CLIMATE CHANGE AND CONNECTIVITY: ARE CORRIDORS THE SOLUTION?

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ABSTRACT

This paper reviews the significance and use of conservation corridors at different geographic scales (local, regional and continental) as a conservation management tool to mitigate the effects of climate change on habitat and biodiversity. Species' habitats are affected by habitat fragmentation, degradation, and now, climate change. The theory of island biogeography holds that the number of species within any given habitat patch exists in a dynamic equilibrium between extinction and colonization. Consequently, a general principle of biodiversity conservation has emerged stating that practitioners should try and connect habitat patches wherever possible. Conservation corridors are habitat strips connecting two main patches together because habitat fragmentation can disrupt natural population dynamics by reducing species dispersal and even causing local extinctions. Climate change will cause changes to mean annual temperature, precipitation patterns, the incidences of severe weather events, and the frequency and intensity of disruption regimes (ex: forest fires). The effects of climate change as well as habitat degradation and fragmentation will compromise species' ability to adapt their habitat ranges to new climate. An analysis of case studies from the peer-reviewed literature shows that the implementation of corridors at broader scales would best mitigate the effects of climate change and maintain the integrity of ecosystem processes.

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1.0 INTRODUCTION

1.1 RESEARCH OBJECTIVES

Conservation corridors serve to link patches of habitat together and are either artificially created through landscape restoration or follow remnant natural landscape features such as gallery forests and riparian corridors. Their effectiveness in increasing connectivity has been both supported and contested. While some studies show that corridors do in fact facilitate dispersal by increasing immigration and emigration rates and effectively improve gene flow from one habitat patch to another, other studies conclude that they can also act as conduits for the spread of diseases, exotic species, and disturbances, such as floods and wildfires (see review in Beier and Noss 1998). The efficacy of conservation corridors is important to consider since habitat loss and degradation is currently one of the main threats to biodiversity.

Species' habitats face two primary sources of stress, both anthropogenic in nature: habitat loss (or the related process of habitat fragmentation) and climate change. The goal of this project is to establish the significance and use of conservation corridors of different types and at different scales as a tool for responsive conservation management under the continued threat of climate change. These goals are achieved by accomplishing the following steps:

1. Defining the types of corridors that have been used based on both their habitat and their scale
2. Using the forecasted climate change-induced habitat losses and threats
3. Establishing the characteristics of both the corridor and the surrounding matrix which can affect the effectiveness of a corridor. This is done by assessing changes in a certain targeted biological property, including genetic drift, re-colonization after a habitat disturbance or local extinction, and migration. The characteristics

used to define the applicability of a corridor were compiled from the available literature either in the form of explicit tables or as described variables in the study.

4. Determining the effects of the selected species on the studies' results
5. Examining some of the current policies regarding habitat management in light of climate change and determining their relevance based on the conclusions found here regarding the type and the scale of the corridor.

2.0 METHODOLOGY

All research was supported by a thorough literature review of peer-reviewed scientific articles and books. The majority of the literature used in this paper was published within the last ten years, ensuring that the most recent findings were reported. This project's scope was limited to the available, published data in peer-reviewed journals and in books, as well as by the fact that many of the studies are not replicable due to their scale.

In selecting the studies to be examined in this report, it was important to choose a variety of conservation corridor types: there needed to be a variety of habitats, of focus species or taxonomic groups, and of matrices. Consequently, this report features recent studies that examined the role of conservation corridors in rainforests, rainforests along rivers (riparian), agricultural systems, montane habitats, and coniferous forests for example (see Appendix B). While some studies focused on the use of conservation corridors by a single species or taxon, others examined the role of conservation corridors across multiple taxa. As such, this report presents results relevant to avian species, plant communities, insects, amphibians, and mammals, from rodents to top carnivores.

The studies examined were selected because of their diversity of systems but also because they present an assortment of climate-change and anthropogenic threats. These direct anthropogenic habitat loss and fragmentation threats include the intrusion of cattle from adjacent ranches and the intensity of farming systems. As a result, all of these systems are facing two pressures: habitat loss and degradation from the above threats as well as rapid climatic changes which affect habitat quality. Studies reflecting different scales were selected in order to examine the relationship between habitat preservation and connectivity and climate change. The studies are considered in light of current and ongoing climatic changes like rising temperatures and an increased fluctuation in weather patterns. The chosen studies examine the different roles of corridors: immigration, movement, prevention of genetic drift, and reducing the effects of demographic stochasticity.

Studying conservation corridors immediately implies that the habitat is, in some way, fragmented. But it was further important to study fragmented systems experiencing land-use threats and climate change threats because there is a very close relationship between these two pressures. "For example, a doubling of CO_2 concentration can lead to a production increase of 15-50%, depending on crop and weather conditions, which would have major effects on the area needed for farming" (Opdam and Wascher 2004). As such, it is critical to study the effects of climate change on current habitat networks and examine the importance of preserving and improving habitat connectivity by way of conservation corridors.

Defining the characteristic features of each scale fell into one of two categories: either determining the physical dimensions that would define each scale, or defining each scale by the ecological functions and processes it protects. Giving each scale physical dimensions in meters or kilometers was too arbitrary for this project, although practitioners may find it useful to have scale dimensions for different ecosystems. A thorough literature review supported the idea that processes are scale-dependent and as such, each scale was defined in terms of its level of connectivity to another corridor system.

The effectiveness of the conservation corridor was evaluated based on two factors: the study's reported values on the measured feature (genetic drift, number of species, reported usage by a species, mortality in the matrix vs. mortality in the corridor), and through a critical examination of the corridor system's resilience in the face of climate change.

3.0 BACKGROUND INFORMATION ON CONSERVATION CORRIDORS

3.1 THEIR USES AND SCALE-DEPENDENCY

Different types of corridors characterize the connectivity of the landscape and at different scales (local, regional, and continental). Conservation corridors can be defined as a "linear, two-dimensional landscape element that connects two or more patches of wildlife (animal) habitat that have been connected in historical time" (Soule and Gilpin 1991). They are surrounded by a matrix of degraded, mostly unsuitable habitat. The scale of a conservation corridor system is defined by the ecosystem processes it preserves. For example, a local conservation corridor which connects a woodlot to another woodlot with a river allows for the preservation of that river system. A regional corridor system would include the majority of the watershed or many interconnected local corridors, while a continental conservation corridor would connect the watershed to either another watershed or another regional scale corridor system. "Functional connectivity is a scale-dependent feature that depends on the spatial scale at which individuals perceive and interact with landscape structure by dispersal" (Steffan-Dewenter *et al.* 2002). Because each species perceives connectivity in relation to its own characteristics (size, dispersal patterns, etc.), it is difficult to define scales with respect to a single species: what may be a movement corridor to one species may include the full habitat range of another. As such, it is important to recognize the role of processes in addition to the scale at which they operate.

