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Toward Understanding the Ecological Impact of Transportation Corridors

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Abstract

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Transportation corridors (notably roads) affect wildlife habitat, populations, and entire ecosystems. Considerable effort has been expended to quantify direct effects of roads on wildlife populations and ecological communities and processes. Much less effort has been expended toward quantifying indirect effects. In this report, we provide a comprehensive review of road/transportation corridor ecology; in particular, how this new field of ecology has advanced worldwide. Further, we discuss how research thus far has shaped our understanding and views of the ecological implications of transportation infrastructures, and, in turn, how this has led to the current guidance, policies, and management options. We learned that the impacts of transportation infrastructures are a global issue, with the potential to affect a wide variety of taxonomically diverse species and ecosystems. Because the majority of research to date has focused on the direct and more aesthetic and anthropocentric implications of transportation corridors, mainly wildlife-vehicle collisions, it is a fairly standard practice to incorporate underpasses, green bridges (i.e., overpasses), fencing, and barriers into road corridors to alleviate such impacts. Few studies, however, have been able to demonstrate the efficiency of these structures. Furthermore, it is becoming increasingly evident that the indirect implications of transportation infrastructures (i.e., behavioral responses of wildlife individuals to roads) may be more pervasive, at least from the standpoint of biological diversity. Understanding how road corridors influence the functional connectivity of landscapes is crucial if we are to effectively manage species of concern. With these issues in mind, we propose a program of study that addresses the indirect and cumulative implications of transportation infrastructure on species distributions, community structure and ecosystem function.

Keywords: Comprehensive review, direct effects, ecosystem function, evaluation, functional connectivity, habitat fragmentation, indirect effects, landscape permeability, transportation corridors.

Summary

The purpose of this report is to provide researchers, land-use managers, and conservation practitioners with a detailed review of the state of the knowledge regarding ecological impacts and implications of transportation infrastructures. Many of the standards and guidelines implemented by transportation and land management agencies in relation to transportation corridors were based on previously published research. Recent and ongoing research has shown that current road management policies may be dated and ineffective. Thus, our objectives were to (1) assess how transportation ecology has advanced, (2) discern whether guidance and policy have effectively been developed in response, and (3) identify areas of research in which there is little or incomplete knowledge. We discuss how research in understudied areas may significantly advance understanding of the overall implications of transportation networks and how this may influence current standards and guidelines.

Our review begins with an overview of how transportation ecology has advanced and shaped our current understanding of the ecological implications of the transportation infrastructure. We then consider the broader as well as more specific implications of transportation corridors and networks on species, communities, and ecosystems, including habitat loss, degradation, connectivity and fragmentation. Next, we discuss current management actions and mitigation implemented to reduce or offset the impacts of transportation corridors on plants, habitats, and wildlife species. We establish that there is a bias in research toward the immediate and direct effects of roads (i.e., habitat loss and fragmentation and road-related mortality). Consequently, current policy and guidelines do not address the indirect (e.g., behavioral avoidance), long-term, or cumulative ecological effects of transportation corridors. Furthermore, very few studies have been conducted to assess the performance of management strategies currently in practice. In the "Informational Needs" section, we highlight four topics of required research to (1) explore the extent to which various species or groups of species avoid transportation corridors, (2) determine the effect of transportation corridors on the functional connectivity of the landscape, (3) investigate the cumulative implications of transportation networks on species and habitat, and (4) understand the cascading implications of the transportation infrastructure on community and ecosystem dynamics. Finally, we present a program of research that we propose to pursue to address areas of required research.

Contents

Background

It is widely acknowledged that transportation corridors affect landscapes, wildlife species, and ecological systems (Fahrig and Rytwinski 2009). For a little over three decades, efforts have been made to understand, quantify, and where possible, offset their impacts. Efforts have primarily focused on road networks, and as a result, spawned a field of science known as road ecology (Forman 1998, Forman et al. 2003, Roedenbeck et al. 2007). Globally roads are common among all landscapes, and relative cover continues to increase with growing human populations (Forman and Alexander 1998). To date, with the exception of Antarctica, impacts and ecological implications of roads have been documented across every continent: North America (Alexander 2008, Ament et al. 2008, St. Clair and Forrest 2009), South America (Coelho et al. 2008, Develey and Stouffer 2001, Laurance et al. 2004), Eurasia (Elazanowski et al. 2009, Grilo et al. 2009, Plaska and Yarovenko 2008), Africa (Laurance et al. 2008, Ndibalema et al. 2008, Weiermans and van Aarde 2003), and Australia (Goosem 2001, Hobday and Minstrell 2008, Lee and Croft 2006).

The most visible, and therefore well-documented, impact of roads is direct mortality of wildlife through wildlife-vehicle-collisions (WVCs) (Coelho et al. 2008, Glista and DeVault 2008, Grilo et al. 2009). Motivated by public safety and economic repercussions (Conover et al. 1995), road ecology research has focused significantly on determining which species (Elzanowski et al. 2009, Glista et al. 2008, Litvaitis and Tash 2008) or groups of individuals are most likely to cause collisions (Barrientos and Bolonio 2009, Rondinini and Doncaster 2002, Steen et al. 2006), when incidents are likely to occur (Lesinski 2007, 2008, Reshetylo and Mykitchak 2008), and locations along road networks that constitute collision "hot-spots" (Alexander 2008, Kolowski and Neilson 2008, Ramp et al. 2005). This information is then used by the appropriate authorities to develop more informed management strategies to reduce incidents (Hobday and Minstrell 2008, Lee and Croft 2006, Orlowski 2008). Where species or habitats of conservation concern are involved, it is fast becoming a standard practice for transportation authorities to address the ecological implications of road networks.

Studies have shown that direct mortality of wildlife individuals on roads can have implications for local population dynamics (Ramp and Ben-Ami 2006); however, direct mortality is not the only consequence of road networks. There are many indirect effects of roads that have far-reaching implications for regional population dynamics, species diversity, and ecosystem function (Bissonette 2002, Reeves et al. 2008). Consequently, transportation policy and decisions often include some level of environmental protection (WDOT 2008). Where there are policies in place, transportation planners and designers are required to offset, where possible, the immediate effects of road construction, including disturbance, habitat loss, reduced habitat quality, and habitat fragmentation (Jaeger et al. 2005, Shepard et al. 2008b). Counter measures and mitigation are likely to include a reduction of the construction footprint, pollution control strategies (such as balancing ponds, weed management, etc.), avoidance of habitats and species of concern through appropriate route design, translocation and relocation of wildlife individuals, enhancement and creation of suitable replacement habitat, and the inclusion of wildlife crossing structures (Bissonette 2002, Forman et al. 2003). Such strategies, however, currently do not necessarily consider implications of roads postconstruction, nor do they consider the cumulative impact of a proposed road development in regard to the existing road network (Belisle and St. Clair 2001). A road can reduce landscape “permeability” (the ease with which organisms can move through a landscape) by acting as a barrier or filter restricting wildlife individuals from accessing available habitat and other valuable resources, or dispersing (van der Ree 2006). We currently know little about the indirect effects (such as the behavioral responses of wildlife individuals to roads). Only a few studies have explored the extent to which road networks influence the functional habitat connectivity of landscapes (Walter et al. 2009). As a result, transportation authorities (or any other responsible authority) are not aware that there is a need to offset indirect effects, nor are there any guidance, mitigation, or management options available to do so.

