to dispersal zones) to determine final Panther Habitat Units.
Utah Prairie Dog Habitat Credit Exchange	Utah School and Institutional Trust Lands Administration	Two credits per Utah prairie dog observed during annual population counts with additional credits in increments of 50 for every additional 25 prairie dogs sustained for 2 years. The maximum number of credits is equal to the number of acres preserved.
Habitat Equivalency Analysis	National Oceanic and Atmospheric Administration (NOAA)	Years of lost services from a degraded habitat can be compensated for by providing acres of additional habitat by calculating a discounted-service-acre-year (DSAY), which represents the value of all of the ecosystem services provided by one acre of the habitat in one year. Services for future years are discounted, placing a lower value on benefits that will take longer to accrue and requiring additional restoration the longer that recovery is delayed.
Resource Equivalency Analysis	National Oceanic and Atmospheric Administration (NOAA)	Resource Equivalency Analysis is used to quantify the number of years lost by habitat degradation with restoration projects designed to restore or create habitat, scaling the size of the project so that it fully compensates for lost years. A discount rate is applied to future years so that additional restoration is required the longer that recovery is delayed.
Stream Quantification Tool	U.S. Army Corps of Engineers	Organizes distinct stream functions into a hierarchical pyramid with parameters. Metrics within each parameter are scored based on optimal conditions to calculate a score for the functional category.
New England District Method	New England District, U.S. Army Corps of Engineers	Modules for different resources (wetlands, streams) that calculates credits as a function of ecosystem condition multiplied by the number of linear feet affected. Credits can be generated for multiple restoration benefits as part of the same project.
The Missouri Stream Mitigation Method (MSMM)	U.S. Army Corps of Engineers, EPA, and the Missouri Departments of Natural Resources, Conservation, and Transportation	The number of credits is determined by multiplying linear feet of mitigated stream length by benefit factors, including functional benefits (e.g., sediment transport, water quality, hydrologic balance and biological support), the type of stream, the importance of the stream to aquatic

		habitat and species, the type of site protection, and the time lag between the impact and offset.
The Wilmington District Method	Wilmington District, U.S. Army Corps of Engineers in collaboration with EPA, USFWS, the North Carolina Division of Water Quality, the North Carolina Wildlife Resource Commission, and the North Carolina Division of Water Resources	Developed specifically for the purpose of assessing the functional benefits of dam removal, "Potential Baseline Credits" are first calculated, which are determined by the linear feet modified by the stream length protection and width of the riparian buffer. These potential credits are multiplied by an adjustment factor based on water quality, aquatic community restoration, and listed species habitat. Additional credits can be awarded for projects that increase anadromous fish passage or human factors (recreational use or scientific studies).

Model-Based Metrics

Model-based metrics are another option for valuing the functional gain of wildlife connectivity projects . Modeling is likely to be less labor-intensive than some function-based metrics approaches, and better at evaluating benefits to multiple species, but it requires significant data and analyses at the outset of a project. Regional connectivity analyses can be a great starting point for available datasets and are often already reviewed and endorsed by regulatory agencies. Wildlife connectivity models, such as those used to identify ideal locations for crossings, can also be used to value connectivity projects based on predicted increases in connectivity. Such models would need to be statistically valid, at the right spatial scale, and with correct assumptions for the characteristics of the focal species (McClure et al. 2016, Samanns et al. 2020). Modelling as an approach to valuing wildlife connectivity projects has the added benefit of being transparent and repeatable (Wilkinson et al. 2017, Samanns et al. 2020). Midpen's proposed MCA project on highway 17 is presented as a case study outlining the data and methodology required.

Various modelling approaches exist to quantify connectivity. Circuit theory modelling has been used to detect and rank barriers to connectivity and movement paths at both large and small spatial scales, as well as to model gene flow (McRae et al. 2008, 2012, Pelletier et al. 2014). Circuit theory uses the same underlying resistance data used by least-cost and other connectivity models, however instead of expressing movement as the least-cost between two focal points, circuit modeling considers the probability of movement of random individuals through a grid cell (Marrotte et al. 2017, Dickson et al. 2019). Centrality analysis is another modelling method. Centrality analysis looks at paths between all possible pairwise combinations of sites to rank each site's contribution to facilitating flow across the network (Carroll et al., 2011).