For example, soil quality is integral to habitat quality. The scale at which soil decomposers can colonize new habitat patches is a function of the scale of the corridor system: small and distant patches are less successfully colonized than larger, closer patches (Rantalainen *et al.* 2005). Since soil quality is such a vital component of habitat quality and in turn the maintenance of biodiversity, it is important that the scale at which these processes operate is understood and taken into account when designing conservation corridor systems (Rantalainen *et al.* 2005). This approach recognizes the importance of the preservation of ecosystem functions and processes as well as the interconnections at all scales: the local conservation corridor is at its strongest when it is part of a broader network of habitat connectivity (see Appendix A). This nested design approach strengthens the value of conservation corridors at all scales and provides the strongest resilience in the face of climate change because it best preserves connectivity between the most habitat types.

For biodiversity, conservation corridors have four primary reasons to exist (Simberloff *et al.* 1992):

1. To increase the rate of species immigration rates by connecting one habitat patch to another and allowing for the movement of individuals
2. To provide movement routes for species with large home ranges whose habitat is otherwise completely fragmented, for daily foraging for resources, for seasonal relocation, and for the dispersal of individuals

3. To decrease inbreeding depression by increasing the number of individuals in a species, and
4. To reduce demographic stochasticity: should an event (e.g. disease) jeopardize a population

3.2 ISLAND BIOGEOGRAPHY THEORY

The study of the interactions between and within discrete habitat patches embedded in a different matrix allows scientists to better understand the impact of connectivity on species distribution and ecosystem health. Like islands, habitat patches are surrounded by a different matrix. Island biogeography theory states that the number of species within any given patch exists in a dynamic equilibrium between extinction and immigration. Individuals from a species can migrate to and from a habitat patch using conservation corridors as a conduit for this movement. Consequently, a general principle of biodiversity conservation has emerged stating that practitioners should try and connect habitat patches wherever possible to accomplish the four functions of conservation corridors: to increase immigration, to prevent genetic inbreeding, to increase movement across fragmented home ranges, and to prevent demographic stochasticity. A great deal of attention and effort has been placed on implementing this principal into conservation programs at local, regional and continental scales by way of conservation corridors.

Habitat fragmentation can disrupt natural population dynamics by reducing species dispersal and even causing local extinctions. The species' characteristics put them at different levels of vulnerability to extinction (Purvis *et al.* 2000):

1. Small populations are at a higher risk than large populations. Habitat loss and degradation combined with the effects of climate change exacerbates population declines by reducing

the availability of suitable habitat. Moreover, inbreeding and low population densities also make small populations more vulnerable to extinction.

2. Highly endemic and specialized species are at a higher risk of extinction because they are so adapted and specialized for a particular habitat that they cannot migrate and adapt to a new habitat or set of climatic conditions. They have likely evolved in isolation from other predators and competitors and so they are very susceptible to extinction in the face of newly introduced species. Furthermore, they likely have small habitat ranges and small populations.
3. Species higher on the food chain are more vulnerable to extinction as they depend on other species' survival (chains of extinction) and often have larger home ranges. This has great significance in the analysis of studies about corridor use since the chosen specie's use of a corridor is a factor of its trophic level.
4. K-selected specialists living in habitat patches are more vulnerable to extinction because they produce fewer offspring that take longer to reach maturity. This means that they are less able to compensate for increased mortality with increased fecundity, increasing their vulnerability to extinction.
5. Highly social species with complex mating and foraging social structures are at risk because survival of individuals depends on the survival of the group.
6. Species with a large habitat range are especially vulnerable to habitat degradation and loss because their fragmented habitat exposes them significantly to the negative impacts of edge effects. Being bigger and more visible, they are also more likely to roam in the matrix, further exposing them to hunting.

7. Species that have a large body size are more susceptible to extinction because they tend to be K-selected specialists, have large home ranges, low population densities, and are more vulnerable to hunting.
8. Diurnal species are vulnerable because they display many of the above species: they are social, they have large home ranges, and have large body sizes.

In assessing the conservation role of corridors in mitigating the extinction of species, it is important to consider the focal species in the study and whether it is especially prone to extinction as based on the above criteria.

3.3 THE IMPACT OF CLIMATE CHANGE ON BIODIVERSITY

The impact of global climate change on biodiversity is complex. The rise in greenhouse gas emissions has caused global temperatures to change, affecting regional precipitation patterns, and causing changes in disturbance regimes, including in the length and intensity of forest fires (Opdam and Wascher 2004). Extensive habitat fragmentation, changes to disturbance regimes, habitat destruction and degradation from anthropogenic sources and global climate change complicate habitat and species management plans. Flexible, multi-scenario management plans must be created in order to address the needs of an ever-changing climate and habitat.

Global climate change will impact habitat by causing the loss of colder climate habitats and by increasing the incidence of intense weather events such as droughts and coastal floods (Opdam and Wascher 2004). One of the anticipated climate change scenarios describes a situation where habitats with the most altitudinal gradient could ideally provide the most adaptability to climate change, allowing for the "linear migration of all remaining habitats upslope" (Halpin 1997). However, even the "top habitat" has its limits and most habitats do not even have an altitudinal gradient. Conservation managers must develop creative methods to maintain the integrity of the habitat-species relationship, in particular for habitat specialists who are most likely to be locally extirpated or globally extinct as their distinct habitat characteristics are jeopardized.

Even local reforestation initiatives cannot completely recreate a desired habitat for a species in a timely way. The red-backed vole (*Clethrionomys gapperi*), a habitat specialist preferring closed-canopy old growth forests lives side-by-side with the deer mouse (*Peromyscus maniculatus*), a habitat generalist, in a more limited closed-canopy forest area despite there being nearby newer growth forests (Mech and Hallett 2000).