Furthermore, we know even less about ecosystem-level impacts to roads. Although the majority of studies are species specific, such investigations have shown that wildlife species within every taxonomic group have been affected by the presence of road networks: plants and invertebrates (Munguira and Thomas 1992, Rao and Girish 2007, Severns 2008), fish (Park et al. 2008, Singkran and Meixler 2008), amphibians (Glista et al. 2008, Orlowski et al. 2008, Sillero 2008), reptiles (Andrews and Gibbons 2005, Ashley et al. 2007, Shepard et al. 2008a), birds (Breuer et al. 2009, Dunkin et al. 2009, Orlowski 2008), and mammals (Richardson et al. 1997, Rico et al. 2007, Yale Conrey and Mills 2001). It is therefore not unreasonable to assume that where one or more species are affected by a road, there can be secondary or cascading effects on the other species within an ecosystem. Thus, focusing research and management merely on species of concern may be insufficient. Moreover, any road-related changes in ecosystem dynamics can potentially have an influence on target species despite specific efforts to reduce the impact of roads on those individual species.

This paper provides a detailed, comprehensive review of road/transportation corridor ecology. We discuss how research thus far in this field of ecology has shaped our understanding and views of the ecological implications of transportation infrastructures, and in turn, how this has led to the guidance, policies, and management options currently in practice. Finally, we evaluate how effective available management strategies have been and identify further research needed to better inform future policies and practices.

Patterns and Implications

The development and presence of transportation corridors results in three primary consequences: (1) reduced landscape permeability, (2) habitat loss, and (3) increased habitat fragmentation. These fundamental changes to landscape structure, which can occur during the construction and postconstruction phases of corridor development, can all have profound cascading ecological implications (i.e., direct effects such as increased juvenile mortality, secondary or indirect effects such as reduced reproductive rates, etc.). Below we discuss these implications based on the research conducted to date.

Landscape Permeability

The degree to which wildlife individuals are able to move across a landscape is known as landscape permeability (Andreassen et al.1998, Frair et al. 2008). A landscape is functionally connected (has high permeability) when individuals are able to move unhindered through benign habitats (areas of little or no resource value) to access suitable habitat patches, essential resources, mates, or disperse (Kramer-Schadt et al. 2004). A landscape with low permeability has features that are barriers or filters, which impede movement, potentially limiting individuals from accessing resources (Singleton et al. 2002). Transportation corridors represent such barriers or filters to movement (Dyer et al. 2002, van der Ree 2006). However, it should be noted that the permeability of a transportation corridor is specific to species and can even be specific to groups of individuals within a species (sex, age, or life history stage) (Kerth and Melber 2009, Steen et al. 2006). For example, a corridor acts as a barrier when certain individuals overtly avoid crossing or coming near the corridor. Alternatively, when individuals are susceptible to mortality as a consequence of crossing a corridor, the corridor acts as a filter to movement. Road-related mortality is the most visible and direct effect of roads. It has the potential to significantly affect the dispersal or immigration and emigration rates of wildlife populations as individuals attempt to move across the landscape. As previously discussed, the frequency of WVC has been long recognized as a public safety issue with economic consequences (Allen and McCullough 1976, Dussault et al. 2006, Joyce and Mahoney 2001, Lee et al. 2004). As a result, many investigations have been conducted to determine whether it is possible to predict locations along road networks where WVCs are likely to occur (mortality hot-spots) (Alexander 2008, Kolowski and Neilson 2008, Malo et al. 2004, Ramp et al. 2005) and thus inform management efforts accordingly (Hobday and Minstrell 2008, Lee and Croft 2006). These studies have concentrated on determining the species (Elzanowski et al. 2009, Glista et al. 2008, Litvaitis and Tash 2008) or groups of individuals that are most at risk (Barrientos and Bolonio 2009, Rondinini and Doncaster 2002) and when they are at risk (Barthelmess and Brooks 2010, Joyce and Mahoney 2001, Reshetylo and Mykitchak 2008). For example, freshwater turtle populations in proximity to roads have been found to have skewed sex ratios, as females are very vulnerable to road-related mortality during their breeding season (Gooley 2010, Steen et al. 2006). Such studies have shown that road-related mortality can affect a taxonomically diverse range of species. Not surprisingly, the majority of studies have focused on species that pose a public safety risk, such as deer (*Odocoileus* spp.), elk (*Cervus elaphus*), wolves (*Canis lupus*), bears (*Ursus* spp.), and moose (*Alces alces*) (Mech 1989, Flynn et al. 2008, Puglisi et al. 1974, White and Barten 2009a, 2009b), or represent high-profile cases (both ecologically and aesthetically) (Ramp et al. 2005). Road-related mortality of amphibians and reptiles, for example, has drawn considerable public and scientific attention (Andrews et al. 2006). The seasonal movements of many amphibian species en masse from winter habitat to aquatic breeding habitats have resulted in large numbers of individuals on roads at the same time (Elzanowski et al. 2009, Glista et al. 2008, Orlowski et al. 2008). Not only are these events highly visible and potentially distressing to road users, but in the midst of an amphibian global decline, such mortality is perceived to have severe population implications (Langen et al. 2009, Orlowski et al. 2008, Sillero 2008).

However, only a few studies actually explore the cascading implications of road mortality (such as the population-level impact mentioned above). For example, pied flycatcher chicks (*Ficedula hypoleuca*) in nests close to roads have been shown to have higher levels of mortality (Kuitunen et al. 2003). This is not due to pollution or degraded habitat quality but rather to the road-related death of a parent. Hence, simply focusing on the adult mortality may underestimate the population-level impact of roads (Forman and Alexander 1998). Furthermore, if roads have a population-level implication, how does this influence the local community or the ecosystem dynamics (Bissonette 2002, Clevenger and Kociolek 2006)? These issues represent an avenue of road ecology research yet to be thoroughly explored.

