2020

PRIORITIZING PARCELS FOR CONSERVATION EASEMENTS USING LEAST-COST PATH ANALYSES OF LAND OWNERSHIP: CASE STUDY WITHIN THEORIZED GRIZZLY BEAR MIGRATION CORRIDORS OF WESTERN MONTANA

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By

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Thesis

presented in partial fulfillment of the requirements
for the degree of

Master of Science (Community and Environmental Planning)
in Geography

The University of Montana
Missoula, MT

October 27th, 2020

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As the world's human population has grown and converted large natural habitats to human dominated landscapes, the planet's biodiversity has decreased. To combat the loss of biodiversity from human development, many conservation professionals champion the concept of conservation corridors between intact habitats. Conservation corridors, made up of protected land, serve as a connection for wildlife populations to intermix genetics and, subsequently, help reduce the risk of extinction. The ideal geographic location of corridors is generally determined through geographic information system modeling using biophysical conditions and theorized animal movement. However, the resulting corridors are often expansive and protecting entire corridors is usually impossible. Therefore, determining where conservation actions, such as placing a conservation easement on a private parcel, have the most opportunity for connecting landscapes is key to maximizing benefits with limited resources.

This study examines how public land can be considered as protected habitat, due to federal mandates, and serve as a facilitating factor for establishing conservation corridors with conservation easements on private parcels. It utilizes least cost pathway analyses within theorized grizzly bear migration corridors of western Montana to show the potential for conservation easements to provide connectivity of protected lands within conservation corridors. The case study compares differing cost values for varying land ownership types to aid in corridor implementation planning. From the analysis, the resulting least cost pathways show promise for identifying individual private parcels, and therefore specific areas, within the larger wildlife corridor for concentrated conservation action. The approach shows promise for land trusts and other organizations working to place conservation easements on parcels with the highest conservation opportunity to connect large intact landscapes.

ACKNOWLEDGMENTS

Thanks to all who have helped me along at various steps of this project. David Shively for his willingness to work through changes of ideas and timelines, again and again, and again. Kevin McManigal for teaching me everything I know about geographic information systems, and for being a great supporter throughout my graduate school experience. Alex Metcalf for his direction and interest in this project, if only I had reached out earlier. Jeremy Sage for his guidance on focusing this study and instruction. Montana Land Reliance staff members, especially Matt Bell, for bringing the need for this study to my attention and for early guidance on the project's direction. Morgan Anderson and Ryan Rock for countless hours spent helping me hone this project's scope over two years of coursework together and, more importantly, support as officemates and through great friendships. Finally, to my family and friends for continuing to push me to take this study off the backburner when there were so many other pulls for my time and energy.

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Introduction

Protecting wildlife corridors has become a frequently cited solution to the world's decreasing biodiversity (Mateo-Sánchez, Cushman, and Saura 2014). Corridors are intact habitat through which animals can move in marginalized landscapes between larger expansive habitats. Fully protected wildlife corridors are called conservation corridors and are a collection of parcels with various ownership types (Iftekhar and Tisdell 2014). The creation of fully protected conservation corridors can be accomplished by multiple means of land-use planning related actions, ranging from policy creation to wholesale acquisition (Rissman et al. 2007). A middle-ground alternative to these two approaches is the placement of conservation easements on private property. Easements are a legally binding agreement between a landowner and an external party, often a land trust or similar conservation organization, that restricts development on the impacted parcel. When compared to land use policy, conservation easements are often more attainable then largescale policy creation and are less costly than complete acquisition, making them an ideal tool for corridor construction (Farmer et al. 2011).

Although conservation easements are a practical and realistic protection option, they still require resources to implement, such as staff time from the easement holding organization and money for their purchase. Therefore, when considering an entire corridor for protection the ability to prioritize individual parcels or regions within the entire wildlife corridor is important (Schuster and Arcese 2015). This study considers the potential of least cost pathway (LCP) modeling to identify parcels, and subsequently their surrounding areas, for prioritization. Since corridors run through a patchwork of land with differing ownership, from public to private, the different ownership types can be classified by their potential for protection. Public lands hold strong protection potential due to federal regulations, such as the National Environmental Policy Act and the Endangered Species Act, whereas, private land is only encumbered by existing land use policies, which are often negligible and, therefore, have minimal protection potential (Said et al. 2016; Copeland et al. 2013).

To test the feasibility of utilizing LCP modeling for prioritization, this study considers a set of theorized grizzly bear migration movement corridor within western Montana as a case study for application of the conservation easement approach to corridor creation. Western Montana's landscape between the Greater Yellowstone Ecosystem (GYE) and Northern Continental Divide Ecosystem (NCDE), where the bear's two isolated populations live, is a collage of private and public lands that has long been prioritized by conservation organizations, such as the Yukon to Yellowstone Conservation Initiative and Vital Ground Land Trust, for corridor protection. This study 's LCP analyses provide a spatially explicit prioritization of privately owned parcels. Such an ability to identify parcels for conservation action by land trusts and other conservation organizations should prove to be of value for efforts to protect grizzly bear migration corridors between the Greater Yellowstone and Northern Continental Divide Ecosystems. The study's products, while specific for the region, show the potential and importance of considering such analyses for future corridor protection work throughout the world where ownership types restrict protection possibilities. Additionally, the modeling approach employed in this study, which links biophysical modeling of wildlife movement potential with the realities of protecting existing conditions, is a unique contribution to the conservation field in its current state.

Background

Biodiversity, Habitat Fragmentation, and Conservation

Natural systems have generally experienced a significant decrease in biodiversity throughout the world over the last half century. One of the leading causes of decreased biodiversity has been rampant human development, and its associated land conversion (Hautier et al. 2015; Newbold et al. 2016). As development has spread and land uses have changed, landscapes that were once able to support wildlife populations over vast connected ecosystems and habitats have been diminished and become disconnected and fragmented. Habitat fragmentation is the division of large-scale natural landscapes and habitat into smaller disconnected tracts. The reduction and disconnection of these original expansive habitats causes once connected wildlife populations to become isolated and vulnerable to localized extinctions (Parks and Harcourt 2002). This increased risk of extinction is caused by many things, not the least of which is bottlenecking of genetic diversity within the smaller populations. Decreased genetic variability from isolation can lead to a lack of genetic fitness and an inability to adapt to changing conditions and subsequently extinction (Lande 1998).

To combat the fragmentation of natural environments and its detrimental impacts on biodiversity through localized extinctions, the field of conservation planning arose in the latter half of the 20th century (Margules and Pressey 2000; Bottrill and Pressey 2012). Informed by the principles of conservation biology, conservation planning is a landscape-based approach to mitigating adverse environmental changes through collaborative planning processes that aim to conserve and connect existing, and potential, habitats. One of the many apparatuses that has been born from conservation planning for connecting fragmented habitats across wide-expanses of varied landscapes is conservation corridors (Keeley et al. 2018). Conservation corridors function as protected lands, through any number of techniques, ranging from policy formation to wholesale acquisition, that link larger habitats through developed and marginalized landscapes (Beier et al. 2008). While conservation corridors are a common tool of conservation planning, their creation can be difficult. Using land-use policy to create conservation corridors can be cumbersome and encompass a painstakingly long timeline, due to political climates and bureaucratic processes (Stokes et al. 2010). Examples of planning process related conservation corridors are wildlife corridor overlay zones in Ventura County, California and Vermont's wildlife corridor land-use directives (Rudnick et al. 2012). And local governments and conservation organizations find that fee simple acquisition of enough land to fully complete a conservation corridor is generally cost prohibitive (Nobrega et al. 2009). Therefore, corridors are generally constructed using multiple conservation planning tools including regulatory policy, land acquisition, and conservation easements on targeted land parcels (Iftekhar and Tisdell 2014).

Conservation easements are a legally binding restriction, or severance, of development rights from a land parcel's deed and are generally held as an agreement between the parcel's owner and a conservation organization, frequently a land trust (Stroman, Kreuter, and Gan 2016). Unlike regulatory policy, conservation easements can be completed without burdensome political activities and are significantly cheaper than complete fee simple acquisition (Naidoo et al. 2006). This is because most conservation easements are entered into on a voluntary basis by the landowner due to personal motivation to protect the land's natural characteristics or the desire for reduced tax burdens associated with reduced development potential (Bastian et al.

2017). However, it is important to note that motivations vary and are among the many aspects of conservation easements that are in need of further academic study (Farmer et al. 2011). The difference in cost between easements and fee purchase agreements is due to the landowner retaining control of the land, albeit with limitations as outlined in the easement's specific language (Schuster and Arcese 2015). These two characteristics make conservation easements among the most practical of options for landscape managers in completing targeted conservation measures, such as conservation corridors (Main, Roka, and Noss 1999; Hardy, Hepinstall-Cymerman, and Fowler 2016). Additionally, another benefit of conservation easements is the ability for one easement to lead to another. It has been shown that the feelings of neighboring landowners towards entering into an easement with a conservation organization frequently increase after a neighbor or community member has already done so (Vizek and Nielsen-Pincus 2017). However, conservation easements are not a perfect fit as they too require financial resources for their acquisition and staff time for the organizations that hold and execute conservation easements.

Corridor and Least Cost Pathway Modeling

Due to the difficulties and expenses associated with establishing conservation corridors, and for all conservation planning more generally, identification of the most ecologically valuable land for wildlife movement between protected habitats is of extreme importance. Coincidentally, with the advent of conservation planning came an increased ability for wildlife movements to be modelled by geographic information systems (GIS). GIS technology has allowed biologists to use known animal behaviors to predict theoretical movements of animals as they traverse a landscape. In fact, habitat and movement modeling are among the most widely used applications of GIS within conservation biology and ecology (Baldwin et al. 2014; Perkl 2016). Specifically, among the most common methods used to model animal habitat preference and movement is the analysis and creation of movement corridors (Shirabe 2018). Movement corridors within GIS models are often created using a theorized resistance layer, known as a cost surface, to determine the overall "cost of movement" for a desired action over a landscape. In the modeling, the cost surface is the most important part of the model, as it significantly determines the model's outcomes (Zeller et al. 2017). However, creating cost surfaces can be extremely difficult and often includes significant subjectivity. Frequently the layers are produced solely from expert analysis of landscape characteristics, animal behavior, and the theorized impact of geographic features on the species for which the model is created (Clevenger et al. 2002; Zeller, McGarigal, and Whiteley 2012). Once the surface is created, a corridor analysis tool is run using source and destination locations situated within the cost surface layer's geographic footprint. Source and destination points are generally intact functional habitats known to support the species in question. The final theorized movement corridor is a product of the cost surface, source and destination locations, and selected level of randomness allowed for movement. Randomization levels are important for wildlife movement modeling due to the fact that animals will not always take the shortest and most direct path, therefore a wide swath of habitat must be identified and allowed for likely movement. The corridor created from these analyses represents the most likely geographic setting for movement, as determined by the resistance values on the cost surface, between the source and destination, and can serve as a blueprint for conservation actions by identifying the most ecologically important areas within a landscape for connecting fragmented wildlife populations (S. A. Cushman, McKelvey, and Schwartz 2009; S. A. Cushman, Lewis, and Landguth 2013). This is of immense importance for maintaining or restoring habitat connectivity as it helps prioritize the areas with the most benefit for wildlife movement. Knowing where animals are most likely to move between two protected habitats often translates into too large of an area to realistically protect using the planning tools outlined above. This is especially true today as conservation activity throughout the world faces decreased budgets and seemingly more objectives than ever before (Remme and Schröter 2016; Brooks et al. 2006). Therefore, to fit within the constraints of limited resources, more geographically explicit areas and realistic prioritizations of land for corridor protection must be identified (Lombard et al. 2010; Arponen 2012). There are many ways to narrow down the larger habitat models to provide realistic avenues for protection. Perhaps the most logical is the same tool used to create the movement corridors in the first place, GIS. Modeling within a GIS can be used to further breakdown wildlife habitat models to identify the greatest impacts to movement within the entire wildlife corridor, be those infrastructure developments or incompatible land uses (Nobrega et al. 2009; Perkl 2016). This type of modeling has been conducted for all sorts of animals, from salamanders to elephants, with the overall goal of gaining a better understanding of the areas necessary for linking the habitats theorized as most important for migration between intact habitats (Wang, Savage, and Shaffer 2009). Many studies and models have gone even further, using GIS tools to specifically identify the most ideal individual locations, and even procedures, for protections within determined wildlife habitat (Snyder et al. 2008; Lee, Chon, and Ahn 2011). The common thread between these studies has been the tool utilized for prioritization within the study areas. Using a cost surface with theorized resistance values for conservation protections is nearly identical to the methods used for determining wildlife movement preferences over a landscape. However, in the case of human activities (e.g., development, protection, other land use activities) the need to address unpredicted movement via randomness is negated (Pullinger and Johnson 2010). Without randomization, the model is known as a least cost pathway (LCP), which is a generated line between the selected source and destination locations with the absolute lowest theorized cost of movement over the cost surface. From previous research in conservation corridor prioritization modeling (S. A. Cushman, Lewis, and Landguth 2013; Pressey, Visconti, and Ferraro 2015), it has been shown that there are a wide variety of outcomes produced by different approaches to LCP creation. Therefore, multiple studies have called for increased research that will lead to the standardization of tools and models for identifying suitable elements, such as land ownership or cost of land acquisition, for conservation corridor construction (Pullinger and Johnson 2010).