A species' ability to cope with habitat loss and degradation due to climate change is influenced by a number of factors (Halpin 1997), including:

1. the rate of climate change as influenced by anthropogenic greenhouse gas emissions and land use changes
2. the species' ability to migrate to more suitable habitat as dictated by its habitat range, habitat connectivity, and the actual mobility of the species (ex: plants that are wind vs. animal dispersed)
3. the biological competition between co-existing species: generalists and specialists adapt differently to habitat loss and degradation, since generalists may be able to better utilize resources and survive in the degraded habitat than specialists
4. changes in the ecosystem's disturbance regime (ex: the length and intensity of a forest fire may impact the suitability of a habitat for a species)

5. physical barriers to migration and use of suitable habitat: an unsuitable matrix which increases their risk of predation, urban development and sprawl which fragments a habitat

In general, individual members of species respond to changing habitats and climates by adapting their habitat range to the stress(es) in question, be it climate change, fragmentation, or both (Lyons 2003). The reconstruction of past ecosystem community structures has shown that communities are highly variable and can very often present non-analog scenarios, or perhaps it is that modern ecological communities have no past analogs. Late Pleistocene and late Holocene mammal assemblages show that in response to receding glaciers, certain species (montane vole (*Microtus montanus*) and eastern chipmunk (*Tamias striatus*)) migrated gradually westward following the changing precipitation pattern along a moisture gradient. Other species like the southern bog lemming (*Synaptomys cooperi*) shifted their habitat range north as the glaciers receded (FAUNMAP Working Group 1996). However, as modern ecological communities have no historical analog, it remains difficult to predict how specific communities will change.

4.0 LITERATURE REVIEW

4.1 LOCAL HEDGEROWS IN AN AGRICULTURAL SETTING

Hedgerows are narrow corridors of shrubs, trees, and bushes that have often been used in agricultural landscapes either as barriers between agricultural patches or, in the context of connectivity, to connect one non-agricultural patch of habitat with another. In examining the use and impact of connective corridors at the hedgerow scale in agricultural settings, Baudry *et al*. (2003) determined that modes of agricultural production actually affect the use of hedgerow corridors. They compared two farm land types with similar landscape connectivity patterns but which housed different farming systems. The two farming systems differed in their level of farming intensity, with one having more permanent grasslands and hedgerows and the other more maize. Baudry *et al*. (2003) rejected the "suitable habitat" and "unsuitable matrix" dichotomy because in an agricultural setting, the "unsuitable matrix" can often be used as a corridor in and of itself, almost simulating a temporarily suitable habitat. For certain insect species, maize fields can give the same traveling protection as forests (Baudry *et al.* 2003).

The study shows that while hedgerows are somewhat important at the local scale, their effectiveness is heavily affected by small changes in farming practice, like the distribution or rotation of crops. If hedgerows, as an isolated system, barely offer any connective resilience in the face of these very small-scale changes, it is difficult to foresee their usefulness in light of the global scale climate changes.

4.2 LOCAL HEDGEROWS IN WOODLOTS

The effectiveness of hedgerows in the face of climate change was also studied in the context of a woodland habitat (Davies and Pullin 2007). Hedgerow connective corridors in woodland habitat have been criticized because they produce significant edge effects, exposing the species that use them to edge predation. Davies and Pullin (2007) conducted a literature review about hedgerows in various forest systems. They classified their results by taxonomic group. Their results indicate that for mammals (mostly rodents), hedgerows did increase the dispersal rate of individuals between woods. In the case of birds, hedgerows were used by smaller birds, but larger birds tended to fly directly from one woodlot to another. This is, of course, limited by the proximity of one woodlot to the next. The invertebrate study species of choice are the carabid beetles (of the beetle family Carabidae) because they are sensitive to forest fragmentation (Oates *et al.* 2005). Moreover, the many species of carabid beetles respond differently to forest fragmentation and degradation. The larger, specialist species of carabid beetles don't tend to disperse as much as the smaller, generalist species whose populations were found to increase as forests become more fragmented (Oates *et al.* 2005). Overall, there was a direct relationship between habitat connectivity and mortality: beetles, big or small, that traveled across the habitat matrix had a much higher mortality (Davies and Pullin 2007). Amphibians used hedgerow corridors as connective habitat between the two habitats they need in their life cycles, namely land and water. Davies and Pullin (2007) note, however, that none of the studies so far adequately assess the long-term viability of hedgerow corridors, in particular while facing climate change. However, if hedgerows are considered as habitat in themselves, as they are for nesting and roosting birds, and many rodents, their preservation remains important as long as they are part of a broader network of connectivity.

Climate change will change species' habitat range. Ideally, conservation corridors provide a conduit to more suitable climate and habitat. Climate functions at a much bigger scale than the hedgerow. Given the limited resources allocated to conservation management, it is perhaps best to allocate the majority of them to conservation management plans at larger scales. Hedgerows cannot be dismissed as a conservation tool as long as they are integrated as part of a larger scale network of habitat connectivity.

4.3 LOCAL FOREST CONSERVATION CORRIDOR

A forest corridor is a linear corridor composed of the same forest type as the two forest habitat patches it connects. Forest corridors have lately been developed as part of an adaptive forest management strategy whereby forest patches and corridors are left unlogged to study the effectiveness of corridors in mitigating loss of biodiversity (Mech and Hallett 2000).

At the local level, the effectiveness of forest corridors has been examined through a genetic approach. The Pend Oreille River drainage located in northeastern Washington has a coniferous forest which includes Douglas fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), western hemlock (*Tsuga heterophylla*), western larch (*Larix occidentalis*), lodgepole pine (*Pinus contorta*), and western red cedar (*Thuja plicata*). This coniferous forest has a diverse combination of old growth, new growth, clear cut, and regenerated forest areas. Mech and Hallett (2000) undertook their study using linear forest corridors that were less than 150 meters wide that directly link two forest patches. They chose two study species: the red-backed vole (*Clethrionomys gapperi*) and the deer mouse (*Peromyscus maniculatus*). These two species differ most significantly in their preferred habitat: the deer mouse (*P. maniculatus*), as a habitat generalist, can live in both old growth and new growth forests, while the red-backed vole (*C. gapperi*) prefers mature forest cover. The habitat matrix analysis used two unseparated sites in the same large patch as a control system for genetic change, and identified unconnected sites with which to also compare the results from the corridor networks. By examining the genetic differences between fully connected, isolated, and corridor-bridged landscapes, the usefulness of corridors in this ecosystem was determined. In the case of the red-backed vole (*C. gapperi*), the genetic distance in isolated sites was significantly higher (0.59 +/- 0.18) than that of the vole populations in contiguous forest sites (0.19 +/- 0.01), with the populations living in corridor-connected sites being between the two (0.41 +/- 0.11), indicating that the corridors improved gene flow for this species. In the case of the deer mouse (*P. maniculatus*), however, there was no significant difference between any of the landscape types, and Mech and Hallett (2000) attribute this to the deer mouse (*P. maniculatus*) being a habitat generalist that can thrive in the clear cut forest matrix.