Graph-theory, as used often in connectivity planning, represents a landscape as a series of nodes, or habitat patches that are connected to some degree (Urban and Keitt 2001). With some modifications, this approach could be used by Midpen to calculate a functional gain metric. Graph theory has previously been used to illustrate gain in connectivity for multiple species in different crossing scenarios. Mimet et al. (2016) presents a methodology for modeling increases in connectivity enhancements consisting of five steps: (1) defining the species groups, (2) land-cover mapping, (3) constructing graphs to model ecological networks, (4) prioritizing crossing locations by connectivity gains, and (5) combining the results in a multispecies diagnosis.

To create a multi-species assemblage, attributes of species in the surrounding area were synthesized based on characteristics important for connectivity (e.g., daily and dispersal distances, area needed for viable habitat) and habitat preferences. Land cover maps that represented different land uses were developed at resolutions of 10 m to assess the impacts of different scenarios on connectivity: a landscape without highways, with over- and underpasses, and with highways but no over- or underpasses. Habitat patches were defined by considering land cover, elevation, and proximity to sources of disturbance, with links between patches determined by least-cost distances. Each type of land cover was classified according to its resistance to species movement based on existing literature. Constructed graphs were based on metapatches sufficiently large and interconnected to support populations over time, using different methods for graph selection depending on whether the species had low or high movement abilities. Computing a global index of connectivity of the network and evaluating the contribution of a crossing along the highway to the connectivity index allowed for calculating connectivity gain for each virtual species. A principal components analysis of the connectivity gain for each species was used to identify best crossing locations in a multispecies approach.

In order to develop a similar model, Midpen would need to gather land-use data and life history data for their focal species – mountain lion *(Puma concolor),* California red-legged frog *(Rana draytonii),* American badger *(Taxidea taxus),* and Western pond turtle (*Actinemys marmorata).* Fortunately, habitat suitability analyses have previously been conducted for these focal species, and patches have already been calculated for mountain lion and American badger for this region as part of the Critical Linkages: Bay Area & Beyond analysis (Penrod et al. 2013). The Critical Linkages analysis was initiated in 2010 to identify areas that are vital for connectivity within the nine-county Bay Area and beyond, including Midpen's proposed MCA project area, to ensure the regions connectivity. This analysis may provide Midpen with data resources and methodology that are more locally relevant and user-friendly.

The data used for the Critical Linkage's habitat suitability analysis included expert consultation and extensive literature reviews for each focal species. Habitat suitability analyses were used to evaluate the quality of potential habitat, ranging from non-habitat to optimal habitat, with patch sizes defined as the habitat needed to support individuals or populations, including core habitat and breeding patches. To conduct a least-cost corridor Geographic Information Systems (GIS) analysis, the resistance surface was defined as the inverse of habitat suitability with endpoints, or cores and patches, of potential breeding habitat identified within each landscape block. The value for each pixel was calculated as the lowest accumulated cost of traveling from a pixel to the source, which was used to identify an appropriate least-cost corridor wide enough to facilitate movement. The least-cost corridors analysis from the Critical Linkages was performed in a broader landscape context with expert input, and all raw data is readily available from CDFW's Biogeographic Information and Observation System (BIOS) or from the Bay Area Conservation Lands Network.

Midpen could adapt this methodology to explore the change in cost of travel for mountain lion and American badger by adjusting the resistance surface to account for a scenario with and without a wildlife undercrossing structure. A potential limitation that would need to be considered is the spatial resolution, as 30 m may not be suitable depending on the area defined for study. Adapting this analysis to calculate the functional gain for Highway 17 undercrossing project would allow for a credit valuation that is scientifically robust, transparent, easy to implement, includes input, and takes into account the landscape context (Wilkinson et al. 2017).

Long-term Monitoring

Monitoring the long-term effectiveness of a connectivity project is essential to meeting objectives and success metrics for mitigation projects. Long-term monitoring is also essential for model validation if a wildlife connectivity mitigation project values its credits with the modelling techniques described previously. However, long term benefits of wildlife crossings have historically not been measured over time, and studies focusing on population-level effects of wildlife crossings are scarce (van der Ree et al. 2009, Taylor and Goldingay 2010, van der Grift et al. 2013). This is likely due to the significant financial and time commitments, with only a limited number of the 460 terrestrial wildlife crossing structures in the U.S. monitored for effectiveness after construction (Cramer and Bissonette 2005, Samanns et al. 2020). The effectiveness of a wildlife-crossing structure can be impacted significantly by the level of maintenance it receives, as directional fence failures, invasive vegetation, and other factors can determine wildlife usage (Glista et al. 2009, Gagnon et al. 2011). Long term maintenance and management funding as well as identification of responsible management entities are barriers to successful implementation of wildlife-crossing projects (McGuire et al. 2020).