While different approaches may be taken in modeling the wildlife ranges needed as the base for conservation corridors, perhaps the most widely used is the multi-species approach (Dilkina et al. 2017). Another method for corridor modeling is through the usage of an umbrella species as the species for which the corridor's habitat modeling is directed (Carroll, Noss, and Paquet 2001; Beier, Majka, and Spencer 2008). In general, analyses of past conservation corridors have shown that habitat models for umbrella species, often large apex carnivores, include habitat for a large number of additional wildlife species (Carroll, Noss, and Paquet 2001). This is caused by the need for these large animals to cover large expanses of land to meet their habitat and foraging needs. Another benefit of using umbrella species is that they commonly fit into the classification of charismatic megafauna. This means that the species are well known and can often generate public support for conservation measures, whether that is public policy or funding for easements and acquisition (Clucas, McHugh, and Caro 2008; Minin and Moilanen 2014).

Grizzly Bear Migration Corridors

The grizzly bear (*Ursus arctos horribilis*) of North America represents a classic example of a species that fits the bill for being an umbrella species with large appeal as a charismatic megafauna species. Grizzly bears are emblematic of the American West and require large home territories, making the species an ideal candidate for usage as a corridor creating species (Carroll, Noss, and Paquet 2001). Together with these characteristics, grizzly bears within the lower 48 live within a highly fragmented landscape. The species was listed (as endangered) under the endangered species act in 1975, and since then grizzly bear populations have increased throughout their range in the contiguous United States. However, the population of grizzly bears in the country is divided between two distinct ecosystems lacking connectivity, the Northern Continental Divide Ecosystem (NCDE) and the Greater Yellowstone Ecosystem (GYE), both of which can be classified as ecosystems with extensive protected lands surrounded by lands at risk of development (Walker and Craighead 1997; White et al. 2017). While the NCDE population has strong genetic variability from connectivity with Canadian grizzly bear populations, bears within the GYE are genetically isolated due to a lack of migration between the two populations (Figure 1) (Proctor et al. 2012; 2015). Biologists have long cautioned about the continued viability of isolated bear populations due to inbreeding and genetic health (Kendall et al. 2009; Mace et al. 2012). Due to these fears, the establishment of connectivity between the two isolated grizzly bear populations has been identified as a priority for wildlife managers in Montana, Idaho and Wyoming (White et al. 2017). With the population's growing numbers, there is great potential for reestablishing connectivity that has not existed since the populations were originally disconnected by westward expansion and hunting in the early 1900's (Bjornlie et al. 2014).

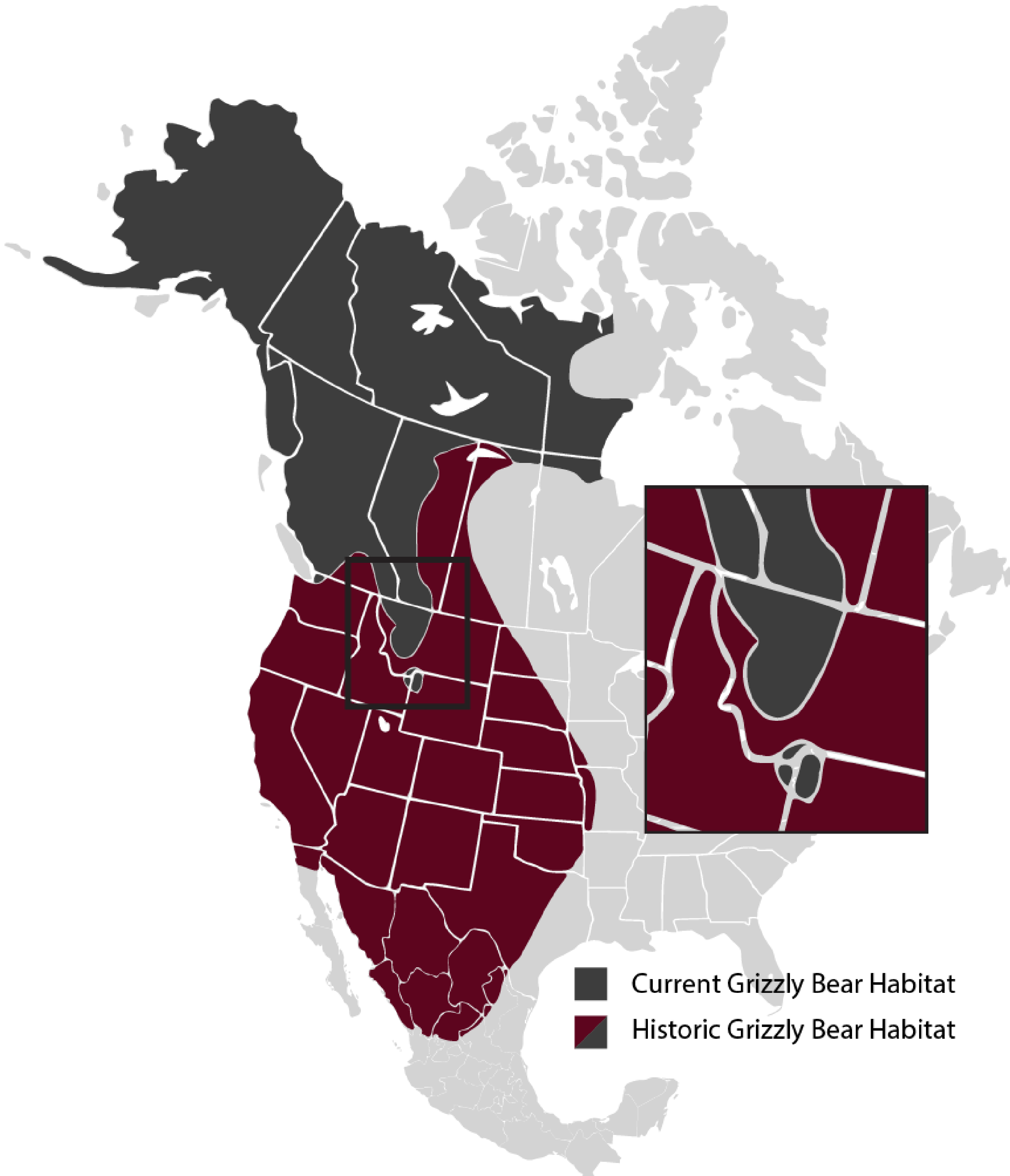

Figure 1. Current and historic grizzly bear range (Range data from George A. Feldhamer et al. 2003).

Peck et al's Study: Potential Paths for Male-Mediated Gene Flow to and from an Isolated Grizzly Bear Populations

Recently, to better understand where connections between the NCDE and GYE populations could be made, researchers from the Interagency Grizzly Bear Study Team (IGBST), Montana Fish, Wildlife and Parks and the Wyoming Game and Fish Department produced a model of corridors for potential migration of male grizzly bears (males generally colonize new habitats) in the landscape between the NCDE and GYE (Peck et al. 2017). Their corridors were created using a step-selection function to produce resistance layers using ecological, physical, and anthropogenic landscape features informed by known GPS locations and movements for 124 male grizzly bears in the study area. The specific resistance layers included data relating to stream/riparian presence, roadways (all types), and human development, all of which can influence habitat and movement preferences of grizzly bears. From these conductance layers the team used a randomized shortest path model to estimate the amount of theorized grizzly bear movements over all grid cells within the geographic region of focus. The resulting number of passages between source and destination, being the NCDE and GYE, over grid cells produced an estimation of movement potential. From this analysis, the areas within the study area with the highest amount of movement potential were identified as representing areas with the highest ecological importance for grizzly bear movement and habitation between the two populations' current ranges.

In the study team's final product, multiple distinct corridors are apparent. The corridors generally run along mountain ranges and encompass lands corresponding to several of Montana's national forests (Figure 2). Each of the corridors, however, also run into constrictions near western Montana's population centers. These constrictions are a fundamental issue for the long-term usage of the team's data, and generally for any wildlife movement model, because models can only consider the state of the landscape at the time of the study. Therefore, rather than showing long term habitat, Peck et al's study and similar wildlife movement models show the areas in most need of protection to prevent landscape changes (i.e., development) from occurring before the constrictions become permanent. Western Montana, the study's focus region, is experiencing strong population growth and development (i.e., land conversion) due to amenity migration (Shafer 2015), a trend that has been apparent over the last several decades (Gosnell, Haggerty, and Travis 2006). These developments threaten the viability of these potential corridors and their future connectivity with the NCDE and GYE.