The width of the corridor itself likely affected the results found for the red-backed vole (*C. gapperi*). As all corridors were less than 150 meters wide (100 m wide, on average), the edge effects likely limited the suitable habitat within the corridor itself and therefore somewhat limited the population's movements and the associated gene flow (Mech and Hallett 2000). Their study indicates that conservation corridors are very useful in promoting gene flow for habitat specialists but are less critical to populations of habitat generalists.

In light of climate change's effects on habitat availability and suitability, this will have an important impact on the differential survival of generalist and specialist species.

Local corridors will also be important in avoiding local extirpation of species. This is particularly true for species requiring more than one habitat in their life cycle, as is the case with amphibians. They may require corridors to connect them to their aquatic and land habitats (Rosenberg, Noon and Meslow 1997).

4.4 LOCAL CORRIDORS AND PLANT DIVERSITY

Henein and Merriam (1990) aptly demonstrated that the quality of the habitat affects the conservation of populations. If a local scale corridor is set-up but is of low quality, and if it connects a new habitat patch to a network, the low quality corridor will reduce the survival probability of its users and it will create a population sink by reducing the population's size (Fahrig and Merriam 1994). Conservation corridors at the local scale suffer most from edge effects and so implementing low quality corridors at those scales may ultimately be detrimental to population size.

While most studies focus on the use of corridors by animal species, their survival ultimately depends on their habitat quality. This is largely affected by the distribution of suitable plant species. Damschen *et al*. (2006) examined the long-term role of corridors in plant species richness. Their study provides a broader ecosystem study on the use of corridors. They created six study landscapes to replicate their study. Each included a 100 meters by 100 meters central patch surrounded by four other patches 150 meters away. One of these four patches was connected to the central patch by a 150 meter by 25 meter corridor. The unconnected patches had the same total area as the central patch and its corridor. The unconnected patches were of two different types: winged or rectangular. They had the same edge-to-area ratio (Figure 1.0). The patches consisted of open habitat with young longleaf pines (*Pinus palustris*) while the surrounding forest was a dense pine forest. The number of species in connected and unconnected patches was the same when the landscapes were created. However, at the end of five years, their results show that the connected patches had 20% more plant species than the unconnected ones. Their results also show that given an equal edge-to-area ratio, patch shape does not affect plant species richness. This study strongly supports the use of local corridors in maintaining plant species richness (Damschen *et al.* 2006). Ultimately this plant species richness strongly determines the quality of the habitat itself.

In the last 10,000 years, vegetation communities have changed in response to climate change and they will most continue to do so in the face of added anthropogenic climate change. This study is a good indication that we must continue to mitigate the loss of connected landscapes and to restore connectivity because their plant community richness is significantly higher than in disconnected landscapes. Protecting habitat is at the root of protecting biodiversity, and connectivity provides a great advantage to the protection of biodiversity.

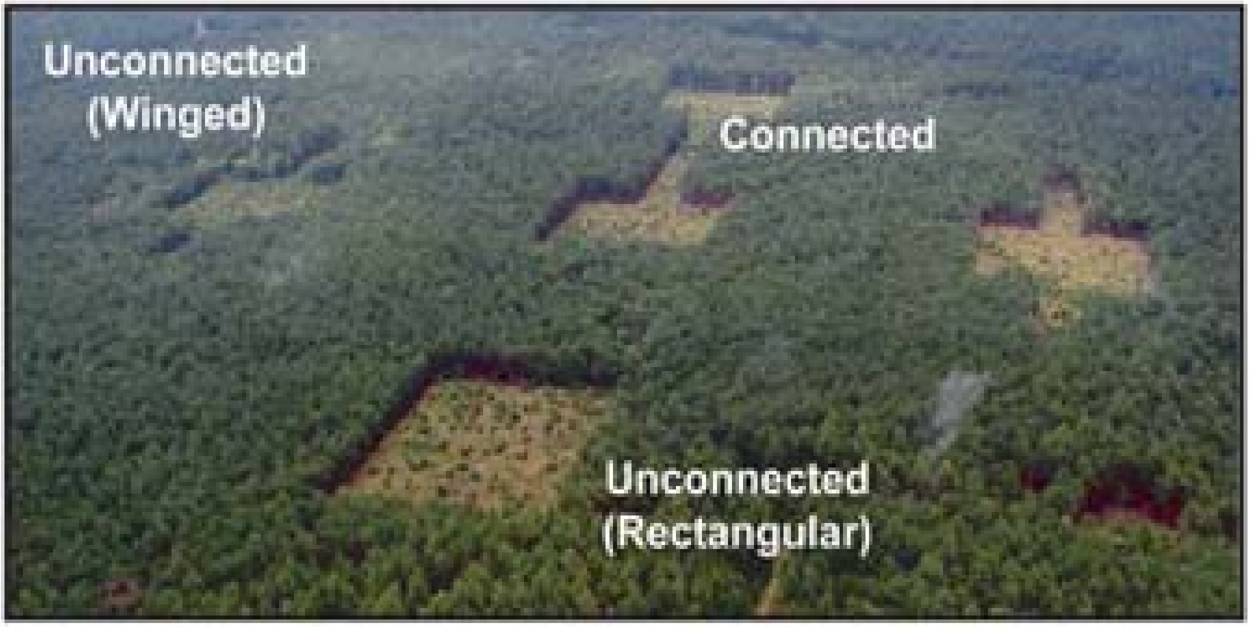

Figure 1.0 (Taken from Damschen *et al*.2006) This is one of the six study sites created to examine the role of conservation corridors in plant species richness.