Nevertheless, many studies have been undertaken to identify the factors (particularly those that can be managed) that influence the likelihood of WVC. In addition to season, associated life history stages, time of day, diet, and an individual's size

(Allen and McCullough 1976, Barthelmess and Brooks 2010, Coelho et al. 2008), key factors influencing WVC include habitat variables (e.g., suitable habitat in proximity to roads, such as ponds or woodland edges) (Cain et al. 2003, Kramer-Schadt et al. 2004, Munguira and Thomas 1992, Nielson et al. 2003) and road characteristics (e.g., gap width, road type, traffic volume and speed, surface substrate, etc.) (Hobday and Minstrell 2008, Hubbard et al. 2000, Mazerolle 2004, van Langevelde et al. 2009, van Langevelde and Jaarsma 2004). Road-related mortality of bats, for example, is strongly influenced by the time of year, the use of commuting routes that cross roads, whether young bats are dispersing, whether there is attractive foraging habitat beyond roads near roost sites, the characteristics of their flight (height of flight, speed, and behavior), and traffic volume (Lesinski 2007, 2008; Russell et al. 2009). Recent road-mortality studies have found that factors differ considerably between species and sites (Kerth and Melber 2009). Consequently, whereas it may be relatively easy to identify and predict mortality hot spots for some species, for others, it may be difficult to impossible (Glista and DeVault 2008, Gunson et al. 2009, Litvaitis and Tash 2008). Knowing how to mitigate appropriately for species with unpredictable hot spots is still a major issue for transportation planners. With very few options available to effectively reduce road-related mortality of such species, transportation planners are often forced to implement generic management strategies, such as fencing, to prevent any wildlife from crossing a road (Roedenbeck et al. 2007). However, such strategies may be more detrimental to all wildlife species within a landscape because fenced roads themselves become barriers.

Even without fencing, transportation corridors can represent a physical and behavioral barrier, or partial barrier, to the movement of wildlife (Clark et al. 2001, Rondinini and Doncaster 2002, St. Clair 2003). Yet, only recently have studies been conducted to explore the characteristics of the transportation corridor and its area of influence that contribute to these barrier effects.

Roads are physical barriers in that they offer no cover, thereby exposing individuals to the elements, and they may consist of a substrate that is physically difficult to move across (Richardson et al. 1997, Tremblay and St. Clair 2009, Trombulak and Frissell 2000, Yamada et al. 2009). For example, northern leopard frogs (*Rana pipiens*) have been found to move much more slowly across roads in comparison to other habitats (Andrews and Gibbons 2005, Bouchard et al. 2009). Other studies have shown that landscape features as unobtrusive as dirt tracks can impede the movement of some species (Clark et al. 2001, DeMaynadier and Hunter 2000, Develey and Stouffer 2001, Laurance et al. 2004). Additional features, such as gap width (number of lanes), median, hard versus soft shoulder, ditches, verges (edge of the road), and fencing may constitute additional obstacles to movement (Rico et al. 2007, Swihart and Slade 1984, Yale Conrey and Mills 2001). The median by its very nature is a barrier, and these solid concrete structures often extend for miles, creating a wall that can disrupt wildlife movements (Epps et al. 2005, Forman et al. 2003, Servheen et al. 1998).

However, movement is primarily a behavioral process governed by a set of decisionmaking rules (Severns 2008). Thus, the permeability of a transportation corridor may be influenced simply by how a wildlife individual perceives that corridor. Dictated by environmental cues (such as adequate cover, predators, food resources, etc.) one species may perceive a transportation corridor as a risk, whereas others do not. Those features that are avoided because they are deemed risky or unsuitable by a species become barriers to movement. A few studies have demonstrated that there are a number of species that perceive a road to be a threat and as a result alter their behavior accordingly (Andreassen et al. 1998, Baker et al. 2007, Lovallo and Anderson 1996, Shepard et al. 2008b). For example, black bears (*Ursus americanus*) have been found to shift their home ranges away from areas with high road densities (Brody and Pelton 1989). Similarly, brown hare (*Lepus europaeus*) abundance decreased not only within the road's area of influence but also at the landscape scale as the density of the road network increased (Roedenbeck and Voser 2008). Ultimately, the behavioral responses of wildlife to transportation corridors, and therefore the barrier effects that potentially affect populations, differ considerably among species (Clark et al. 2001, Lima and Zollner 1996, St. Clair 2003). Permeability can be dependent on species size, mobility, behavior, and population densities (Goosem 2001, Singleton et al. 2002). For habitat specialists—forest-dwelling invertebrates, small mammals, or small birds—an open road corridor with grass-covered verges can be a formidable barrier (Rico et al. 2007, Yamada et al. 2009). Similarly, wetland species have displayed a reduced tendency to cross roads (Fahrig et al. 1995).

There are three main road characteristics that are considered to contribute to behavioral responses of wildlife and thus the barrier effects of roads: (1) traffic volume, (2) road width, and (3) road surface (Fahrig and Rytwinski 2009, Forman and Alexander 1998, Tremblay and St. Clair 2009, Yale Conrey and Mills 2001). Because continuing increases in traffic volume is seen to pose a serious ecological concern for many wildlife species, this characteristic of roads has readily been explored (e.g., Ament et al. 2008). Such studies have shown that traffic density is a significant deterrent to wildlife movement (Chruszcz et al. 2003, Eigenbrod et al. 2009, Forman et al. 2002). Both spatially and temporally, road traffic can profoundly influence crossing probabilities and thus the distribution and abundance of wildlife nearby and across the landscape (St. Clair and Forrest 2009). For example, Forman et al. (2002) found that light traffic volume (3,000 to 8,000 vehicles/day) had no significant effect on grassland bird distribution, whereas moderate traffic (8,000 to 15,000 vehicles/day) had an influence within 400 m of a road, and heavy traffic (>15,000 vehicles/day) had a significant impact on the presence and breeding activities of birds up to 700 m from a road. Temporal variation in traffic volume also is an important consideration; increased traffic density during weekends was found to be a significant deterrent to raptor movement (Bautista et al. 2004). However, the barrier effects of roads are most prominent when wildlife individuals respond negatively to multiple characteristics (e.g., road surface and traffic) (Jaeger et al. 2005, McGregor et al. 2008, Richardson et al. 1997).

Lastly, an especially challenging and increasing concern is that barrier and filter effects of transportation corridors will significantly contribute to the loss of species owing to climate change (Parmesan et al. 1999, Thomas et al. 2004). That is, the less permeable the landscape, the less likely species affected by climate change will be able to shift their ranges and move into more suitable habitats. Understanding the role of transportation corridors in reducing or increasing the permeability of landscapes likely will be especially critical when considering the implications of climate change.