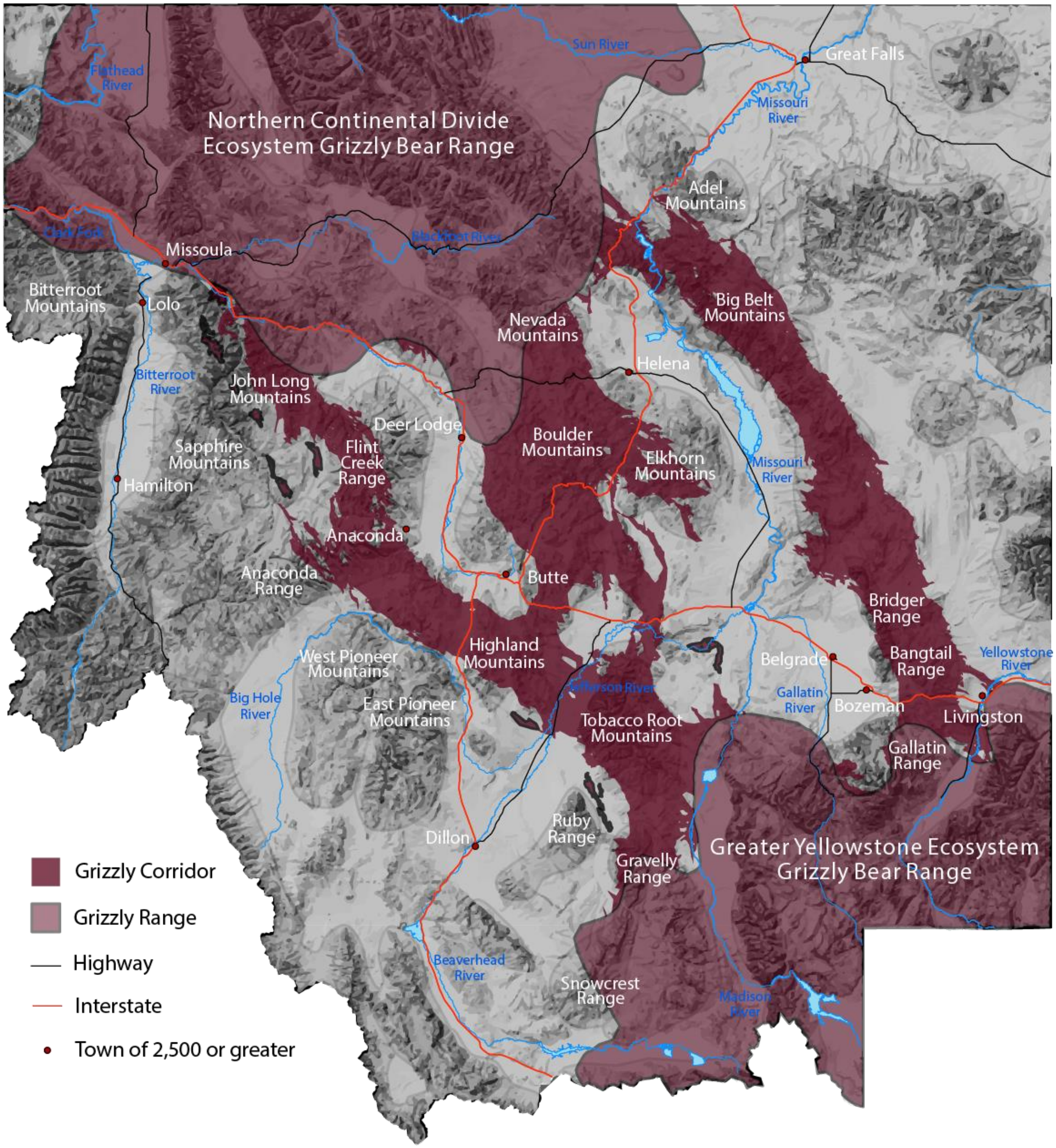

Figure 2. Current range and migration movement corridors of grizzly bears from Peck et al's study in relation to western Montana's largest population centers and mountain ranges.

This case study, then, considers the prioritization of privately owned parcels of land for protection through conservation easements to create a fully protected conservation corridor between the GYE and NCDE to link the separate two grizzly bear populations. Such a corridor would also help to facilitate the long-term viability of wildlife movement for all species that inhabit the same landscape. To do so, the study uses least cost pathway analyses within ESRI's ArcGIS software to determine the most direct routes across public and private lands within the theorized grizzly bear migration corridors. Using Peck et al's grizzly bear migration corridors as a framework for examining parcels, the modeling used the known distribution of grizzly bears in the largely protected landscapes of the NCDE and GYE to identify a complete conservation corridor between the two ecosystems. It is important to note that this study does not seek to validate the products of Peck et al's study on potential biophysically-based grizzly bear migration corridors. Instead, this study uses Peck et al's products as a framework to move from theoretical biophysically-based modeling to realistic conservation action. This assessment was completed with the goal of producing a guide for cooperative action between land trusts and other land managers within the study area. Subsequently, an additional goal of this study was to show the potential for this approach to be applied to additional biophysical movement studies, which in turn would allow for such modeling to be used as a tool for standardizing the identification and prioritization of conservation efforts on individual parcels when creating conservation corridors across the planet.

Methods

Data Acquisition and Preparation

To develop models that produce the most direct and cost-effective protected conservation corridor based on grizzly bear migration corridors in western Montana, the first step was to obtain the needed geographic shapefiles and raster files. This study benefited greatly from the state of Montana's state library geographic information clearinghouse (http://geoinfo.msl.mt.gov/). This online clearinghouse contained all necessary cadastral data, as well as shapefiles for public lands and conservation easements across the state. Additionally, all needed shapefiles for grizzly bear habitat and population range were readily available through the federal government's geographic data website (https://catalog.data.gov/).

The most important base data were the migration corridors developed by the IGBST, which are publicly available as raster datasets (https://www.sciencebase.gov/catalog/item/59149ee6e4b0e541a03e9a58). Within its study, the IGBST ran multiple analyses of different theorized migration directions, from the NCDE to the GYE, from the GYE to the NCDE, and an analysis using movement modeling in both directions. Additionally, the team ran their model at three levels of randomization, thereby producing three spatially distinct datasets for each of the three directional models. Because of the multiple analyses (nine total), determining which dataset to use for this analysis and how to utilize the selected dataset was among the first issues for this study. Ultimately, the dataset representing movement in both directions from the two grizzly bear populations was selected, as it allowed for a more geographically constrained analysis, while also encompassing all theorized potential movements. In terms of the level of randomness selected for the multi-directional modeling, the model with the highest level of randomness was selected so as not to constrain the model artificially. However, even with the migration data selected, the next question for the study was how to exclude erroneous information in the selected dataset. Most of western Montana was used as the geographic setting for the conductance layer for movement in the IGBST's study; therefore, raster cells throughout the larger region contained values for movement potential. To limit the raster data to only the parts of the landscape with significant movement potential, the selected IGBST model's corresponding raster file was modified to contain only cells with a movement potential of .05 (5%) or higher. In doing so the resulting raster file contained only cells within a fully connected corridor and removed stray cells or fingers without connections between the two ecosystems.

The next step was compiling the shapefiles for private and public ownership, as well as conservation easements in western Montana. Private ownership data were derived from the state's cadastral database by overlaying a shapefile showing the nearly 600,000 records of all private and public parcels with state's shapefile for publicly owned land (federal, state, tribal, and municipal) and erasing the public parcels. For a more complete study of parcel ownership of interest for the conservation corridor, a vector file containing conservation easements in Montana was also be obtained. The same process for erasing data from the parsed cadastral shapefile was executed to remove parcels with already existing conservation easements. After simplifying the three base layers of ownership types (private, private with a conservation easement in place, and public), the three files were then be merged to create a single vector file, and further simplified using the dissolve tool in ESRI's ArcGIS to insure that only the desired ownership type was included for each parcel. With a singular shapefile created for the state, the next step was clipping the shapefile within ArcGIS by the preselected and modified corridor raster produced in the previous steps from Peck et al's study. The last step in this initial process was creating a raster image of the parcel data to be used for the least cost path analyses for parcel prioritization. To accomplish this, ESRI's polygon to raster tool was on the clipped ownership shapefile (Figure 3).

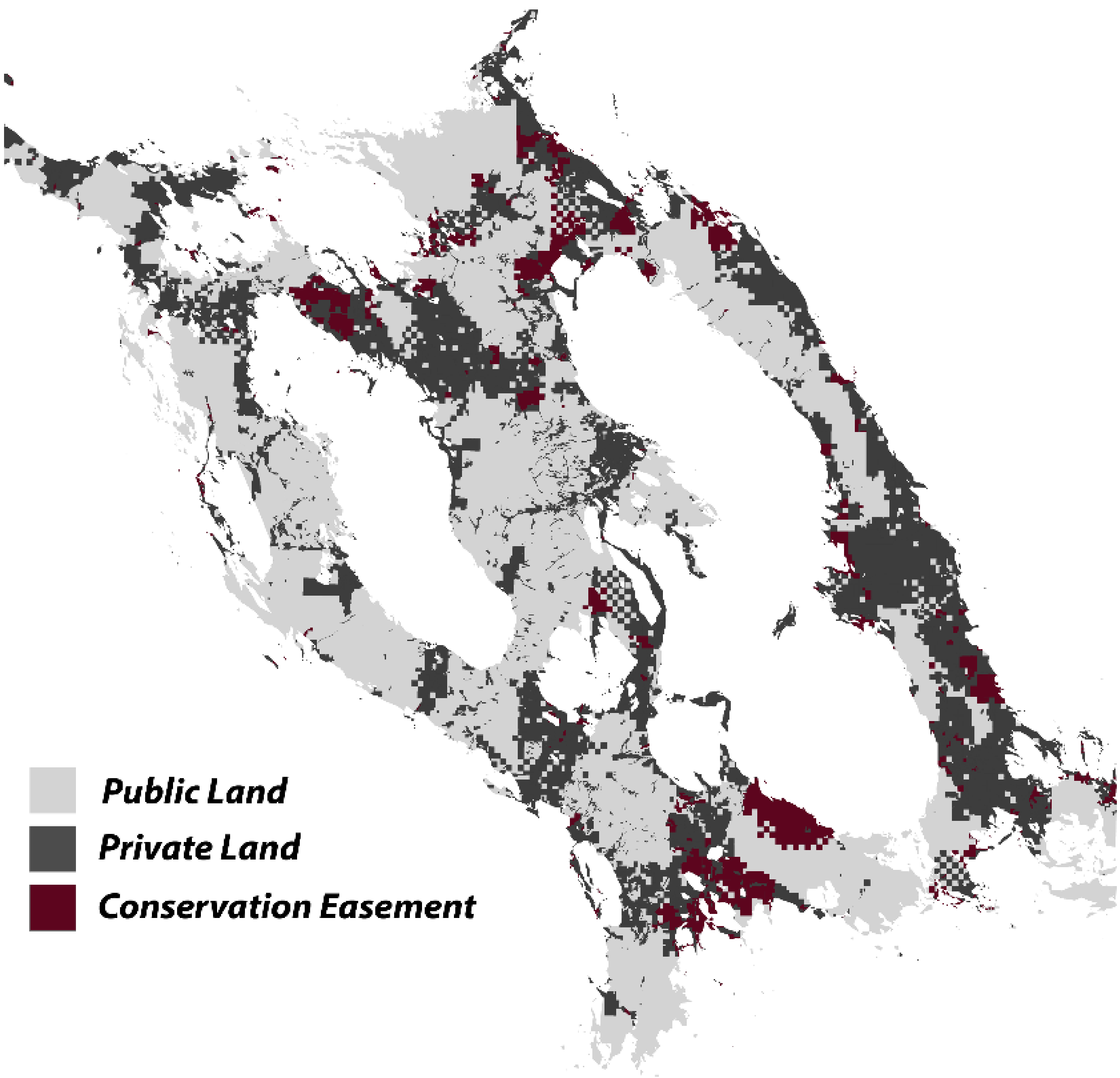

Figure 3. The mosaic of land ownership within the theorized grizzly bear migration corridors.

Least Cost Path Modeling and Analysis

The raster dataset produced using the methods described above functioned as the base data necessary for the study's least cost path assessments (Figure 4). The first step in the least cost pathway modeling was to reclassify the data to produce cost surfaces based on varying costs for protection and conservation opportunity; three different resistance surfaces were created (Table 1). For the first model, the entire grizzly bear migration pathway created by Peck et al was considered equal. Therefore, the public parcels, private parcels with conservations easements, and unrestricted private lands were all assigned resistance weights equal to one (1). The resulting model then functioned as the control as the resulting LCPs without any regard for ownership were expected to be the shortest. For the second model, the resistance of private parcels without conservation easements are treated as being higher (owing to their higher cost for protection) and were assigned values of two (2); private parcels with conservation easements were treated as equal to public lands and assigned values of one (1) again. The final model considered all three ownership types to be different in their costs for protection. Public lands have a score of one (1), conservation easement restricted private lands have values of two (2), and unencumbered private lands values of three (3).