4.5 REGIONAL CONSERVATION CORRIDOR IN AMAZONIA

The Amazon Rainforest is one of the world's most biodiverse regions and is experiencing very rapid forest fragmentation and deforestation (Laurance and Williamson 2001). The forest has been deforested for agricultural production, cattle ranching, logging, and for fuel wood (Laurance and Williamson 2001). Deforestation reduces plant evapotranspiration, thereby limiting regional rainfall, which increases the incidence of forest fires (Laurance and Williamson 2001). Furthermore, cattle pastures are regularly burned all the way to the forest's edges which already have drier trees, making them even more susceptible to forest fires, especially with the warmer, drier climate caused by global climate change (Laurance and Williamson 2001). Whether corridors in this tropical rainforest could help mitigate biodiversity loss is an important question as this forest is a critical carbon sink in a world with increasing carbon dioxide emissions (Laurance and Williamson 2001). "Protected area systems and conservation corridors can help mitigate the impacts of climate change on Amazonian biodiversity" (Killeen and Solorzano 2008). While most studies concerned use an animal species to assess the usefulness of corridors, Killeen and Solorzano (2008) examine a central feature of the Amazon rainforest: its precipitation regime. The precipitation regime is central to the biodiversity of the rainforest, and it is strongly affected by the available forest land cover. As such, it is important to examine how different corridors will impact this regime and in turn biodiversity. Killeen and Solorzano (2008) promote the use of conservation corridors with a buffer ecotone all along the edges of the corridor. An ecotone is a transitional habitat between two ecosystem types and thus contains a multitude of habitat types (Killeen and Solorzano 2008). These conservation corridors should "span environmental gradients to ensure that species can shift range distributions" (Killeen and Solorzano 2008).

They add that some species may have the genetic plasticity to adapt to climate change and continue to live in the habitat gradient provided by the corridor. However, they do not provide a timeframe for this genetic plasticity or specify which species are most and least likely to suffer in these corridor gradients over time. As an example of a corridor gradient, they propose an altitudinal corridor, ranging from lowland forest to higher montane habitat as a single, uninterrupted corridor. This allows the conservation of the full range of species in the different ecosystems while allowing for possible displacements as an adaptation to the effects of climate change, as on the precipitation regime (Killeen and Solorzano 2008). But where do the species living at the top go?

4.6 REGIONAL RIPARIAN CONSERVATION CORRIDOR

Riparian corridors are strips of habitat that follow rivers and forest streams. Their protection could be advantageous because it encompasses aquatic, land and aerial habitat for many species, making it a hot spot for conservation potential. Riparian habitats are highly sensitive to the effects of climate change because they are heavily reliant on macroclimatic cycles and regimes (ex: precipitation cycle) that are affected by anthropogenic climate change. Moreover, while the development of other corridor types (ex: forest) focuses more on their value in species dispersal, riparian corridors must also be examined as the actual home range of many endemic and non-endemic species.

To assess the conservation value of riparian corridors, Lees and Peres (2007) conducted a study using 37 riparian sites in the heterogeneous, fragmented Amazon forest of Brazil. They compared their results from connected riparian sites, riparian patches separated by at least 300 meters from the closest forest patch, and control sites in large, undisturbed forested areas. Their selected indicator species included avian species (except waterbirds, nocturnal birds, and aerial insectivores) and mammal species (diurnal primates, ungulates, carnivores, large rodents, armadillos), making their results especially useful in assessing the effectiveness of riparian corridors across taxa. The study's focus was on the corridor width that best preserved the biodiversity assemblage and the canopy structure of the Amazon. Logging companies are required by Brazilian federal legislation to leave intact riparian forest strips of various widths along rivers. In this legislation, the corridor's width is based on the river's width (Lees and Peres 2007).

Their results show that the use of corridors by birds is species-specific. For example, the availability of palm (*Mauritia flexuosa*) in unconnected corridors affected the distribution of the red-bellied macaw. This species was found to be present in both connected and unconnected areas but was more abundant in palm-rich unconnected areas (Lees and Peres 2007). Their study also described the quality of the habitat based on the amount of canopy cover, how fragmented it is, and how affected it is by local cattle intrusions. Their results show that sensitive species only thrive in high quality habitat while less sensitive species can be found in fragmented, lower quality habitat (Lees and Peres 2007). If the results are interpreted in light of biodiversity, it becomes clear that unconnected riparian corridors and narrow, connected riparian corridors have fewer species than the wider, connected riparian corridors and the undisturbed control riparian habitats (Lees and Peres 2007).

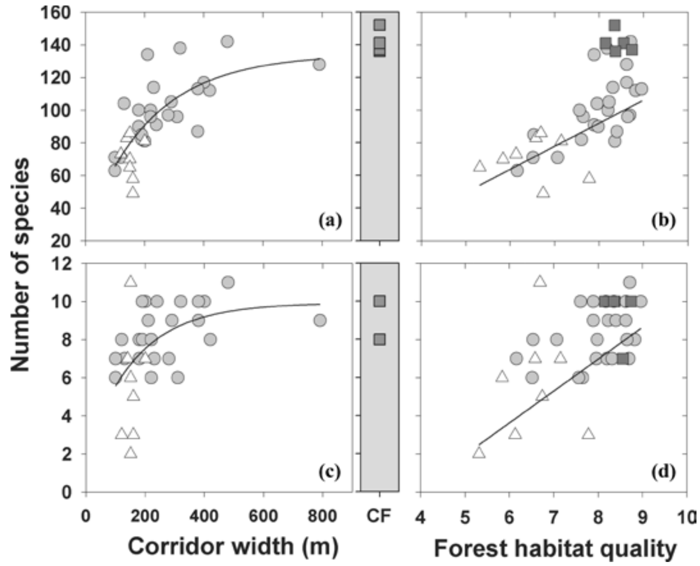

Figure 2.0 (taken from Lees and Peres, 2007): The relationship between the number of avian species (a, b) and mammal species (c, d) in relation to corridor width and forest habitat quality (the shaded circle is connected habitat, the open triangle is the unconnected habitat, and the dark squares are the continuous forest areas).

In the case of mammalian diversity, the response is also species-specific. While some species, like the spider monkey [*Ateles* sp.], were not found at all in corridors, many other species were found to use riparian corridors as habitat or for migration from one area to another.

Lees and Peres (2007) show that corridor width is a primary indicator of riparian corridor success. Narrow riparian corridors fail to preserve the “intact canopy structure” required for effective biodiversity management (Lees and Peres 2007). A narrow corridor is less than 200 meters wide and is much more susceptible to edge effects. There is a plateau in the increase in biodiversity once a corridor reaches 400 meters in width and can actually consist primarily of interior habitat (Figure 2.0). This study shows how riparian corridors can benefit from increasing their width to avoid species overcrowding and to mitigate edge effects. Wider riparian corridors also allow for a larger range of heterogeneous microhabitats, thereby increasing species diversity and allowing sensitive species to thrive (Lees and Peres 2007). Current forest management practices in the Brazilian Amazon do not conserve biodiversity because the width requirements are seriously inadequate. For example, the minimum corridor width is 30 meters for rivers or streams less than 10 meters wide (Lees and Peres 2007).