Habitat Loss

Road construction results in the direct and immediate loss of habitat (Chen and Chen 2009). The construction of a road and its margins (i.e., soft or hard shoulder, road verges, etc.) often permanently reduces or diminishes (through degradation, see below) available habitat (Maki et al. 2001). Furthermore, the construction footprint (the area required to build the road and associated ecotone edge) represents another immediate source of habitat loss. In some cases this may be temporary (more likely with grassland and scrub habitats), but in others, this can involve deforestation and the draining of wetland habitat up to 60 m on either side of a road (Cui et al. 2009, Thorne et al. 2009).

Habitat degradation—

A transportation corridor can reduce the quality of the immediate surrounding habitat and potentially the quality of habitat farther afield (see below). This is referred to as habitat degradation and is often considered to be another form of habitat loss. Habitat degradation can be brought on by pollution, generally caused by the movement and emissions of vehicles along existing transportation corridors (Forman 2004, Forman and Alexander 1998). In addition, a few studies have shown that the materials and products used to construct such corridors can be a source of pollution (e.g., salts, sediments, and other materials) to surrounding land, air and water resources (van Bohemen and van de Laak 2003). Habitat degradation can also occur through light and noise pollution.

Air resources can be polluted by gas emissions from vehicles, including carbon dioxide, nitrogen oxides, hydrocarbons, and heavy metals (Forman and Alexander 1998, Huang et al. 2009). For example, high concentrations of lead and other heavy metal compounds can be found in plants (including crops) (Kalavrouziotis et al. 2007a, 2007b; Vissikirsky et al. 2008), invertebrates, amphibians, and small mammals near roads (Getz et al. 1977, Jefferies and French 1972). Those compounds can raise mortality rates and reduce reproductive success (Forman et al. 2003).

Studies have also shown that dust generated and disturbed by moving vehicles can influence the composition of vegetation and distribution of wildlife species near roads. The dust that settles on the leaves of vegetation can have two different effects. The first is to reduce the ability of some plants to photosynthesize. In certain species, this may inhibit growth rates, whereas in others, it may cause death (Hirano et al. 1995, Nanos and Ilias 2007, Sharifi et al. 1997). Those plant species able to thrive under such conditions become dominant, replacing dust-sensitive species and thus changing the composition and dynamics of the vegetation community near roads (Farmer 1993, Thompson et al. 1984). The second immediate implication of dust deposition on vegetation is that many wildlife species will not graze on plants covered in dust (Ndibalema et al. 2008). In short, it degrades habitat quality within an area of influence from the road rendering it unsuitable for certain wildlife individuals. The result is that the impacted area is avoided, which in turn may affect the distribution of wildlife across the landscape (Bissonette and Rosa 2009, Eigenbrod et al. 2009, Laurance et al. 2008).

Salt, sediment, and chemical runoff from roads are a primary source of pollution (Evink 2002, Jones et al. 2000, Oberts 1986). Deicing salt leached into the soils and water sources can have far-reaching implications for vegetation and wildlife species composition (Cernohlavkova et al. 2008). Salt-intolerant species are quickly lost as their habitat becomes unsuitable and dominated by more tolerant species (Davison 1971, Forman and Alexander 1998). This form of pollution can have an extensive area of influence. Contaminated water from roads entering the ground water can discharge into streams, rivers, lakes, wetlands, and marine habitats potentially some distance away (Beach 2002, Godwin et al. 2003, Harrison and Wilson 1985, Rosenberry et al. 1999, Williams et al. 2000). Changes in the chemical composition of ground water and surface water from road salt and other chemical contaminants have negatively altered the assemblage of native plant species in aquatic habitats (Dubois 1994, Richburg et al. 2001, Wilcox 1986) and reduced diversity and density of aquatic invertebrates (Blasius and Merrit 2002, Demers 1992). In addition, the dependence of many amphibian species on aquatic ecosystems for at least one life history stage has made this taxon particularly susceptible (Birdsall et al. 1986, Karraker et al. 2008, Turtle 2000). Amphibians in their larva stage exposed to increased concentrations of salt, heavy metals, and other chemical compounds from roads have exhibited physical abnormalities and increased mortality rates (Dougherty and Smith 2006, Karraker 2007, Reeves et al. 2008, Sanzo and Hecnar 2006). Interestingly, although it is widely acknowledged that water pollution has an influence on fish populations, few studies explicitly explore the implications of road runoff on fish mortality, breeding success, fitness, distribution, and abundance (Beach 2002, Forman and Alexander 1998). However, the resulting algal blooms, reduced oxygen, and diminished water clarity owing to road runoff are considered to degrade water quality to levels that many aquatic species cannot tolerate (Forman et al. 2003). Only a few studies have explored the fitness consequences of road-related pollution on mammals and birds. One such study, found that European hedgehogs (*Erinaceus europaeus*) along roadsides had higher ectoparasite burdens which can have fitness consequences (Thamm et al. 2009).

Another primary cause of habitat degradation is the introduction and expansion of invasive plants and wildlife species to habitats and landscapes. Vehicles and thus transportation corridors are considered to be primary vectors for the movement of such species. The introduction, for example, of nonnative plants can lead to significant changes in the composition of the vegetation not only along road margins (Kalwij et al. 2008), but depending on dispersal abilities, may enable plant species to spread into nearby habitats and beyond (Tikka et al. 2001). The cascading ecological implication of this form of degradation is further habitat loss (Kuitunen et al. 1998, Laurance et al. 2008, Weiermans and van Aarde 2003).

Roads also have been avenues for the movement of a number of wildlife species (Forman 1998). In some circumstances, this can be beneficial. As movement corridors, roads have been used by several species (such as declining butterfly populations) to access fragmented habitat patches (Söderström and Hedblom 2007). By increasing the permeability of the landscape, roads contributed to an increase in functional connectivity and population viability. In contrast, many pest species (mostly exotic invertebrates) have been able to more successfully spread and access habitats they can effectively parasitize and thus degrade (Forman and Alexander 1998). In the United Kingdom, for example, road-related mitigation measures are required to prevent gray squirrels (*Sciuris carolinensis*) from accessing red squirrel (*S. vulgaris*) habitat through dispersal along roadside plantings. The introduced gray squirrel effectively outcompetes the red squirrel for food resources, consequently resulting in a significant decline in red squirrel populations (Usher et al. 2003).