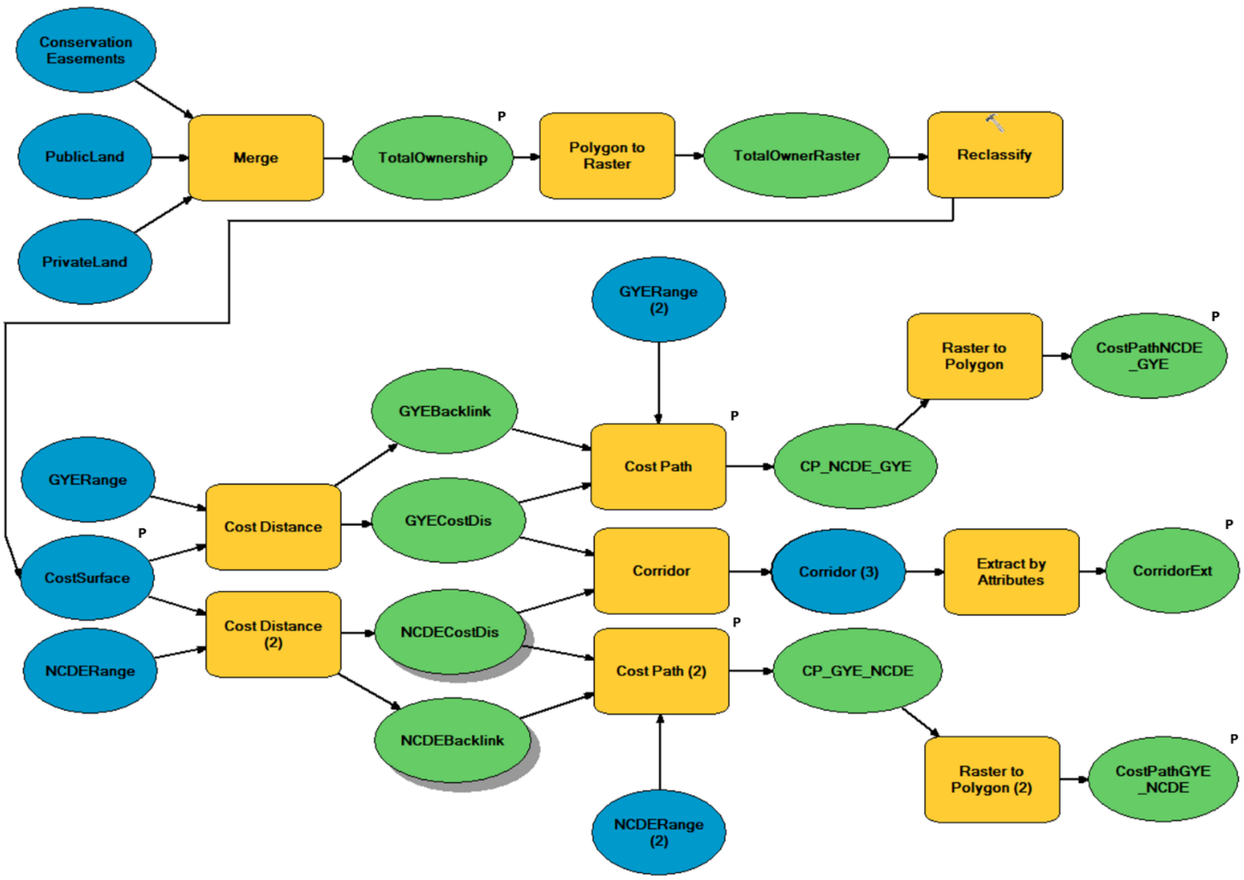

Figure 4. Overall framework of this study's GIS methods.

Table 1. Associated cost values for each of the three model's resistance surfaces.

Cost Values for Land Ownership Types	Public	Private Land with Conservation Easement	Private Land without Conservation Easement
Model 1	1	1	1
Model 2	1	1	2
Model 3	1	2	3

These scores were based on the assumption that publicly owned land will be protected into the future from development that would negatively impact habitat for grizzly bears and other wildlife. For the past half century this has been largely true due to the protections from federal land use planning regulations, such as the National

Forest Management Act, National Environmental Policy Act and, for grizzly bear habitat, the Endangered Species Act (Laschever 2011). Contrary to the protections found on public lands, the private lands within the migration corridors were assumed to have the highest cost for protection. This belief is based on the lack of land-use policy, which is significantly higher than the cost-values of publicly owned land; doing so will represent the high cost associated with removing development rights from land currently unencumbered by restrictions. The most important part of the cost surface valuation was the private land with an already existing conservation easement in place. These lands were given a cost value of two. This is based on the premise that those parcels will already have limited potential for future development because of existing easements, and therefore stronger habitat potential than fully unencumbered parcels. It is important to note that these parcels' conservation easement purposes (e.g., agricultural, forestry, or wildlife habitat related) are not known as such data are not included in the state's dataset. However, regardless of the type of easement it can be assumed that the amount of development and landscape change would be minimized into the future.

With the resistance layers created, the next step was to input the current grizzly bear population range boundaries, as determined by the IGBST, for both the NCDE and GYE populations. These two ranges served as the source and destination for the various LCP model runs. From the two ranges the resistance layer was run in each direction, from GYE to NCDE and from NCDE to GYE, through ESRI's cost distance tool to produce a cost distance and backlink raster for each directional model. Backlinks are an important aspect of a least cost path analysis in that they are a raster dataset showing the least costly movement between cells from the destination to the source. This is important to note when comparing the final LCP products, with each LCP modeling being run in both directions the lines will not take the same exact course due to geographic locations of parcels and the predetermined least-costly movement direction of each created backlink. The subsequently produced raster images served as the raster foundations for the final stage of the least cost modeling. To further deepen the projects ability to demonstrate the power of LCPs to prioritize parcels, the LCP models 1 and 3 were run using individual corridors within the entire study area (Figure 5). To do so, the GIS masking tool was used to segregate each corridor for two runs, in each direction of potential movement, to allow for more in-depth analyses of how this study's resistance layer creation impacts the prioritization of parcels.

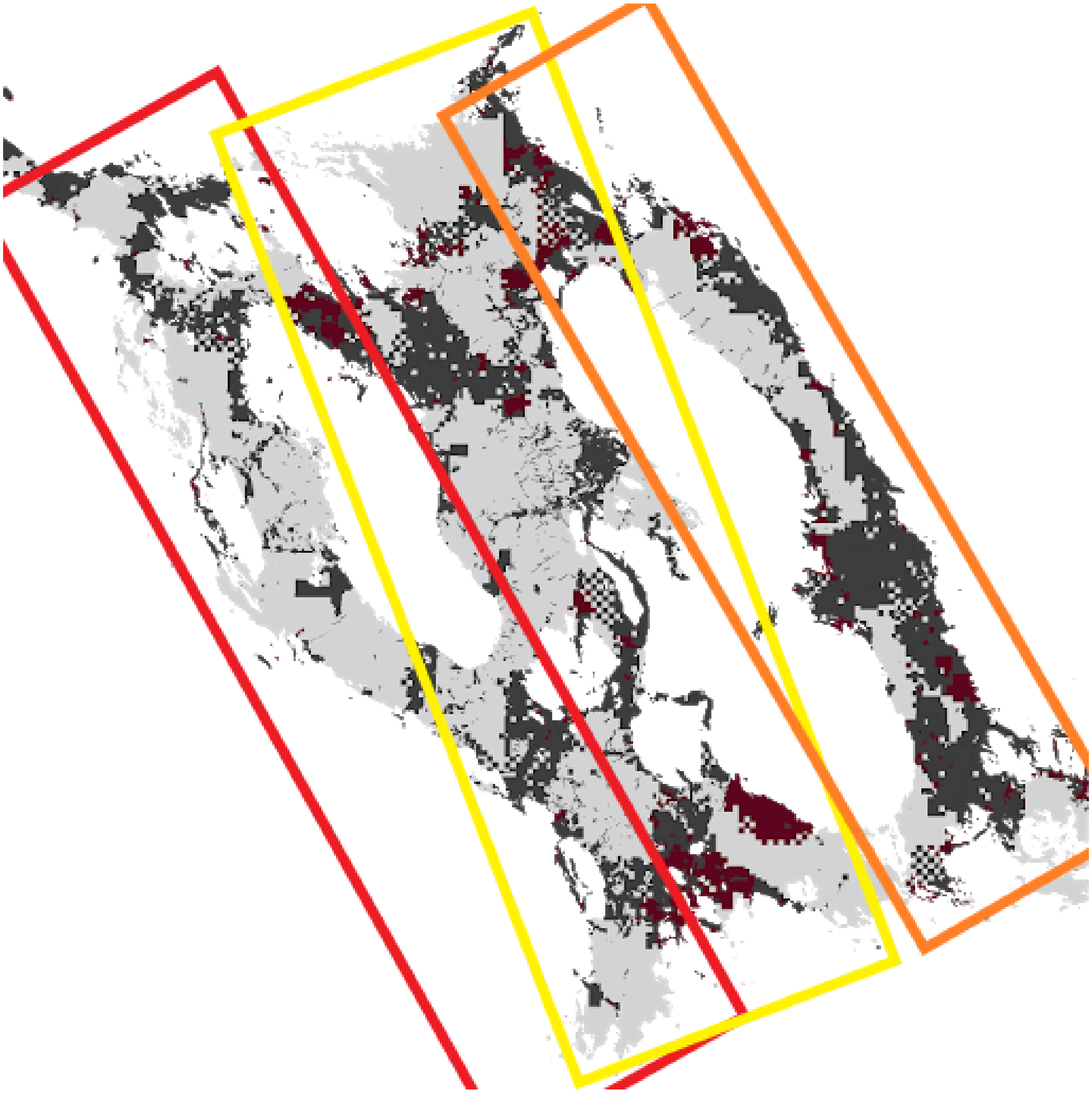

Figure 5. The entire study area from Peck et al's grizzly bear migration corridor study, with the three corridors used for further study within this study.

Following model runs, the ArcGIS's "tabulate intersection spatial analysis tool" was utilized for the LCPs overlaid on the derived cadastral private parcels data to generate statistics describing path length and number of parcels crossed or intersected by each LCP.

Results

Overall Process

In total, 14 different least cost pathways (LCPs) were created in this study. The LCPs were created using three different cost valuations, and therefore resistance surfaces, within different geographic corridors of the entire grizzly bear migration corridor (Table 2). The three different cost valuations produced markedly different LCPs for the geographic areas they were considered within. To analyze the different cost valuations for their potential benefit for conservation opportunity prioritization, five factors were considered for each LCP in the three different valuation schemes. The five factors were: 1) number of individual parcels each LCP passed over, 2) the percent of the LCPs' footprint over private land, 3) percent over private land with an existing conservation easement, 4) percent over public land, and 5) total LCP length between the population ranges.

Table 2. The different geographic constraints of the project's LCP models within the project's overall study area.

Geographic Constraints on Pathway Analyses	Entire Study Area	Western Corridor	Central Corridor	Eastern Corridor
Model 1	X	X	X	X
Model 2	X			
Model 3	X	X	X	X

Model One: All Equal

In the first model, with all parcels having equal resistance values (value = 1), which functioned as the control analysis, six LCPs were created (Figure 6). Two LCPs were created over the equal resistance surface, one from NCDE to GYE and one from GYE to NCDE, for each of the three corridors of the grizzly bear pathway model (western, central, and eastern). In this modeling, the LCPs were simply the shortest geographic lines between the two population ranges due to the equal resistance values, hence their ability to function as a control for the other model runs.