For projects that do implement monitoring, most focus on single species usage through camera trapping or footprint tracking (Clevenger 2005, van der Ree et al. 2009, Barrueto et al. 2014, Schmidt et al. 2021). Fish-passage barrier removal projects, for example, often target anadromous fish populations, such as steelhead or salmon due to their need for connectivity between freshwater and marine habitat. Other projects target single species due to incidental take under the Endangered Species Act. For example, United States Fish and Wildlife Service (USFWS) has calculated connectivity mitigation credits for the Florida Panther as they require wildlife crossings and habitat mitigation for transportation projects that adversely affect the Florida panther (Samanns et al. 2020). Use by single focal species, however, does not adequately capture whether a crossing has successfully restored habitat continuity and population processes for all species that may use a crossing.

One important process that conservationists aim to restore with connectivity projects is gene flow, yet there is limited evidence on whether wildlife overpasses and underpasses facilitate gene flow (Corlatti et al. 2009). This could partially be due to the inherent difficulties of studying wide-ranging, fragmentation-sensitive species, with methods that include live-trapping, marking, and closely monitoring fine scale movements of individuals (Nathan et al. 2003, Clevenger and Sawaya 2009, Muha 2021). However, there have been successful demonstrations of non-invasive genetic sampling techniques, like hair-snares, on species such as black bears (Dixon et al. 2006) and grizzly bears (Clevenger and Sawaya 2009). Non-invasive hair, scat, and saliva sampling for large mammals can be used for DNA testing to identify whether movement and dispersal were aided by connectivity features (Waser and Strobeck 1998, Luikart and England 1999, Hardy et al. 2003).Environmental DNA (eDNA) can also be an effective tool for comparing community compositions and abundances before and after connectivity enhancements (Muha 2021).

The ultimate test of a connectivity project is whether community and ecosystem processes have been restored and maintained (Hardy et al. 2003, Clevenger 2005, Taylor and Goldingay 2010). Demonstrating success for functional connectivity metrics takes a significant time commitment, in some cases over ten years (Hardy et al. 2003), which may not make them ideal success criteria for mitigation credits. One recommendation for a project with such success metrics is to have performance-based milestones at various levels of connectivity. For example, the first few years of performance-based milestones could simply be usage or adult male movement. DNA profiling of individuals, as described previously with hair-snare sampling, is a promising technique that takes a relatively short period of only two to three years (Foran et al. 1997). The remaining credit release could be dependent upon reaching some functional connectivity milestones. Having a credit release schedule would also assist managers with long-term operations and maintenance costs, something that has proved challenging (McGuire et al. 2020).

To increase transparency, an additional recommendation would be to develop a repository for data and reports that were generated as part of monitoring. Data from connectivity mitigation projects would show the effectiveness of crossings over time and would allow other project proponents to view the metrics that were used to assess increases in connectivity. These data could also be used to ground truth models, increasing their applicability and usefulness.

DESIGNING EFFECTIVE CROSSINGS

In addition to developing ecologically sound metrics for connectivity, incorporating best design practices into crediting valuation can increase the likelihood that wildlife crossings are effective. Important considerations include identifying a strategic location that will enhance or restore habitat connectivity and compliment wildlife movement corridors, adjacent land use and zoning that is conducive to long-term habitat protection, design characteristics that attract animals and provide habitat, and fencing and other structures that guide animals to crossings (Carr et al. 2003).

The best locations for wildlife crossing structures are areas that already experience high levels of movement or attempts at movement. To be most effective, crossings should be built as close as possible to existing corridors or breeding areas (Mimet et al. 2016). A study conducted at two locations on Colorado highways found that the presence of suitable habitat on either side of the road was the baseline condition required for consistent crossings by mid-size and large animals, especially those which had narrow habitat requirements. Topography also played an important role, where most animals preferred to cross at areas that were not topographically complex. However, even when the surrounding areas were suitable for crossing, the study identified "crossing hotspots," which were most likely to be used. Habitat characteristics that contributed to these hotspots included linear landscape features such as drainage ditches or ridgeways, as well as distance to cover. It is important to emphasize that every landscape and crossing will have a unique set of variables that make it more or less suitable as a crossing site. Therefore, it is important to consider not only species movements, but also the surrounding landscape.