Another form of pollution comes from noise generated by passing vehicles during and after construction (Forman 1998, Kuitunen et al. 1998). Many animals have been shown to avoid an area or change activity patterns near roads owing to noise levels (FHA 2004). For example, a number of bat species avoid foraging in suitable habitats next to roads as the noise of traffic can disrupt their ability to echolocate effectively (Kerth and Melber 2009, Schaub et al. 2008). In fact, any species that relies on acoustic communication is likely to be affected by the noise produced by traffic. Recent studies have shown that road-related noise is a significant factor contributing to a reduction in songbird density along roads (Tremblay et al. 2009). Amphibians that use acoustic calls to attract mates either avoid suitable habitat near roads, thus affecting their distribution and abundance (AMEC 2005), or have experienced reduced reproductive rates owing to limited breeding success (Barrass 1986).

Artificial lighting associated with transportation corridors degrades habitat by rendering it unsuitable for the nocturnal activities of many wildlife species. Some bat species, for example, actively avoid roads with lights (Stone et al. 2009, Wray et al. 2005). It is thought that the lighted roadside increases risk to predation much like moonlight (Lang et al. 2006). Conversely, there are bat species that forage for moths and other insects that are attracted to artificial lights (Blake et al. 1994, Rydell 1992). Thus, as an often plentiful source of food, lighted roadsides also can benefit some species that may gain access to food resources without negative consequences.

Modifications and changes to vegetation structure and composition associated with roads and their maintenance may also make roadside habitat suitable for other wildlife species (Forman and Alexander 1998). This can result in an increase in the abundance and distribution of those species along roads (Bissonette and Rosa 2009, Munguira and Thomas 1992, Whitaker et al. 2006), which in turn encourages predators to forage along roadsides and increases their risk of vehicle collision (Barrientos and Bolonio 2009). Under such circumstances, transportation corridors essentially become an ecological trap (Dwernychuk and Boag 1972, Hawlena et al. 2010). That is, wildlife individuals become attracted to what is perceived to be quality habitat but are unable to recognize certain features that reduce the suitability of the habitat and the fitness of individuals that use it. As an ecological trap it creates a sink population; i.e., a habitat in which the rate of mortality is greater than reproduction. Because it attracts individuals from nearby locations, this ecological trap potentially contributes to the depletion of the overall population (Kriska et al. 1998).

Habitat Fragmentation

Habitat fragmentation occurs when changes in habitat configuration occur as a result of the breaking apart of habitat, independent of habitat loss (Fahrig 2003). This is one of the main implications of land use change, and it is widely acknowledged that the construction of transportation corridors is a major contributor (Jantz and Goetz 2008, Kramer-Schadt et al. 2004, Shepard et al. 2008b). Direct effects of habitat fragmentation are an increase in habitat edge (and therefore edge effects), potential isolation of a habitat fragment from other similar habitat patches, and a decrease in average patch size across the landscape.

Isolation and habitat patch size—

Isolation and habitat patch size influence the number of species that are able to persist in a fragment. Small habitat fragments, for example, can only support small populations of plants and animals making these populations more vulnerable to extinction, particularly if they are isolated (Alderman et al. 2005, Richardson et al. 1997, St. Clair 2003). In this way, transportation corridors can also affect source-sink and metapopulation dynamics of species that occur in fragmented landscapes (Andreassen et al. 1998, Bennett 1991, Forman 1998). The long-term persistence of a species with a patchy distribution across a large area (a metapopulation) depends on the rate of extinction in each of the patches and the rate of movement between patches (Singleton et al. 2002). By limiting the movement of individuals between habitat patches, particularly if the patches are not large enough to sustain populations indefinitely, there is an increased risk of local extirpation and reduced population viability (Alderman et al. 2005, Smith and Person 2007). The presence of transportation corridors can both increase extinction rates within isolated patches and restrict movements needed to sustain viable metapopulations.

Finally, habitat fragmentation, and thus the isolation of populations and subpopulations, can have genetic consequences (Strasburg 2006, Yale Conrey and Mills 2001). Habitat fragmentation by roads can increase genetic structure (i.e., distribution of genetic variation) and decrease genetic diversity (i.e., amount of genetic variation). Without sufficient gene flow between populations, population viability is further reduced (Balkenhol and Watts 2009).

Management, Mitigation, and Design

As discussed early on in this paper, current policy, management actions, and mitigation for the impacts of transportation corridors on plants, habitats, and wildlife species tend to focus on the immediate and direct effects of roads (i.e., habitat loss and fragmentation and road-related mortality). Although road ecology, still in its infancy, has demonstrated the obvious effects of roads, such as WVCs, there remains a lack of exploration into the less obvious and indirect (such as behavioral avoidance), long-term and cumulative ecological effects of transportation corridors (Belisle and St. Clair 2001, Chen and Chen 2009). Without a thorough understanding of the indirect and cumulative negative effects of transportation corridors, it will be difficult to implement appropriate mitigation (Cuperus et al. 2002, Roedenbeck et al. 2007).

Equally important is recognizing that many management strategies currently in practice (many of which are prescribed by policy) are poorly understood, and very few studies assess their performance (Clevenger 2005). For example, it is common practice for corridors to be fitted with wildlife crossing structures (Bank et al. 2002, Goosem 2001, McGuire and Morrall 2000). These structures are designed to link critical habitat, increase landscape permeability, and provide safe movement of animals across transportation corridors (Clevenger et al. 2001a, Foster and Humphrey 1995). The two main types of crossing structure are underpasses (culverts and tunnels) (Bond and Jones 2008, Cain et al. 2003, van der Ree 2009) or overpasses ("green" bridges and tree canopy linkages) (Woess et al. 2002). Among the few studies that have examined the performance of crossing structures, all have shown that their use is species specific, and frequency of use is site specific (Bond and Jones 2008, Clevenger and Waltho 2000, Falk et al. 1978, McDonald and St. Clair 2004). In instances where crossing structures have been implemented for a target species and assessed, many other species have been unable to use them (Bissonette 2002, Clevenger et al. 2001b, Mata et al. 2008). Thus, if mitigation measures are to be effective and cost efficient, it is essential that crossing structure designs and configurations achieve stated objectives and goals. Important aspects of crossing structures include size, position, and distribution along transportation corridors (Malo et al. 2004). The type of vegetation management implemented to encourage wildlife individuals to use wildlife crossings is crucial (Grilo et al. 2009, McDonald and St. Clair 2004, Tremblay and St. Clair 2009), as is the use of exclusion fencing or partial fencing to funnel wildlife individuals toward crossing structures (Bond and Jones 2008, Clevenger et al. 2001a, Feldhamer et al. 1986, Foster and Humphrey 1995, Puglisi et al. 1974). Local topography and the arrangement of suitable habitat within the landscape should factor into the location of wildlife crossings (Clevenger and Waltho 2000, Hubbard et al. 2000). For example, land cover and wetland habitat distribution provide information about potential amphibian or reptile mortality hot spots, where crossing structures may be especially valuable (Langen et al. 2009).