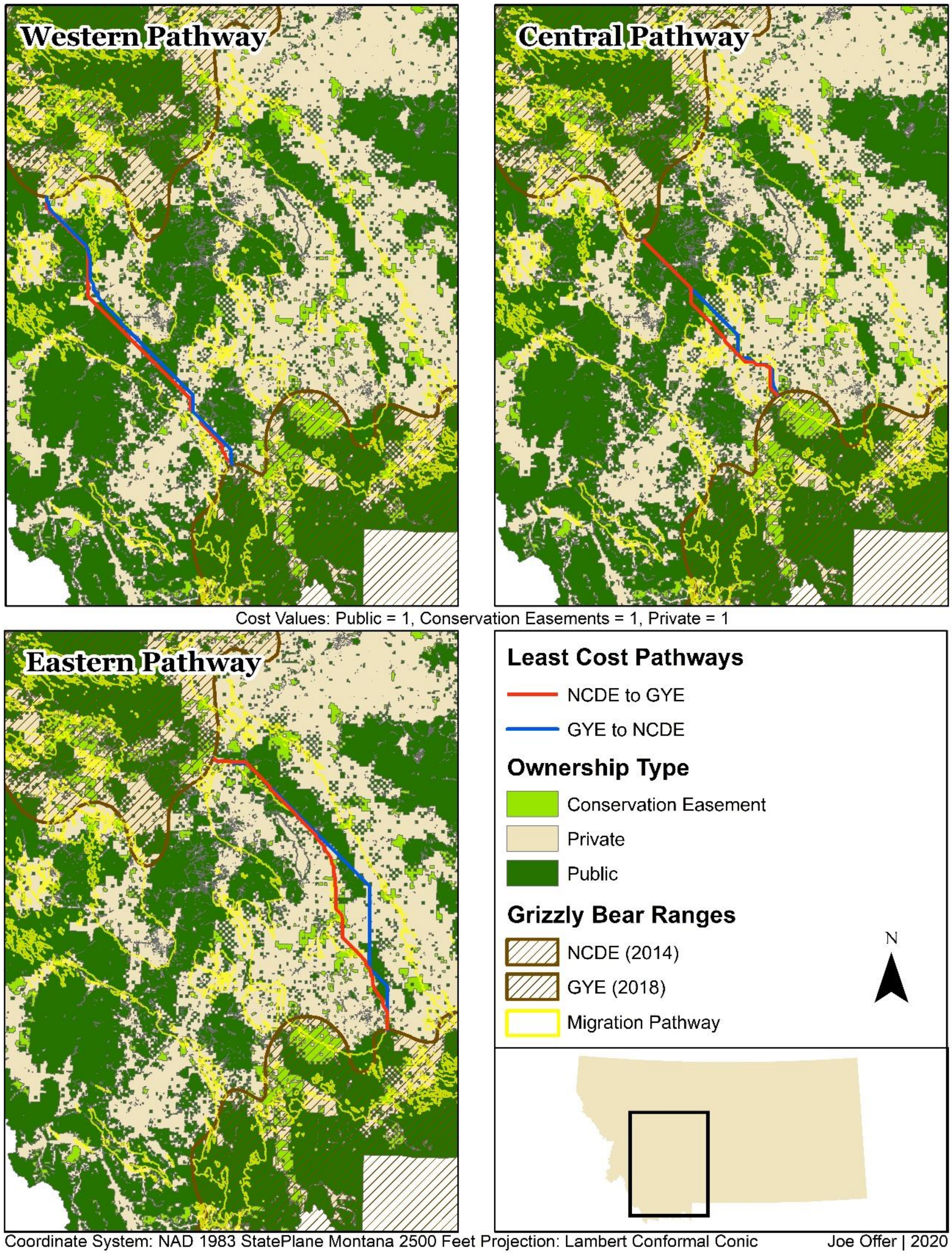

Figure 6. LCPs produced from the equal value resistance model of ownership within the project's study area.

The most direct and least costly pathways are within the central corridor of the entire grizzly bear migration corridor. For each direction of LCP modeling in the central corridor, the total distance covered by the LCPs was 121.48 kilometers. When overlaid on parcel data, the LCP from GYE to NCDE in the central corridor intersects 35 individual private parcels, with the LCP from NCDE to GYE intersecting 50 private parcels. Both of these numbers are the lowest for all of the LCP analyses over the entire equal value resistance surface. For the GYE to NCDE LCP, the line passes through public land 59.6% of its total length and 1% of the length over private parcels already under conservation easement directives. These same numbers were 56.5% and 1.8% respectively for the LCP from NCDE to GYE (Table 3). However, the most important metric is the percent of the LCP intersecting private parcels. For the NCDE to GYE LCP 41.7% of the total length intersects private land, while the GYE to NCDE LCP intersects private land 39.4% of its path.

Table 3. Selected metrics for the central corridor's LCPs of the equal resistance model.

	Number of Private Parcels	Percent of Cost Path Distance on Private	Percent of Cost Path Distance on Conservation Easements	Percent of Cost Path Distance on Public	Length of Cost Path (in Km)
NCDE to GYE (Central)	50	41.7%	1.8%	56.5%	121.48
GYE to NCDE (Central)	35	39.4%	1%	59.6%	121.48

While the LCPs in the central corridor of the grizzly bear migration corridor study area are the shortest of the three areas, the LCPs using equal resistance values within the western and eastern corridors of the corridors show higher percentages of their length over public land and private parcels with existing conservation easements. For the western corridor, the LCP from GYE to NCDE stretched 186.68 kilometers and was over public land for 61.2% of its length, with 3.1% over private parcels with conservation easements in place. The LCP from NCDE to GYE in the western corridor is the same length, but only traverses public land for 59.6% of its total length and conservation easement restricted parcels for 3.1%. Despite both paths covering more public land as a percentage of their paths when compared with the central corridor LCP, 37.3% for the NCDE to GYE LCP and 37% for the GYE to NCDE LCP, both LCPs in the western corridor have higher numbers of individual private parcels traversed, with 104 and 142 respectively (Table 4).

Table 4. Selected metrics for the western corridor's LCPs of the equal resistance model.

	Number of Private Parcels	Percent of Cost Path Distance on Private	Percent of Cost Path Distance on Conservation Easements	Percent of Cost Path Distance on Public	Length of Cost Path (in Km)
NCDE to GYE (West)	104	37.3%	3.1%	59.6%	186.68
GYE to NCDE (West)	142	37%	1.8%	61.2%	186.68

The eastern corridors LCPs from the equal value resistance model are interesting in that they differ from one another, which was not the case in the two other geographically isolated corridors of the migration corridor study area. For the LCP running from GYE to NCDE, 64.7% of the path's length is over public land, which is the highest of all LCPs in the equal value model. However, the eastern corridor's LCP from NCDE to GYE only crosses public land for 41.9% of its total length, which was the lowest percentage of all LCPs in the same resistance valuation. More interesting is that this same LCP from NCDE to GYE has the highest amount of length covering private parcels with existing conservation easements, at 13.2%. Additionally, both lines were the longest of the three corridors with total lengths of 196.06 kilometers yet passing through only 89 and 109 individual parcels correspondingly (Table 5).

Table 5. Selected metrics for the eastern corridor's LCPs of the equal resistance model.

	Number of Private Parcels	Percent of Cost Path Distance on Private	Percent of Cost Path Distance on Conservation Easements	Percent of Cost Path Distance on Public	Length of Cost Path (in Km)
NCDE to GYE (East)	109	44.9%	13.2%	41.9%	196.06
GYE to NCDE (East)	89	33.6%	1.7%	64.7%	196.06

For all of the LCPs created within the equal valuation modeling the lowest number of parcels traversed was 35 for the LCP running from GYE to NCDE in the central corridor of the study area, while the highest number was 142 for the same directional LCP in the western corridor. With the resistance surface being equal, these numbers, along with the other collected metrics helped to establish a baseline for prioritization of parcels for protection. This is caused by the LCP for each corridor only selecting for the lowest cost LCP in terms of distance, not assigned conservation opportunity from ownership type.

Model Two: Public and Private with Conservation Easements Equal Resistance

For the second model, public land and private parcels with conservation easements are considered equal in their conservation opportunity protection costs and private land is considered to be twice as costly, with resistance values of one and two respectively. Unlike the first analysis, only two least cost paths were created moving over the resistance surface between the GYE and NCDE, moving in both directions for the established grizzly bear ranges (Figure 7). The two paths were created by running the analysis over the entire corridor's resistance surface, which meant only the least costly and most direct paths were considered. The reason for this was simply the amount of time and computer analysis additional runs required, as this was neither the least nor most nuanced model it was assumed that one run would provide a comparison with the other models. The resulting paths were located within the central corridor, which is associated with the area's lowest total distance between ranges.

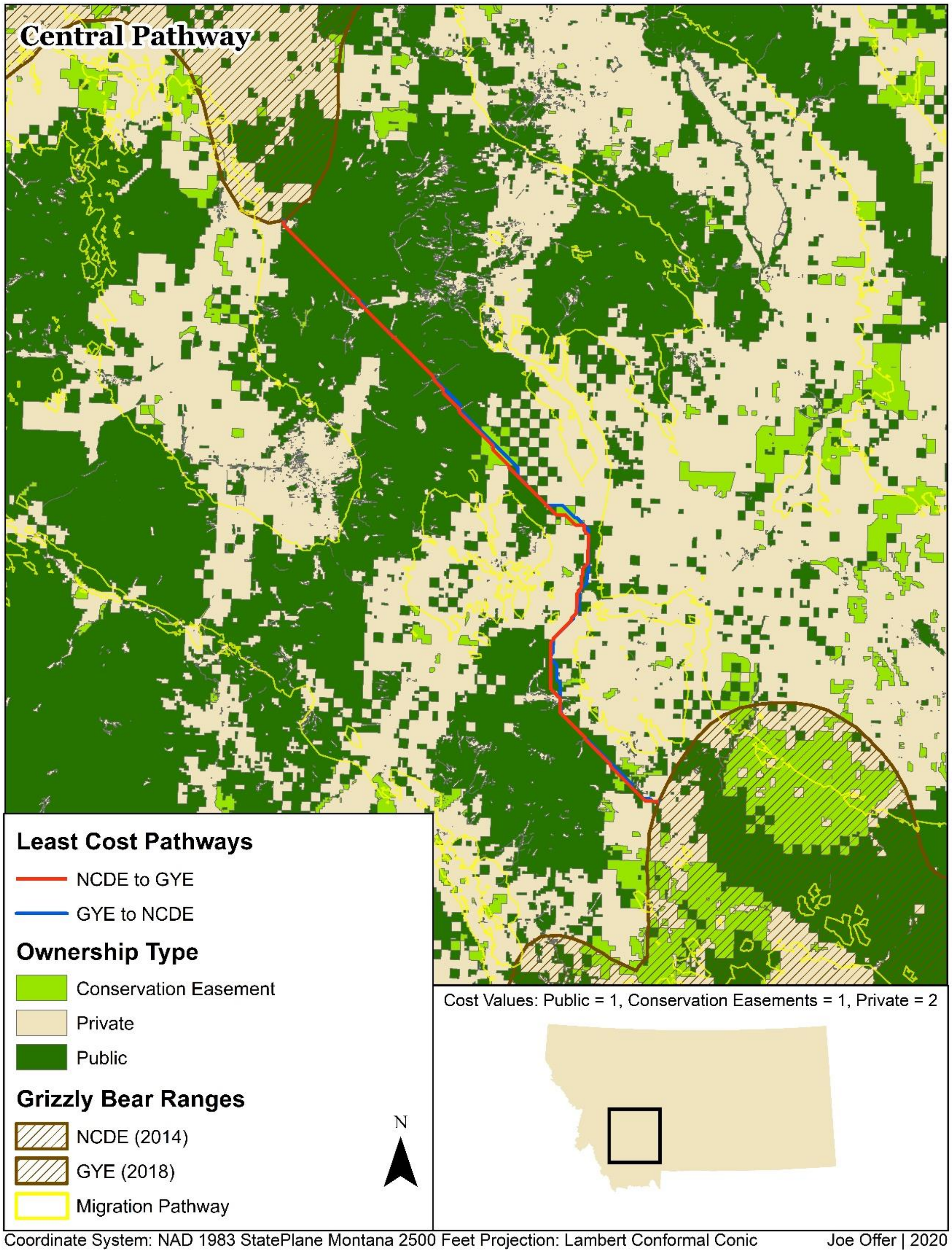

Figure 7. LCPs produced from the public and conservation easement equal resistance model of ownership within the project's study area.