The narrow corridors being implemented provide less protection from erosion, cattle intrusions and edge effects than is required. Changes in climatic patterns will require larger corridors to provide more heterogenous microhabitats and dispersal routes for species at different trophic levels. In the case of carnivores, wider corridors can serve as a movement route to better habitat, and in the case of insect populations or small rodents where the corridor acts as a habitat itself, a wider and more protective corridor can provide multiple microhabitats and better protection from edge predation.

4.7 CONTINENTAL YELLOWSTONE-TO-YUKON PROJECT

At the continental scale, it can be very difficult to preserve large habitats. This is arguably the most important scale at which connectivity must operate because it provides a much more diverse set of habitats to which species can migrate and adapt when facing climatic changes. Moreover, preserving natural ecosystems provides a certain regulatory system on the climate itself. In North America, there are three primary climate drivers. First, global circulation patterns and other broad drivers like solar insolation affect climatic averages. Second, patterns like the Northern Annular Mode (NAM), the Pacific-North American pattern (PNA) and the El Nino-Southern Oscillation (ENSO) regulate climate. Third, “mesoscale” topographic features affect weather patterns (Peters *et al.* 2008). Terrestrial ecosystems strongly affect climate through biophysical and biogeochemical processes, whereby land cover changes affect the energy balance, for example (Peters *et al.* 2008).

The Yellowstone-to-Yukon Project seeks to connect northern Canada and the Greater Yellowstone Ecosystem. It encompasses 1.2 million square kilometers of habitat. In 1991, researchers tagged a five-year-old female gray wolf (*Canis lupus*) with a radio collar and satellite transmitter to determine her home range. Over two years, she travelled over 100 000 square kilometers including over the mountains (y2y.net). The use of large carnivores is often important in determining what habitats are preserved: by protecting the habitat range of large carnivores, it inevitably encompasses that of species with smaller home ranges. However, the Yellowstone to Yukon area is still facing threats from roads and railways which continue to fragment the habitat.

Roads continue to fragment habitat and to kill animals in wildlife-vehicle collisions. In response to this, overpasses and underpasses are created to create safe ways for animals to cross the existing highways and roads, as with the Highway 206 underpass. Underpasses are tunnels built under roads and overpasses are bridges built above the roads. Both are used to provide a safe route across the road fragmenting the habitat.

The available peer-reviewed literature on this corridor at the continental scale is limited because studies focus on the regional and local scale corridors nested within this continental scale.

At the continental scale, the Yellowstone to Yukon project is the most effective in mitigating the impact of climate change on species by providing them with more extensive habitat to which they can migrate and adapt. It is important to note that this project includes mountain ranges which allow for an altitudinal gradient to which species can migrate. The importance of continental scale corridors as well as their limitations are highlighted by the changes already experienced by many species in the region (Blatter and Ingram 2001).

The North American red squirrel (*Tamiasciurus hudsonicus*) now reproduces earlier because of the earlier springs which provide them with an earlier supply of spruce cones (Bradshaw and Holzapfel 2006). In the case of the grizzly bears (*Ursus arctos horribilis)*, the warmer, earlier summers mean that the blister rust, *Cronartium ribicola,* which devastates the whitebark pine trees (*Pinus albicaulis*) can do so for longer periods of time (Schneider and Root 2002). The whitebark pine seeds (*P. albicaulis*) are critical to the bears' diet. These longer summers threaten the bears' food source, but if the preserved habitat is large, the grizzly bears can *potentially* shift their diet or range to find enough food (Schneider and Root 2002). It is critical that we maintain connectivity of habitat so that species can adapt in the face of climatic pressures like the ones described above.

The altitudinal gradient provided by the protected mountain ranges helps maintain America pika (*Ochatona princeps*) populations. Pikas (*O. princeps*) are alpine lagomorphs which eat grasses, lichens and shrubs that grow between rocks on mountains. Their food sources are responding to climatic changes by shifting their ranges to the mountainsides and by growing earlier in the year. In response to this, pika (*O. princeps*) are following their food source but are also separated from each other, limiting their ability to meet and breed. Their populations are already in decline and their upward migration is fragmenting their populations (y2y.net).

The scale of the Yellowstone to Yukon project allows for species to migrate and adapt when facing climatic changes and is the best scale at which conservation efforts should operate.

4.8 CONTINENTAL AUSTRALIAN CONSERVATION CORRIDOR

The conservation potential afforded by continental-scale conservation corridors are also highlighted in the implementation of the Australian Alps conservation corridor. This conservation corridor spans north-south along the Great Dividing Range's watershed in Australia. It is a 690km long corridor encompassing 1,657,570 hectares of continuous habitat. There are currently gaps in the conservation corridor in the upper Jamberoo Valley, for example. "Land clearing [is] the single greatest threat to Australian terrestrial biodiversity" (Pulsford *et al.* 2003). Implementing and connecting this conservation corridor would connect a coastal habitat with an alpine area, providing a stronger connectivity network for the Australian moist eucalypt forests (Pulsford *et al.* 2003).

4.9 TEMPORAL CORRIDORS

Going beyond the traditionally geographic definition of a corridor, the temporal corridor accounts for the climate regime of the area using climate models to enhance conservation planning. Anticipated global climate change should indeed be accounted for in the development of physical corridors (Rose and Burton 2009). If the climate changes so much so that the physical corridors themselves do not give a sufficient chance of survival and adaptability to the species, then an alternate conservation planning method must be created that does account for the future change. As in the case of corridors in the Amazon which account for the precipitation regime, further studies should be conducted to examine the longer-term potential of corridors in supporting biodiversity in a changing climate. It is thus important that the study of corridors be "coupled with process-based models for a more refined projection of climate change impacts on biodiversity" (Rose and Burton 2009). Temporal corridors are maps of a climatic feature's current range and distribution and they present its changes through time using models. This feature of the temporal corridor is especially useful for habitat specialists—as climate and habitat type are intrinsically linked—as well as for migrating species which will need new migration refugia as the changing climate alters their available habitat through extended forest fires, for example.