Similarly, the effectiveness of median barriers, including cable barriers, three-beam, rumble strips, openings or scuppers, spaced concrete median barriers, remains virtually untested (Clevenger and Kocielek 2006, Hostick and Styskel 2005). For example, one obvious issue with spaced concrete barriers is that snow ploughs tend to block the gaps with snow berms, blocking passageways for wildlife to cross (Barnum 2003).

Also, the effectiveness of traffic calming measures or warning signs as forms of mitigation remains unknown (Knapp 2004, Putman 1997). Although a number of studies suggest that the speed of traffic is a major factor in WVCs, there is little (if any) empirical evidence demonstrating that reducing vehicle speed has been an effective solution (Allen and McCullough 1976, Hobday and Minstrell 2008, van Langevelde and Jaarsma 2004, van Langevelde et al. 2009). Furthermore, the manner and extent to which drivers respond to warning signs is highly debated (Hobday and Minstrell 2008, Knapp 2004). Implementing mitigation measures (e.g., warning or reduced speed signs) for which there is little scientific evidence in support can impede progress in a least two ways: an allocation of resources toward ineffectual management actions, and more importantly, at least for the long-term, a risk that credibility and local cooperation and support will erode.

Finally, there are a number of tools and procedures that can be implemented to prevent or deter wildlife from crossing roads. These include roadside mirrors, reflectors, repellents, and whistles (D'Angelo et al. 2006, Knapp 2004, Ramp and Croft 2006). Such measures are primarily used to reduce WVCs and, by their very nature, exacerbate the ecological impacts of roads by further restricting the movements of wildlife across the landscape (Ikuta and Blumstein 2003). By implementing measures that focus solely on road-related mortality, transportation planners are essentially converting roadways into barriers. The risk of reducing functional connectivity (the degree to which the landscape facilitates or impedes movement among resource patches) for entire ecological communities, as well as target species, should be considered before implementing such restrictive measures, especially in recognition of the ongoing debate over the effectiveness of those measures (Bélisle 2005, Ramp and Croft 2006).

Information Needs

In this section, we highlight and detail issues or circumstances for which there is currently a lack of substantial information regarding the ecological implications of transportation corridors. We have identified four main topics requiring further research, all of which address the less obvious indirect effects of transportation corridors, as this is an area of anthropogenic disturbance that is least understood.

To effectively address and minimize the impact of transportation corridors on wildlife, we need to understand and address all of the potential effects, through appropriate policy and management.

Avoidance Behavior

The majority of studies conducted to date have concentrated on road-related wildlife mortality; largely because of human safety, but also because it is widely recognized that an increase in mortality rates can have profound consequences for wildlife populations. However, the behavioral responses of wildlife to transportation corridors may have equal or greater implications for population persistence by effectively reducing the functional connectivity of the landscape (Shepard et al. 2008b, Zurcher et al. 2010). To completely understand the full range of potential effects of transportation infrastructure on wildlife, we need to focus on the behavioral responses of individuals to roads and other transportation corridors. Specifically, we need to ascertain (1) how wildlife individuals respond to the presence of a road or to traffic on that road (Clark et al. 2001); (2) what characteristics of the road cause a response (e.g., substrate, gap width, traffic volume, etc.) (Richardson et al. 1997, van Langevelde and Jaarsma 2004); (3) the type and extent of response (i.e., level or degree of response) associated with certain road characteristics, alone or in combination (e.g., alert distance, flight initiation distances, time spent fleeing, etc.) (Andrews and Gibbons 2005, Jaeger et al. 2005, Shepard et al. 2008a); and (4) the implications of those responses (such as avoidance, increased stress levels, etc.). By exploring the extent to which individuals respond to certain features and circumstances, we should be able to determine how sensitive different wildlife species will be to a proposed transportation corridor and will be able to develop more informed mitigation measures.

Furthermore, because this area of research is relatively novel and data collection is undoubtedly more complex, there is no standard methodology available. The application of existing techniques (e.g., radiotelemetry, hair snare, harmonic radar, etc.) may need to be modified or innovative techniques devised to effectively conduct appropriate investigations (Balkenhol and Watts 2009). For instance, whereas radiotelemetry is a suitable technique for collecting data on the movements of larger species, this method is often unsuitable or too expensive for smaller species. Transmitters currently glued onto the backs of bats are generally groomed off in less than 10 days, and many species of Microchiroptera are too small for even the lightest transmitters (i.e., transmitters should be <5 percent of an individual’s body mass). This can be a significant limitation to research because smaller species with shorter generation time are likely to yield considerably more information on the effects of roads over a shorter period of time.

Functional Connectivity of the Landscape

For a landscape to effectively sustain viable wildlife populations it needs to facilitate individual movements throughout. This will allow (1) population and genetic interchange, (2) fulfilment of biological requirements (food, cover, and mates), (3) dispersal from maternal ranges and recolonization of habitat patches, (4) redistribution of populations in response to environmental changes and natural disasters, and (5) long-term maintenance of metapopulations, ecological communities, and ecosystem processes.

Determining functional connectivity is thus crucial to understanding how wildlife populations are affected by road networks (in terms of both demographic and genetic consequences). However, only a few studies have explored the extent to which transportation corridors influence the functional connectivity of landscapes (Bélisle 2005, Walter et al. 2009). These types of studies involve more detailed, long-term exploration of wildlife movement dynamics in the presence and absence of roads. Nonetheless, in the midst of human population growth with concomitant creation of roads, as well as climate change concerns, there is clearly a need for such studies. Exploring whether road and other transportation corridors will prevent or hinder range shifts as a consequence of changing climatic conditions may be crucial for the persistence of many species.

Multiple or Cumulative Effects

Research and management have largely focused efforts on addressing individual issues associated with transportation corridors (e.g., WVC, avoidance behavior, habitat fragmentation, or habitat degradation). Relatively few studies consider the combined and potentially synergistic outcome of multiple impacts (e.g., Kuitunen et al. 2003 as an example). However, by not considering cumulative effects, we could potentially misinterpret the population-level impact of transportation corridors. This may be why the majority of studies merely inferred that there could be population-level implications for their target species, but do not explicitly investigate what those implications might be. For example, a large number of studies conclude that road-related mortality of amphibians is a key factor in the global decline of many species. However, very few studies have actually explored the extent to which road-related mortality is influencing such populations, and there has been virtually no consideration of implications for herpetofaunal assemblages or ecological communities

Another fairly neglected aspect of road ecology research is the cumulative effects of road networks (Belisle and St. Clair 2001). Many studies, and certainly most mitigation measures, focus on the impact of a single, specific road coridor.