The resulting LCPs created with the resistance model containing values of 1 and 2 are quite different from those created with the equal resistance surface analysis. The LCP running from NCDE to GYE crosses only 28 total individual parcels and is located within public land for 84.2% of its total length. Additionally, the NCDE to GYE LCP had 11.2% of its length over parcels with existing easements. For the LCP from GYE to NCDE in the same analysis, the results are similar. The GYE to NCDE LCP traverses only 30 individual parcels, crosses public lands 82.8% of its length, and crosses parcels with existing conservation easements for 12.7% of its length. In total, the two paths are located within private lands for only 4.6% and 4.5% of their entire reaches, respectively (Table 6).

Table 6. Selected metrics for the LCP products of the public and conservation easement equal resistance model.

	Number of Private Parcels	Percent of Cost Path Distance on Private	Percent of Cost Path Distance on Conservation Easements	Percent of Cost Path Distance on Public	Length of Cost Path (in Km)
NCDE to GYE (Central)	28	4.6%	11.2%	84.2%	133.80
GYE to NCDE (Central)	30	4.5%	12.7%	82.8%	133.79

When compared with the same LCPs from the previous model, each LCP shows decreases in the total number of parcels traversed and the percent of each LCPs' length over private land, which is expected due to the model's resistance values. Consequently, each LCP also shows significant increases in the length of LCP crossing public land and parcels with existing conservation easements. The increases in length over public lands were 27.7% for the NCDE to GYE LCP and 23.2% for the GYE to NCDE LCP. These differences are associated with LCP increased length of only 12.32 kilometers (Table 7).

Table 7. Differences between selected metrics of the central corridor's LCPs public and conservation easement equal model compared with the control (Model 1).

Central Pathway Differences Between Runs	Difference in Number of Private Parcels	Difference in Percent of Cost Path Distance on Private Parcels	Difference in Percent of Cost Paths Distance on Conservation Easement Parcels	Difference in Percent of Cost Path Distance on Public Land	Difference in Length of Cost Path (in Km)
Model 1 to 2					
NCDE to GYE	-22	-37.1%	+9.4%	+27.7%	+12.32
GYE to NCDE	-5	-34.9%	+11.7%	+23.2%	+12.32

Model Three: Public/Conservation Easements/Private

The third, and final, analysis of this study is the most intricate of the three. In this analysis, public land is given the resistance value of one (1), private parcels with existing conservation easements are scored as two (2), and private parcels are given a value of three (3). As a result, six different LCPs were created, with one running from NCDE to GYE and one from GYE to NCDE for each of the three corridors. Similar to the first analysis of equal resistance values, and unlike the second analysis, this analysis was completed for each of the three corridors within the project's study area. As mentioned previously, this is because the third model is the most varied in valuation of resistance models and, therefore, illustrates the fullest ability of such an analysis. Due to the more variable resistance values used, the LCPs from this analysis have the most complex geographic footprints (Figure 8).

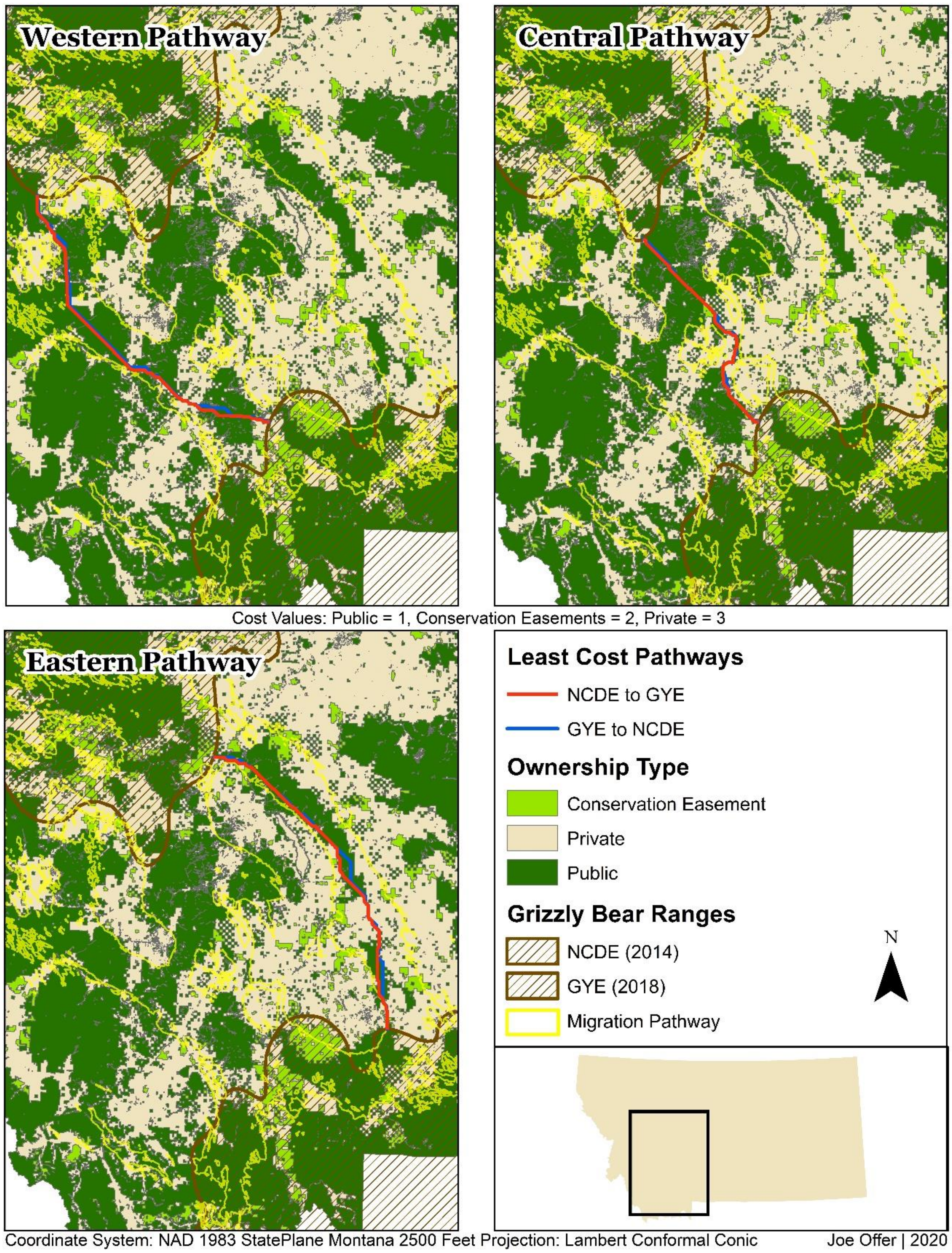

Figure 8. LCPs produced from the public, conservation easement, and private land unequal resistance model of ownership.

The shortest in length of the three sets of LCPs are the two within the central corridor of the grizzly bear migration pathway (Figure 9). Each directional LCP has a total distance of 138.62 kilometers. The LCP from NCDE to GYE intersects only 19 individual private parcels, while the LCP from GYE to NCDE crosses 21 private parcels. Beyond the slight difference in individual parcels traversed, all of the other measured metrics for both lines are identical. The two LCPs intersect public land for 92.9% of their entire length and pass through private parcels with existing conservation easements 4.1% of each segment. This means that for each of the two central corridor LCPs, only 3% of their entire section (4.16 kilometers), is within private parcels (Table 8).

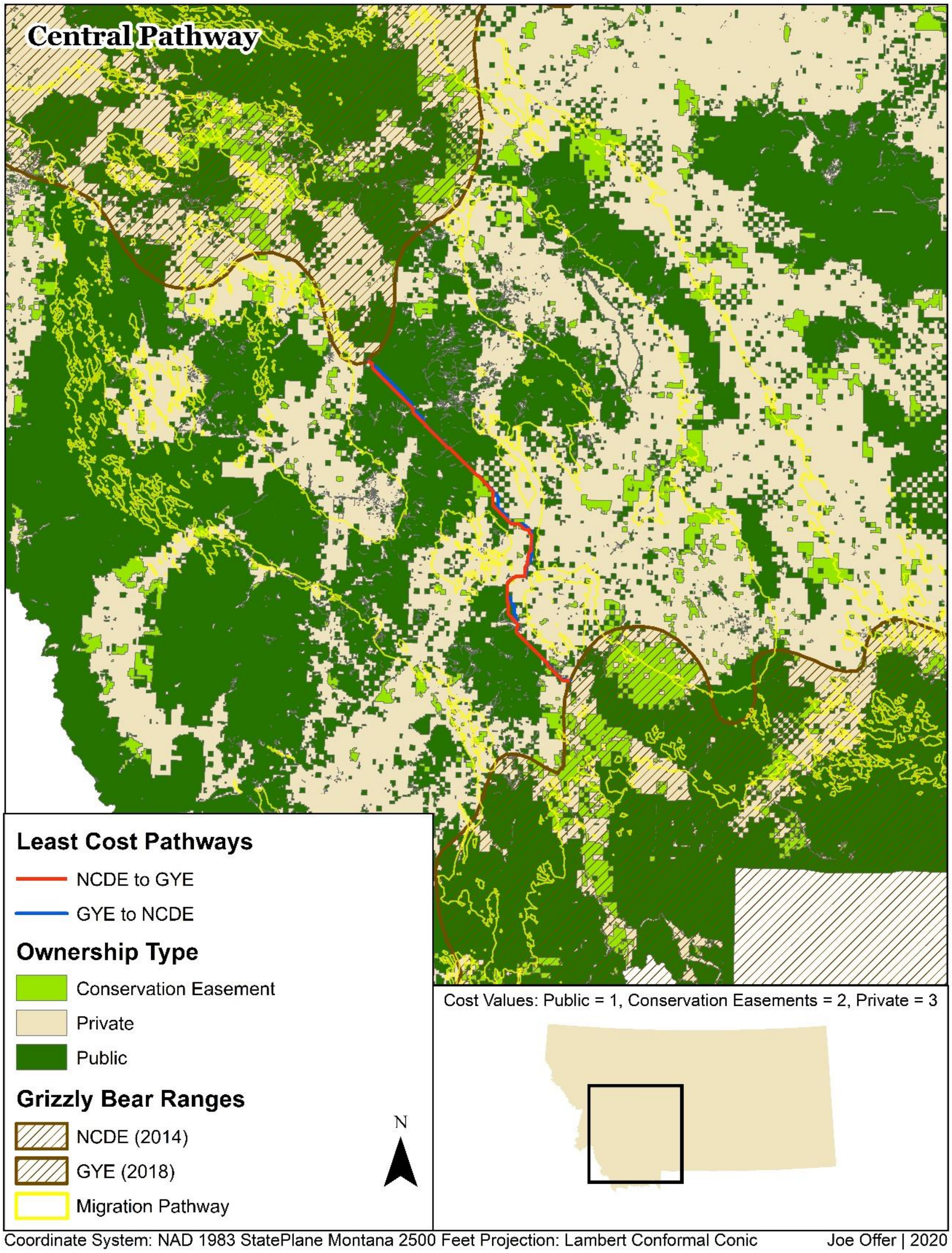

Figure 9. The LCPs from the central corridor of the public, conservation easement, and private land unequal resistance model of ownership.

Table 8. Selected metrics for the central corridor's LCPs of the public, conservation easement, private land unequal resistance model.