The use of temporal corridors strengthens conservation planning because it allows for the implementation of conservation corridors in such a way that they maintain the ecosystem's basic functions and features according to where they will be in the future. Temporal corridors are limited, however, by the fact that there are many climatic scenarios available. Furthermore, these climatic models are constantly changing since climate predictions are affected by our current anthropogenic greenhouse gas emissions.

5.0 RECOMMENDATIONS

Based on the previous analysis of conservation corridors at three geographic scales (local, regional, continental), the following recommendations emerge to strengthen the implementation of corridors in light of global climatic changes:

1. Corridors should preserve the integrity of the ecosystem's functions at all scales.

2. Conservation corridor networks must be connected at all scales to improve the resilience of biodiversity in the face of climate change.

3. Conservation management plans should make good use of models on anticipated climatic regimes to preserve ecological functions based on future climatic patterns, as altered by global climate change.

4. Further emphasis should be placed on the implementation of broader, continental scale conservation corridor networks. This can be done by connecting the current local and regional conservation corridors to one another to enhance their effectiveness and resilience in the face of climatic changes.

5. We should continue investing our reforestation efforts as a buffer area around the current corridors and patches as a means of more quickly rendering what was previously an edge into an actual, suitable habitat. This is a good transition for the corridor strip from its role as a movement corridor to a full habitat. Since it takes decades, even centuries, for newly planted forests to develop the ecosystem functions of older forests, and since they are more likely to be inhabited by habitat generalists for a long time, it may be a better use of our time and resources to reforest the areas directly around forest patches and their connective corridors.

6. It is imperative that governing bodies come to agreements on ways to curb anthropogenic greenhouse gas emissions to reduce the impacts of climate change in the years to come. The inconclusive summit held in Copenhagen in 2009 is a reminder that we must continue to push for a reduction of our ecological footprint.

6.0 SUMMARY

This paper reviewed the use of conservation corridors in fragmented landscapes at three different scales to investigate their effectiveness in mitigating the effects of climate change on habitat and biodiversity. An analysis of studies performed at the different scales show s that the implementation of conservation corridors at the broadest scales would best mitigate the effects of climate change while preserving ecosystem processes. The following is a summary of the conclusions drawn in this paper.

1. Climate change already strongly impacts species ecology (Schneider and Root 2002).
2. Ecological processes are scale-dependent (Steffan-Dewenter *et al.* 2002).
3. The intensity of habitat degradation in the matrix affects the use of corridors by species and the matrix itself can be used as habitat by some species (Baudry *et al.* 2003)
4. Plant species richness, and in turn habitat quality, is significantly improved at the local by connectivity starting at the local scale (Damschen *et al.* 2000).
5. Species characteristics play a major role in their adaptability to climate change (Halpin 1997) and in their vulnerability to extinction (Purvis *et al.* 2000).
6. Local conservation corridors improve the genetic diversity of specialists more so than for generalists (Mech and Hallett 2000).

7. Forest corridors 100-150 meters wide suffer significant edge effects. Whenever possible, we should make them wider than 150 meters to increase the size of utilizable interior habitat , especially for specialists (Mech and Hallett 2000).

8. Riparian corridors should aim to be 400 meters in width to preserve intact core habitats, canopy structure and biodiversity (Lees and Peres 2007).

9. Connective corridors should be aligned upslope, from the coast to the mainland, and poleward in order to conserve the most habitat types and ease the movement of species as the climate changes (Noss 1992). The question remains: what about the species in the top habitat?

10. Local and regional conservation corridors can best mitigate the impacts of climate change on biodiversity when they are included as part of a broader habitat connectivity network.

11. The nested conservation corridor approach recognizes that continental scale corridors are made up of regional corridor systems which are in turn made up of local scale corridors.

12. With global climate change underway, we must recognize that we will see many non-analog vegetation and animal communities. As such, we have to leave enough flexibility in our management plans for these inevitable ecological changes.

13. We must continue to develop and use more localized temporal corridors to strengthen conservation planning.

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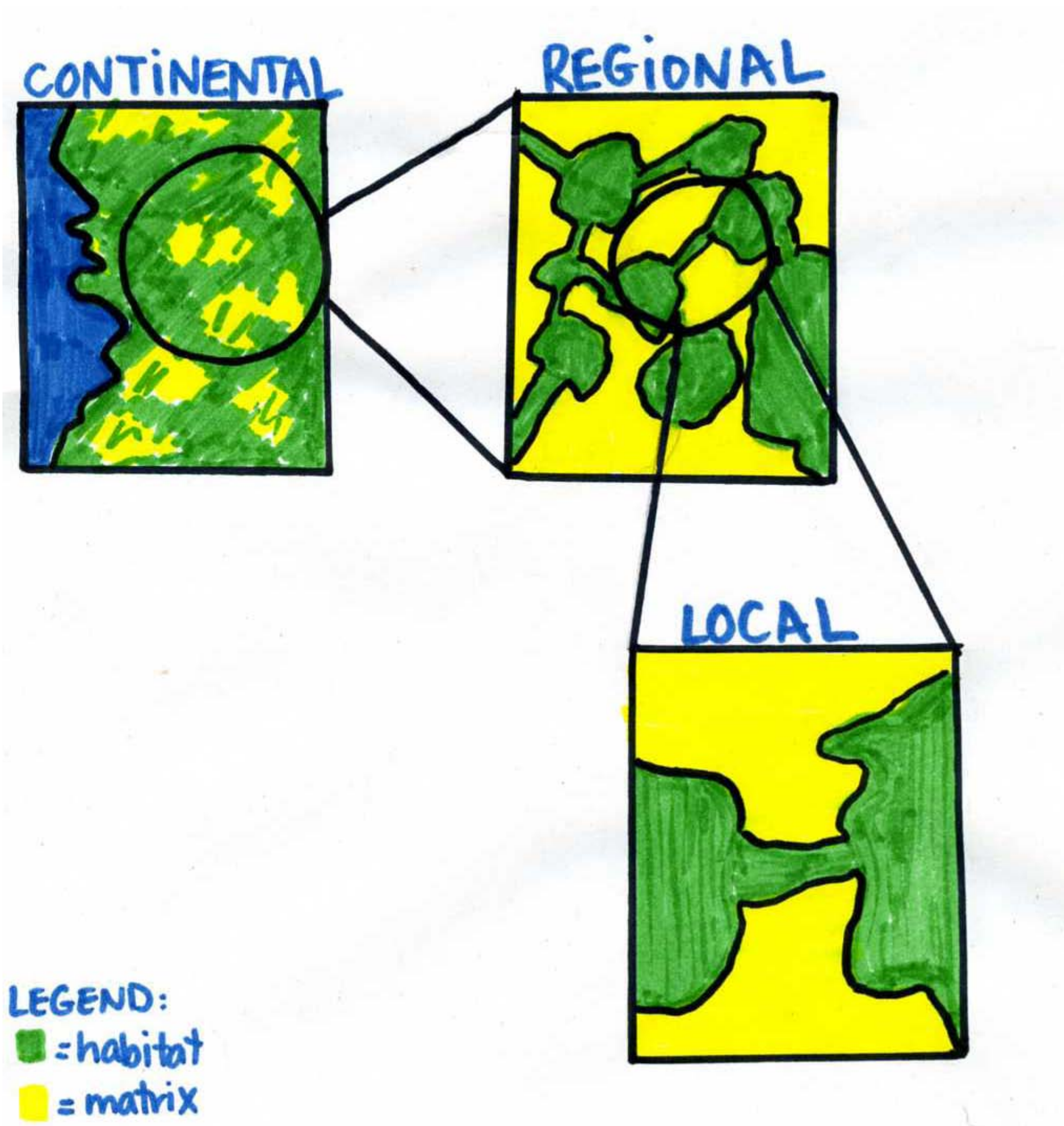
8.0 APPENDIX A