Typically, neither researchers nor managers consider the overall impact of entire road networks on wildlife. A few studies have shown that increases in road density can influence the abundance and distribution of wolves and bears (Brody and Pelton 1989, Chen and Chen 2009, Mech 1989, Mech et al. 1988, Thiel 1985). What little empirical evidence exists underscores the need for further research that explicitly considers cumulative effects of road networks.

Community and Ecosystem Dynamics

The effects of transportation corridors to ecological communities and ecosystems have largely been ignored (Clevenger and Kociolek 2006, Clevenger and Waltho 2005). The majority of research, and thus management, has been focused on species of concern (e.g., imperiled species) or species that risk public safety (Belisle and St. Clair 2001). However, where one or more species (including nontarget species) are influenced by a transportation corridor or network, it can be assumed that there will be secondary or cascading effects on other species within the ecological community and/or ecosystem. Road-related changes to local ecological communities and ecosystems can potentially have an indirect influence on target species, despite efforts to reduce the impact of roads to those species. Understanding the implications of roads on local community and ecosystem dynamics is therefore essential if we are to address the long-term persistence of individual species and their ecological communities, and encourage healthy ecosystems (Clevenger and Kociolek 2006).

Proposed Studies

We propose a program of study that we believe will yield substantial ecological information on the effects of transportation corridors within all the areas of research identified. Known for their sensitivity to environmental and land use changes at multiple spatial scales, butterflies are what we advocate as an effective model system (Balam-Ballote and Leon-Cortes 2010, Mac Nally and Fleishman 2002). With their short generation time, multiple broods within a season and immediate life cycle responses to environmental cues, butterflies have been used to explore the implications of environmental stochasticity and anthropogenic disturbance, site density-dependence, genetic isolation owing to habitat fragmentation, and species richness as an indicator of habitat quality (Akite 2008, Fleishman et al. 2005, Nowicki et al. 2009, Schmitt and Seitz 2002). Furthermore, butterfly systems are fast gaining recognition as a model predictor for climate change, with multiple species already displaying corresponding population-level trends (Bonebrake et al. 2010, Kharouba and Kerr 2010, Westwood and Blair 2010). Equally important, the following proposed program of study represents the interests and expertise of researchers involved in the development of this problem analysis. Still, our example provides a useful framework for scientists with expertise or interests in other taxa or systems to develop a comprehensive research program that will inform effective planning, policy, management actions, and mitigation measures to reduce the overall impact of transportation corridors to biological diversity globally.

Researchable Questions

1. Do rare butterflies perceive roads differently than common species?

Rationale—Understanding how wildlife individuals move across the landscape can be critical for species conservation. Simply managing habitat patches to ensure the persistence of a population is risky. Without suitable levels of immigration and emigration between habitat patches, the risk of extinction at each patch is high. Thus, conservation efforts could also aim to promote habitat connectivity. Many studies have shown that patch distance is important. The farther apart the habitat patches, the lower the movement rate between patches. However, Euclidian (i.e., straight line) distance between suitable habitat is inconsequential if landscape elements are impermeable, such as when wildlife individuals perceive natural or anthropogenic features dividing the patches as a barrier. The proximate response of organisms to transportation corridors determines “effective” distance (i.e., Euclidian distance with explicit consideration of permeability of landscape elements) between habitat or resources and ultimately determines their ability to exploit or disperse and colonize/recolonize suitable habitat patches.

Overall goal—Determine whether there are generalizable patterns in the response of common and rare butterfly species to transportation corridors. The working hypothesis is that common and widespread species do not perceive roads as barriers to movement, whereas rare and isolated taxa are more sensitive to transportation corridors and thus their ability to move across the landscape is more restricted.

Specific objectives—For each species within a local community (1) quantify the extent to which transportation corridors influence the ability of adult and larval butterflies to move across the landscape, and (2) Identify which characteristics (i.e., traffic volume, substrate, road width, etc.) most affect the permeability of transportation corridors to adult and larval butterflies.

Approach—We will use a suite of observational and survey techniques to document the flight paths, habitat use, and behavior of adult and larval butterflies within each taxa. Simulation models parameterized with field survey data will be used to further examine the sensitivity of adult and larval butterflies to specific features of transportation corridors and generate predictions about each species’ ability to move across landscapes as larva or adults.

Potential impact and expected outcomes—The proposed study is one of the first to investigate how wildlife behavioral responses to landscape features can influence movement dynamics. This study has an applied focus with immediate management implications, as the findings will make significant contributions to effective conservation efforts of multiple species of concern. We believe this research will enable policymakers and managers to direct their conservation efforts more effectively, enhancing the persistence of individual populations and viable metapopulations.

2. Do transportation networks influence source-sink dynamics, metapopulation dynamics, and distribution of butterflies, with specific reference to species of conservation concern?

Rationale—Many conservation programs for species of concern, such as butterflies, recognize the value of establishing and maintaining viable metapopulations. Identifying metapopulation structure and understanding the interpatch movement dynamics of individuals across the landscape are fundamental to developing effective conservation strategies and management practices to enhance metapopulation persistence. Currently, investigators focus on either using demographic parameters to establish metapopulation structure or evaluating the ability of butterflies to move between habitat patches. To effectively understand metapopulation dynamics, and thus devise effective conservation plans, we need to determine the extent to which transportation corridors influence movement of butterflies between habitat patches.

Overall goal—Determine the extent to which transportation corridors influence source-sink and metapopulation dynamics of butterfly species of concern. An equally important outcome is to use the findings of this research to develop effective management strategies to reduce the risk of extinction of target butterfly populations.

Specific objectives—(1) Explore innovative applications of existing technology in the study of source-sink and metapopulation dynamics; (2) develop an effective protocol using harmonic radar to examine the metapopulation dynamics of butterfly populations; (3) use simulation modeling exercises parameterized by empirical data collected during targeted field surveys to examine more fully the metapopulation dynamics of butterfly populations; (4) identify conservation strategies and management practices that will effectively reduce the risk of extinction of sensitive butterfly populations.