	Number of Private Parcels	Percent of Cost Path Distance on Private	Percent of Cost Path Distance on Conservation Easements	Percent of Cost Path Distance on Public	Length of Cost Path (in Km)
NCDE to GYE (Central)	19	3%	4.1%	92.9%	138.62
GYE to NCDE (Central)	21	3%	4.1%	92.9%	138.62

Just as was seen in the first analysis, while the LCPs in the central corridor of the grizzly bear migration pathway study area are the shortest, those same LCPs show lower percentages of their length over public land than the LCPs in the western corridor (Figure 10). For the western corridor, public land accounts for 97.8% of the land over which both LCPs run. This percentage is nearly 5% higher than the next highest, in the central corridor. Conversely, the two LCPs only pass through private parcels 2.1% of their length, the lowest of all three sets of LCPs. With such a small percent of the LCP in private, these lands only account for 4.26 kilometers of each LCPs' 203.78 kilometers, the longest total of the three sets. Of interest is the amount of each LCP running through private parcels with an existing conservation easement; only .1% of each LCP pass across land already under conservation easement restrictions (Table 9).

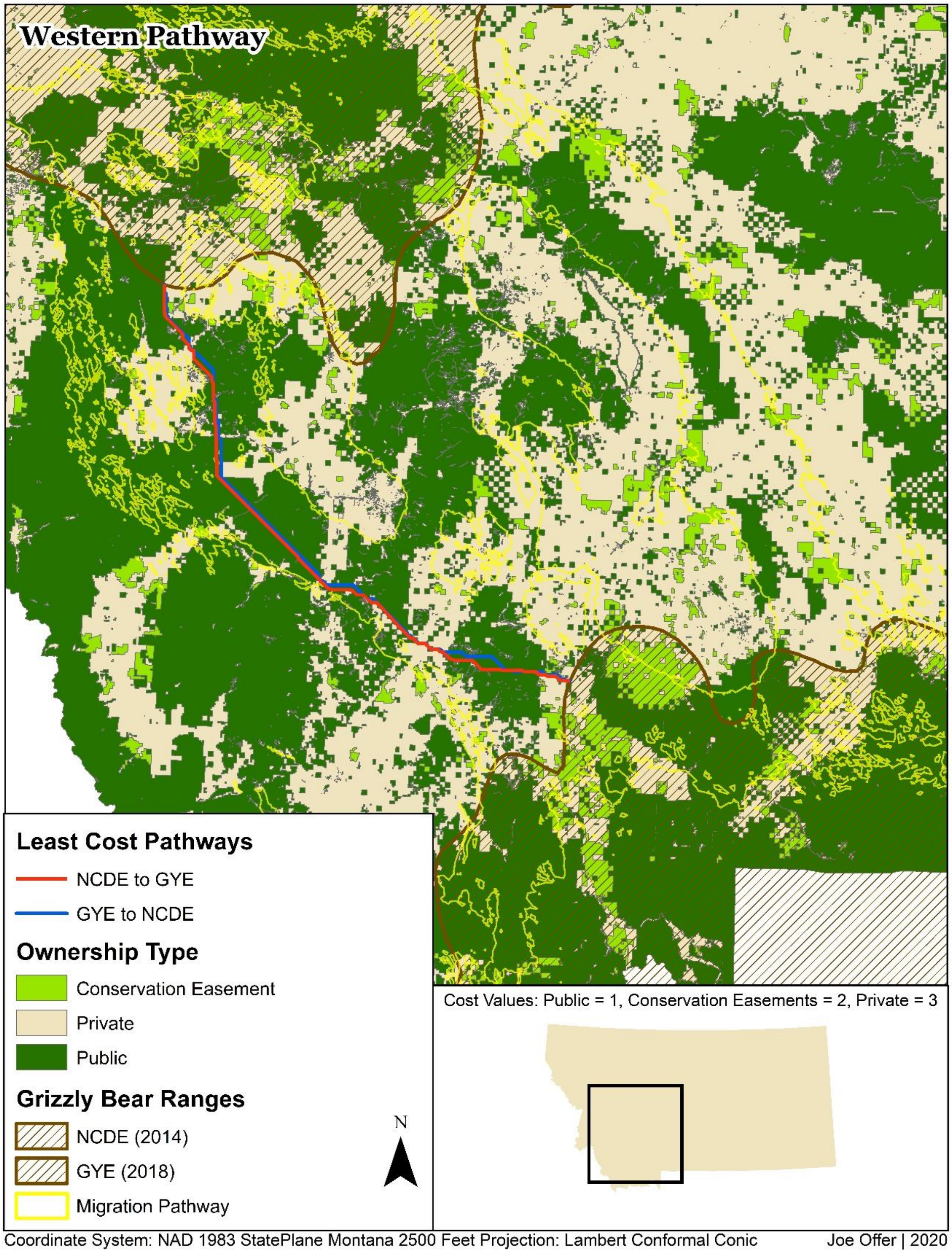

Figure 10. LCPs from the western corridor of the public, conservation easement, and private land unequal resistance model of ownership.

Table 9. Selected metrics for the western corridor's LCPs of the public, conservation easement, private land unequal resistance model.

	Number of Private Parcels	Percent of Cost Path Distance on Private	Percent of Cost Path Distance on Conservation Easements	Percent of Cost Path Distance on Public	Length of Cost Path (in Km)
Run 3	Cost Values: Public = 1, Conservation Easements = 2, Private = 3				
NCDE to GYE (West)	18	2.1%	.1%	97.8%	203.78
GYE to NCDE (West)	17	2.1%	.1%	97.8%	203.78

Unlike in the first analysis, where the two different directional LCPs for the eastern corridor have very different metrics, the two LCPs in the eastern section resulting from the third analysis are identical in their underlaying statistics (Table 10) (Figure 11). Each LCP is 199.06 kilometers long, of which 21.89 kilometers crosses private land. This is due to the eastern LCPs having the highest percentage of their length over private parcels at 11%. As would be expected with the highest rates of passage over private land, these LCPs also have the lowest percentage of their length over public land. In total, only 87% of each LCP in the eastern corridor was on private land, which can be seen from a qualitative look at each LCPs' geographic footprint.

Table 10. Selected metrics for the eastern corridor's LCPs of the public, conservation easement, private land unequal resistance model.

	Number of Private Parcels	Percent of Cost Path Distance on Private	Percent of Cost Path Distance on Conservation Easements	Percent of Cost Path Distance on Public	Length of Cost Path (in Km)
NCDE to GYE (East)	52	11%	2%	87%	199.06
GYE to NCDE (East)	51	11%	2%	87%	199.06

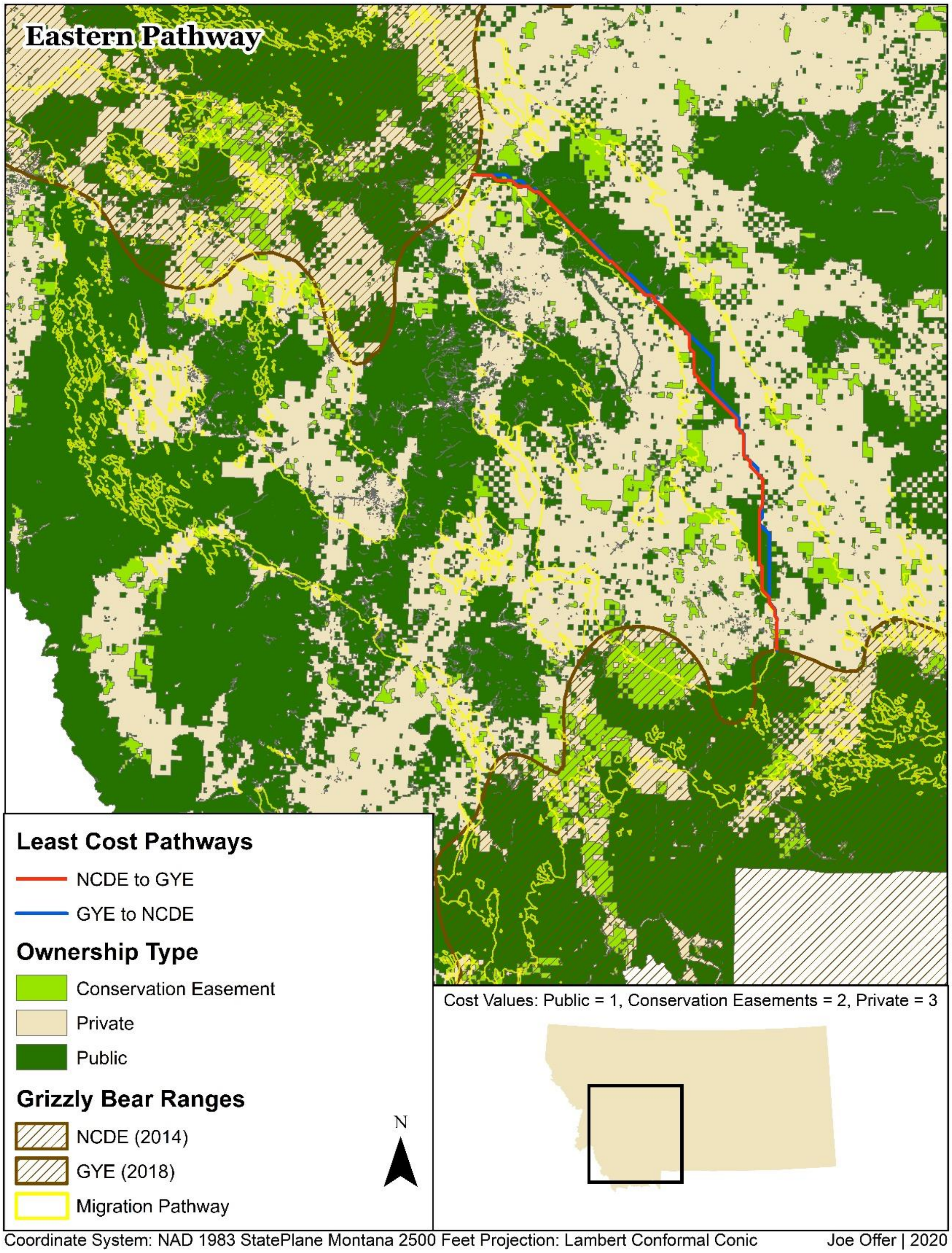

Figure 11. LCPs from the eastern section of the public, conservation easement, and private land unequal resistance model of ownership.

For all LCPs in the third analysis, the western corridor shows the lowest number of individual parcels traversed by each LCP, 18 for the NCDE to GYE LCP and 17 for the LCP from GYE to NCDE. This makes logical sense because both LCPs have the lowest percentage of length over private land in comparison with those in the other corridors in this analysis. However, due to the significant length difference between the current western and central corridors, there is a 65.16 kilometer difference in total length between the two, and more of the western LCPs length traversed private land, albeit only 0.1 kilometer more.

From the first analysis to the third, the smallest decrease between LCPs was for the eastern LCP from GYE to NCDE at -22.9% (Table 11). On the opposite end of the spectrum was the central pathway's NCDE to GYE LCP with a difference of -38.7% (Table 11). Decreasing total length traversing private parcels was echoed in the difference of total individual parcels encountered by each LCP. In the western section, the GYE to NCDE LCP passed through 125 less individual parcels from the first analysis to the third (Table 11).

Table 11. Differences between selected metrics of the LCPs in public, conservation easement, and private unequal model as compared to the control (Model 1).

Differences Between Analyses	Difference in Number of Private Parcels	Difference in Percent of Cost Path Distance on Private Parcels	Difference in Percent of Cost Paths Distance on Conservation Easement Parcels	Difference in Percent of Cost Path Distance on Public Land	Difference in Length of Cost Path (in Km)
Analysis 1 to 3					
NCDE to GYE (Central)	-31	-38.7%	+2.3%	+36.4%	+17.14
GYE to NCDE (Central)	-14	-36.4%	+3.1%	+33.3%	+17.14
NCDE to GYE (Eastern)	-57	-33.9%	-11.2%	+45.1%	+12.32
GYE to NCDE (Eastern)	-38	-22.9%	+.3%	+22.3%	+12.32
NCDE to GYE (West)	-86	-35.2%	-3%	+38.2%	+17.10
GYE to NCDE (West)	-125	-34.9%	-1.7%	+36.6%	+17.10

Discussion

Multiple potential conservation corridors exist within western Montana that could link the two isolated populations of endangered grizzly bears on protected lands if just over four kilometers of private land is placed under conservation easements (Figure 12 and Tables 8 and 9). That is a finding, that, until this case study, was not previously known. When considered in relation to the future vitality of grizzly bear populations, this study shows that prioritized efforts by local land trusts and other conservation easement holding organizations could focus resources to solve a major conservation goal. This study also shows how important conservation easements are in realizing that goal. While public lands are largely protected from development, as noted previously, their landscape footprint is predominantly set into the future, therefore conservation easements hold the key to protecting connected parcels of necessary wildlife habitat. Additionally, this study and the approach it employed serves as an important bridge between wildlife movement modeling approaches and applied landscape protection studies.