Because habitat availability is the baseline consideration for where animals will cross, it is important that the land on either side of a potential crossing is high value, undegraded land, whenever possible. There are also ecosystems or habitats that should be given special consideration, such as wetlands and riparian zones as most wildlife requires access to water. Riparian zones also offer important habitat for both terrestrial and aquatic wildlife and are critical for wildlife movement, particularly under a changing climate (Jensen et al. 2022). Despite comprising a small portion of the landscape, riparian habitats often harbor a disproportionate number of species (Fischer and Fischenich 2000, Catterall et al. 2007). Riparian corridors offer opportunities for movement in undisturbed habitats but are especially important in areas that have been developed as they often are the only remaining link between patches of habitat (Catterall et al. 2007). Protecting and restoring, as needed, these linkages increase the diversity and robustness of populations that may otherwise be isolated. Similarly, protecting critical habitat for listed species can aid in the protection and long-term persistence of species.

In some cases, it may be necessary to conduct restoration efforts to increase the habitat value of the land adjacent to a crossing. This is likely to be true in areas that are along the few remaining developed locations within an area. It will also be necessary to ensure that the land has long-term protections in place, so that the land will not be developed or otherwise obstructed in the future, which would decrease the value of the crossing.

In addition to ensuring high habitat quality, crossing structures themselves must encourage use by animals. Generally, wildlife crossing structures can be divided into two categories: overpasses that offer wildlife the opportunity to cross over a highway and underpasses (bridges, viaducts, culverts, tunnels, and pipes) that allow wildlife to cross under a highway and that are often designed to carry drainage under the highway as well. Different types of structures have varying success rates, which can also depend on the species. Regardless of the type of structure, crossings should be developed in areas that present the widest possible movement corridor to provide cover for wildlife and prevent edge effects, such as light and noise pollution. As a result, corridors should be wider in areas that are urbanized (Ford et al. 2020). Length to width ratio is also an important consideration, with longer structures requiring greater width (Iuell et al. 2003). Additionally, crossings are most likely to be successful if they appear as uninterrupted habitat, such as by using surface materials that mimic habitat on either side of the crossing (Carr et al. 2003). Whenever possible, native vegetation that can be supported by the soil depth of the crossing structure should be used.

In general, wildlife crossings should attempt to minimize the direct and indirect effects of human activity. For almost all animals, with the exception of habituated species like coyotes, raccoons and skunks, use of wildlife crossings decreases with the presence of humans (Ng et al. 2004, Murphy-Mariscal 2015, Longcore et al 2018). While combined passages that incorporate trails or walkways for humans can be more economical by serving a dual purpose, they are likely to have a smaller benefit to wildlife. Limiting light and sound pollution from roadways is also important, as both have been shown to alter behavior (Davies et al. 2013, Francis and Barber 2013). Light and sound can not only affect the number of animals that use a crossing, but also the diversity of species. Fewer species are likely to use wildlife crossings as sound levels increase (Shilling et al. 2018). Quantifying sound and light levels can help inform the best location for a crossing, while mitigation measures such as noise barriers; earthen berms, and vegetation can further reduce harmful impacts, both at the crossing structure and the approach area (Shilling, Fraser et al. 2022).

A successful crossing will guide animals to the structure and minimize the effects of traffic (Smith et al. 2015). This includes modifications that address light and sound levels, as well as measures that funnel animals toward a crossing. Wildlife fencing has been shown to reduce large mammal collisions by around 80% (P. et al. 2001, Klar et al. 2009), and solid or fine mesh barriers at the bottom of a fence can prevent smaller animals from entering the roadway. Jump-outs and one-way gates can allow animals to escape if they become trapped inside a fenced roadway. A meta-analysis of 50 studies found that mitigation measures such as fencing, crossings, and animal reduction systems reduced roadkill by 40-54%, and that the combination of fencing and crossings was associated with an 83% reduction in large mammal mortality (Rytwinski et al. 2016). Similarly, a study in Utah showed a 98.5% decline in deer mortalities between sites with fences, jump-outs, and underpasses compared to sites without these structures (Bissonette and Rosa 2012).