This diagram illustrates the nested design approach applied to conservation corridor scales. It emphasizes the importance of developing a broader network of connectivity comprised of local and regional scale corridors to make up a continental system of habitat connectivity.



9.0 APPENDIX B: SUMMARY TABLE

This summary table was based on the one provided by Beier and Noss (1998). The case studies in section 4.0 of this paper were summarized in this table. It is important to include the taxonomic group on which each study focused because the results indicate that conservation corridor use can be species-specific. The utility of the conservation corridor was assessed in light of climate change and the scale at which it operates.

Study	Country/Region	Scale	Taxonomic Group(s) and Study Species	Matrix	Type of Study (*Sampling effort)*	Study System	Utility of corridor
Baudry *et al.* 2003	France	Local	Invertebrate: forest carabid species	Agricultural land	Simulations and previously radio-traced forest species (*seven year crop succession on 17 farms*)	Farms with small woodlots	Agricultural land use management strongly impacts utility of hedgerows but their implementation should be done in conjunction with managing the intensity of the farming done in the matrix. Seeing as they are sensitive to changes in agricultural intensity, they will likely offer little respite in the face of larger scale climatic changes, especially as isolated systems.
Davies and Pullin, 2007 (review)	Multiple	Local	Mammals, birds, amphibians, invertebrates Rodents, many birds, carabid	Arable and pastoral lands	Literature review of hedgerow effectiveness (27 studies)	Woodland	Hedgerows do increase rodent dispersal. These conservation corridors were used by small birds but larger birds prefer flying from one larger woodlot to

			beetle species, many frogs				the next. This is of course limited by the woodlots' proximity to one another. Carabid beetles traveling across the matrix had a significantly higher mortality rate than those using the hedgerows. Amphibians use hedgerows as habitat. It is unclear from this review how hedgerows will fare in the face of climate change, but as isolated systems they are weak.
Mech and Hallett, 2001	United States	Local	Mammals: The red-backed vole (*Clethrionomys gapperi*) and the deer mouse (*Peromyscus maniculatus*)	Clear cut and new growth forests	Genetic sampling of 10 pairs of populations (*207 individuals over 3 years*)	3 coniferous forest systems: contiguous, with corridors, and isolated patches	Corridors do help increase gene flow for red-backed voles (*Clethrionomys gapperi*) because they are habitat specialists. In the case of the deer mouse (*Peromyscus maniculatus*), they were able to live and move across the matrix and so there was no significant genetic difference in the three landscape types. This study shows that local corridors will play an important role in preventing the extirpation of habitat specialists by allowing them to migrate to more suitable habitat in the face of climate change.
Damschen *et al.* 2006.	United States	Local	Plants: long leaf pine (*Pinus	Long leaf pine (*Pinus palustris*) forest	Sampling of patches (*Five years)*	Long leaf pine forest (clear cut lots)	Their study strongly supports the use of conservation corridors to

			palustris)				enhance species richness and therefore improve habitat quality. Connected cleared patches had 20% more species richness than the isolated patches. Improved habitat quality protects microhabitats for use as species adapt to climate change.
Killeen and Solorzano, 2008	Amazonia	Regional	N/A They examine the precipitation regime. (*N/A*)	Pastoral and arable lands	Simulations	Woodlot and corridor networks, including buffer zones	Corridors help maintain forest land cover and in turn can help regulate changing regional precipitation patterns.
Lees and Peres 2007	Brazil (Amazonia)	Regional	Birds, mammals: for example, the red-bellied macaw, spider monkey	Pastoral and arable lands	Sampling to determine minimum optimal width (*37 sites*)	riparian sites in heterogeneous forests	This study shows that corridor width is a strong predictor of its success in mitigating loss of biodiversity in the face of climate change. A riparian corridor of 400 meters in width is the minimum appropriate width which prevents overcrowding, mitigates edge effects, and preserves a full range of microhabitats to allow for migration with climatic changes.
Yellowstone-to-Yukon	Canada and the United States	Continental	Large mammalian carnivores and some mammals: grizzly bears *(Ursus arctos*	Fragmented industrialized land	Initially, a radio-collared gray wolf (*two years)*	Mountain ecosystem of 1.2 million square kilometers	This is the best scale at which conservation corridors can mitigate the impact of climate change because they provide space for species to migrate and adapt, especially along

			horribilis), gray wolves (*Canis lupus*), North-American red squirrel (*Tamiasciurus hudsonicus*) and pikas (*Ochatona princeps*)				altitudinal gradients. They also protect the large habitat home range of top carnivores, thereby maintaining the integrity of trophic systems. Maintaining this forested mountain land cover also strongly regulates climate.
Pulsford *et al.* 2003	Australia	Continental	Plant: The eucalypt [*Eucalyptus* sp.]	Fragmented industrial land	Simulations	Moist eucalypt forest	This conservation corridor would connect coastal and alpine habitat, providing a stronger network for the preservation of moist eucalypt forest and its reliant biodiversity.

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