Approach—We will use harmonic radar to (1) track the flight paths, habitat use, and behavior of adult butterflies across landscapes; (2) quantify species-specific mobility and movement dynamics; and (3) determine source-sink population structure. We will use those techniques to assess how and to what extent transportation corridors influence intra- and interpatch movement. With this knowledge, we can devise a conservation plan and management practices that increase functional connectivity of habitat patches and reduce the barrier effects caused by the presence of transportation corridors. Through a series of modeling simulations, we will assess the effectiveness of the overall conservation framework. By using a virtual environment, we will explicitly test the implications of each management action and combinations of actions (e.g., habitat manipulation, prescribed burning, habitat corridors) that may otherwise be costly, time consuming, and detrimental to species of concern if resource managers were to implement onsite.

Potential impact and expected outcomes—The proposed research represents the next stage in investigating the extent to which road networks influence population dynamics and metapopulation viability of potentially sensitive species across the landscape. It will provide valuable insights into dispersal, the ability of wildlife individuals to colonize and recolonize suitable habitat (source-sink dynamics), species-specific implications of habitat fragmentation and degradation, habitat connectivity, and species distributions. The development of a simulation tool will be of substantial practical value for studying source-sink dynamics by enabling investigators to examine landscape-level movement patterns and the population structure of an array of species that currently cannot effectively be studied.

3. Are transportation networks hindering the ability of butterflies and bees to pollinate flowers across a fragmented landscape?

Rationale—Entomophily, the pollination of plants by insects, is a fundamental ecological process essential in both natural ecosystems and agriculture. For example, 89 percent of flowering plants are pollinated by animals (Ollerton et al. 2011). If transportation networks are hindering the ability of primary pollinators to reach and successfully pollinate flowers, then ecosystem dynamics and industry may be severely affected. An understanding of the extent to which roads limit pollination is fundamental to effective habitat conservation, the conservation of species of concern (which require specific nectar opportunities), and a pollination-dependent agricultural economy.

Overall goal—Investigate whether the presence and configuration of transportation corridors hinders the ability of primary pollinators (notably bees and butterflies) to successfully move across landscapes.

Specific objectives—(1) Quantify how often butterflies and bees visit and successfully pollinate plants in habitat patches that are isolated by transportation corridors; (2) identify which characteristics (i.e., traffic volume, traffic speed, gap width, substrate, and associated vegetation management) determine the permeability of roads; (3) establish through simulation modeling exercises the implications of existing and proposed road networks on pollination success.

Approach—We will conduct targeted field surveys among habitat patches isolated to varying degrees by transportation corridors to assess how frequently pollinators are able to visit plants. A range of flowering plants will be selected for study, including those with specialist and generalist pollinators (Bascompte et al. 2003). For plants with a limited number of pollinators, additional surveys will be undertaken to assess the sensitivity of these species to roads or to specific characteristics of roads (i.e., type, speed of traffic, volume of traffic, substrate, etc.). This effort will include mark-release-resight, the use of harmonic radar technology to follow individuals, fine-scale movement surveys, and behavioral surveys in proximity to an array of roads that differ systematically. We will use simulation modeling exercises parameterized by field survey data to explore the influence of the existing road network on the ability of focal species to access nectar resources effectively.

Potential impact and expected outcomes—The proposed research represents one of the first studies to investigate the cumulative and cascading implications of road networks on habitat structure and ecological processes that directly alter ecosystem dynamics.

4. Are transportation networks hindering the ability of wildlife to successfully respond to climate change?

Rationale—Transportation corridors represent barriers and filters to movement. Barrier effects occur when animals consciously avoid crossing or approaching a road. A corridor acts as a filter when some individuals are killed when attempting to cross the corridor. By reducing landscape connectivity, it is reasonable to expect that the effects of transportation corridors can significantly contribute to the loss of species (and biodiversity) owing to significant habitat shifts associated with climate change. That is, the less permeable landscapes become as a result of roads, the less likely such species will be able to adjust their geographic ranges to occupy suitable habitat. Understanding the role of transportation corridors in reducing the permeability of the landscape almost certainly will be a critical consideration when addressing the implications of climate change.

Overall goal—Forecast the potential consequences to select species and ecological communities of the cumulative effects of transportation corridors on the ability of the local fauna to respond to habitat shifts resulting from climate change. Because transportation corridors alone can act as barriers or filters to movement, we hypothesize that the cumulative effects of road networks will significantly reduce (and potentially prevent) the ability of road-sensitive species to colonize or recolonize suitable habitats. Thus, if climate change alters the suitability of existing habitats, resident species negatively affected by road networks will be unable to expand into suitable habitats.

Specific objectives—(1) Map expected local and regional shifts in climate and vegetation using climatic envelope models (e.g., Peterson et al. 2002); (2) use data from previous studies to quantify the extent to which roads restrict the ability of adult butterflies (for each species) to move across the landscape; (3) develop a spatially-explicit, species-specific geographic information system-based model of varying migration probabilities to quantify the likelihood that butterflies will be able to shift to emerging new habitat; these dispersal estimates will be incorporated into envelope models, which typically have simplistic assumptions about the likelihood of dispersal under climate change (Botkin et al. 2007); (4) develop a set of preemptive measures to reduce the anticipated cumulative impact of climate change on the regional diversity of endemic butterflies.

Approach—The proposed research will integrate existing data from climate change models and previous studies of butterflies and transportation corridors. Climate change models will be used to forecast local and regional shifts in climate and vegetation along a varying temporal dimension. Across a range of butterfly species within a local community, data from sensitivity assessments of those species to roads, or to specific characteristics of roads (i.e., type, speed of traffic, density of traffic, substrate, etc.), will be incorporated into species-specific, spatially-explicit simulation models to generate migration probability surfaces across the landscape and regionally. A modeling approach can be used to predict how the existing transportation network configuration will influence the range shift for varying time horizons of a target species.

Potential impact and expected outcomes—The proposed research represents the first effort to quantify the influence of transportation corridor networks on wildlife responses to climate change. The results of this effort will provide valuable insights into species-specific migration capabilities and expected distributional patterns of several endemic and ubiquitous butterfly species under a range of simulated climatic and transportation network scenarios. This new knowledge will establish a framework for developing an effective conservation plan to reduce projected impacts of climate change on local and regional biological diversity through an understanding of how butterflies with varying sensitivities respond to a range of climatic and anthropogenic circumstances.

Metric Equivalents

When you know	Multiply by:	To find:
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	0.62	Miles
Hectares (ha)	2.47	Acres
Kilograms per hectare (kg/ha)	0.89	Pounds per acre
Square meters per hectare (m^2/ha)	4.37	Square feet per acre
Celsius (°C)	1.8 + 32	Fahrenheit

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