While the above recommendations are intended to increase use by all species, most crossing structures are implemented as a form of mitigation and there is a strong emphasis on species listed on state or federal endangered species lists. However, incorporating general best practices for crossings can provide benefits to multiple species. This is likely to become increasingly important in the face of climate change, which is already leading to range shifts and distributions on an unprecedented scale (Parmesan and Yohe 2003, Chen et al. 2011). Planning now for landscape connectivity is therefore critical for mitigating future losses (Krosby et al. 2010). Areas that will provide the greatest benefit from increased connectivity include movement corridors, habitat islands that could serve as stepping stones between larger protected areas, and climate refugia (Mawdsley et al. 2009). Refugia are areas that can buffer the effects of climate change, such as increasing temperatures. Habitat connectivity is an important indicator of whether an area will be able to serve as a refuge, as it increases genetic diversity and gene flow allowing for evolution to the changing climate (Epps et al. 2006, Morelli et al. 2017). Because of the uncertainty around how climate change will impact species' movement patterns, it is important to consider innovative and non-traditional approaches to wildlife crossings, such as modular or adaptable designs (Lister et al. 2015). To reduce impacts on communities as a whole, a variety of underpasses and overpasses should be incorporated at frequent intervals to meet the connectivity needs of all species expected to use a given area (Bissonette and Cramer 2008, Little 2003).

Table 2. Best design practices and considerations for wildlife crossing development.

Project Characteristics	**Best Practices & Considerations**
Crossing Location	• Identify sites where animals are most likely to cross or where connectivity improvements are required to facilitate movement at local and regional scales • Locate crossings in areas that will have the largest possible wildlife corridor • Consider target species' home ranges for determining distance between crossings
Habitat Quality	• Protected, undegraded land or land that has been restored to this condition • Important habitats like wetlands and riparian zones
Crossing Structures	• A combination of overpasses and underpasses is most impactful to communities as a whole • Width, length, and openness determine likelihood of use

	• Most effective crossings will be used by multiple species (e.g., incorporating cover for prey species increases number of species) • Funnel species toward crossing structure through the use of fencing, jumpouts, etc.
Minimizing human impacts	• Dedicated crossing structure for wildlife • Limit light and sound pollution
Climate Change	• Linking movement corridors, habitats that are stepping stones between larger protected areas, and climate refugia • Innovative approaches to incorporate climate uncertainty
Ecological Processes and Ecosystem Services	• Encourage multi-species use • Mimic natural conditions as closely as possible (e.g., natural vegetation, stream simulation)

CONCLUSIONS

Mitigation credit agreements for connectivity offer a potential solution for the difficulties associated with implementing wildlife crossings into transportation projects by increasing access to funding and reducing bureaucratic hurdles. As of today, there are no common methods that can be used to measure the value of a wildlife crossing, and California is currently the only state in which wildlife connectivity mitigation projects can be used to establish mitigation credits. With the passage of SB790, CDFW has the opportunity to develop a credits-for-connectivity program that can serve as a template for other state and federal agencies.

Good crediting and debiting methodologies should be scientifically robust, transparent, easy to implement, include input from interested parties, and consider landscape context (Wilkinson et al. 2017). Methodologies that are more ecologically robust than traditional mitigation valuation approaches like acreage ratios are worth exploring for wildlife connectivity project proponents in California, such as Midpen. Some of these methods include function-based metrics that quantify both habitat quality and quantity. Model-based metrics, where connectivity metrics can be calculated before and after wildlife crossing implementation, are also a potential path for valuing mitigation credits. Projects, such as the one proposed by Midpen, may be able to adapt existing models created for regional connectivity analyses, which often have the added benefit of being reviewed and endorsed by experts and regulatory bodies.

In addition to crediting based in ecological value, there are several factors that should be considered for connectivity projects to be successful. Because the ecological benefits of a crossing can take years or even decades to be fully realized, long-term monitoring of species movements, population sizes, and genetic connectivity are critical to determining a project's long-term success. Tying credits to performance-based milestones over a longer duration than the construction timeline can help generate funds for upkeep and continued monitoring. Ensuring the success of a project also depends on leveraging partnerships and existing data from the outset to determine locations for crossings that are both ecologically relevant and feasible in terms of movement patterns and topography.

Using ecology as a foundation for crediting valuation and determining long-term success will make connectivity projects more effective than traditional measures. While land use changes are currently the greatest threat to biodiversity, the synergistic effects of habitat loss and climate change will become more important as climate change continues and accelerates (Mantyka-Pringle et al. 2012). Increasing connectivity between populations and habitats will prevent population bottlenecks, increase genetic diversity and evolutionary potential, and allow more species to reach climate refugia, ultimately protecting biodiversity and species persistence

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