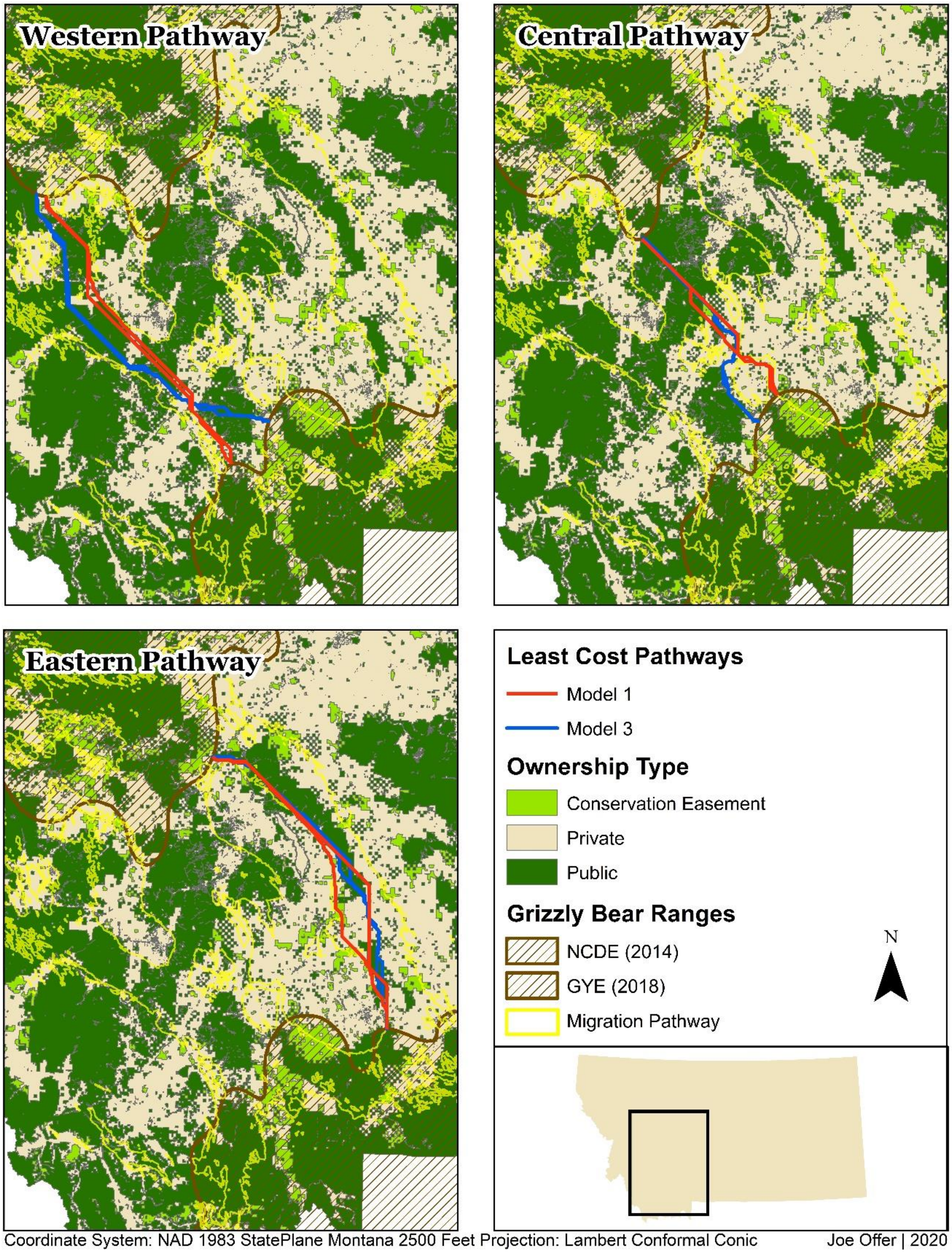

Figure 12. LCPs from the first (control) and third models, showing the difference in geographic footprint as the intricacy of resistance scoring increased.

In the broader context, this study shows the potential for least cost pathway modeling to help quantify conservation costs associated with creating protected conservation corridors for wildlife species of all sorts, in any landscape. The fact that it can be done using a basic geographic information system is one of the most important aspects of the study. The simplicity of this study's methods demonstrates the power that conservation organizations can use to prioritize conservation easement efforts, depending upon their own designs and goals, to bring about conservation successes.

Overall Case Study Outcomes

The products of this case study show that there truly is great potential for connecting the long isolated grizzly bear populations of western Montana through a protected landscape. Whether the different models are utilized to quantify and identify parcels for protection, or total length of distance on protected public lands, there are obvious examples of how LCPs can inform and quantify the conservation efforts needed. Model 3, which accounts for both the impact of unprotected private lands on potential travel and the cost of acquiring these lands, clearly shows that prioritizing parcels based on conservation opportunity is possible. The clearest indicator of this is through the percent of length each LCP spent traversing private land, which can be seen very clearly in Table 11. In total, the connection could be made with only 17 conservation easements, which is a surprisingly low number. However, the LCP models have broader utility because they can be used to identify areas in which conservation organizations should focus outreach and other resources. This LCP modeling approach can also be utilized to adjust for information or knowledge that is gained relating to individual owner preferences for conservation easement establishment. But isolating singular parcels for protection is only of so much importance. Instead, being able to identify areas that emerge as LCP bottlenecks by is also of immense value.

For example, looking at the LCPs produced in Model run 3 for the western and central corridors, one can clearly see that these enter and exit the GYE from the same location (Figure 6). Therefore, it is clear that the private parcels within that area have high importance for the establishment of conservation corridors connecting to this source/destination area. In this case, the parcels are roughly between the towns of Ennis and Norris. With this information, land trusts can begin to use their limited resources individually or in larger landscape collaboratives to construct plans to target these most important regions. Additionally, there are other areas in which both the second and third models pass, which suggests that they may have similar importance. And from the geographic footprint of any LCP, much can be learned for conservation action on a broader scale.

In a similar sense, the LCPs also identify geographically specific areas within large infrastructure projects that are likely to impact the movement and actions of grizzly bears. Grizzly bears have shown a negative response to movement across large roadways and have increased mortality in areas with high traffic. In parts of the grizzly bears' northern range, highway overpasses and roadway shoulder fencing has shown to decrease grizzly bear mortality and increase movement potential (Cushman, Lewis, and Landguth 2014). Throughout western Montana, highways and interstates bisect the movement corridors created by Peck et al's original study. The LCPs created in this study show specific points on many of those roadways where focused conservation action has the lowest total cost for corridor protection. Therefore, the LCPs' intersections with these same roadways could serve to maximize the conservation benefit from wildlife friendly infrastructure at these points. Along with roadways, this same benefit of identifying specific points on roadways could do the same for many other development types, such as pipelines or powerlines.

Study Issues

Despite this project's ability to produce defensible and useful products, there are several ways in which this project's methods and models might be improved. One main issue is simply related to the geographic area in which the case study takes place. Western Montana is a patchwork of different ownership types, which is not unlike the rest of the country and world. However, unlike the rest of the country and world, western Montana is unique in its amount of land under some sort of public ownership. Throughout the western United States, federal agencies like the Forest Service and Bureau of Land Management are responsible for management of large swaths of public lands. Montana as a state has the twelfth highest percentage of land under federal ownership in the country, and most of that exists in the state's western half. Therefore, this study's LCPs were heavily influenced by the amount of public land. Different landscapes with lower amounts of public lands are less likely to produce such clean and clear-cut prioritization outcomes. Instead, LCP modeling in less public land-centric regions is likely to produce greater variation in outcomes (geographic footprints, number of parcels, etc.). Future testing of this approach in a landscape with a higher amount of private land would likely yield much different results and further test the overall feasibility of such a prioritization modeling.

Another shortcoming of the approach used in this study is that parcels were not scored relative to size. In general, larger parcels hold higher conservation opportunity due to the ratio of transaction cost to acreage protection values. In the approach used here, larger parcels are penalized for their size because each individual pixel adds to the total cost of movement. To combat this issue, pixels corresponding to each individual parcel would need to be scored for the parcel's relative size and shape, thus approximating estimated or true costs; additional GIS operations would be required to make produce the raster-based cost surface to accomplish this. This would also require that assumptions or decision rules be developed and employed based on expert knowledge, but that may be imperfect. This issue, unlike the issue of ownership patchworks, is potentially solvable and could be a next step in the model. However, it should be noted that such rules and additional steps in the GIS design would eliminate some of the simplicity and benefit of the basic LCP analysis.

Another area of importance when considering this project is that of cost value scoring. Resistance values are subjective, like in this study, and that brings with it the potential for bias. Instead of a concrete number derived arbitrarily, resistance values for nearly all LCP analyses are set by "experts" in the field. This is of importance because any resistance values have the power to completely change the outcome of an entire study. This study's three different analyses illustrate this issue very clearly. In Model 1, which acts as a control, the equal values produce only the shortest path. From there, as cost values increase and resistance surfaces become more intricate, LCPs start to behave quite differently and are highly dependent upon the range and location of the values. For this study's, and any other LCP analyses, to be stronger and more credible "experts" must be consulted to produce about stronger and more robust products that better represent the actual cost associated with model's goals.

While there are issues with this study's framework, such as those identified above, this study was conducted primarily for the purpose of testing an approach that future prioritization models might follow and expand from. In addition to simply using ownership type to create resistance values for protection, future modeling using a similar approach would be able to include additional geographic information to further identity parcels or groups of parcels for focused conservation action. Examples of such geographic datasets could potentially include additional values for intensity of development or proximity of infrastructure. However, it should be noted that by adding in additional datasets and values the study becomes much more complicated and many such variables would likely be included in the original biophysical modeling of wildlife movement, such as in the case of this study's base migration data.

Further Research and Implementation

Beyond the scope of this project, this study can be refined in many ways to help land trusts and other conservation organizations identify and protect key parcels to bring about success in landscape protection. The most important aspect is the creation of a base GIS model (Figure 4) that can be utilized for similar case studies in specific species related work or on broader landscape characteristic prioritization by creating LCPs. However, another key aspect of this study is the responsiveness of the model to slight changes in the resistance surface and cost valuation. The model showed how important the change in cost values were in producing different corridor conservation outcomes. This same responsiveness could be used to identify "keystone" parcels that would create large changes to the overall path of the model's LPCs should these be placed under easements. To do this, a modeler would simply need to edit the base data for conservation easements in the data acquisition phase of the methods for singular parcels and then run the complete model. By comparing the underlying data for LCPs prior to and after editing the resistance surface, land trusts and other conservation organizations could consider the importance of individual parcels on protecting an entire corridor.

This same responsiveness and ease of running the model is also very important in that changing ownership types, or even subdivision of large parcels, could be done in almost real-time. With the model in place to merge, clip, and join base level ownership data, changes to any aspect of the individual datasets could be seamlessly updated and subsequently help to adjust conservation planning. These changes could have significant impacts upon the overall dynamics of a potential corridor, and being able to adjust quickly would allow for conservation action with limited resources.

Conclusion

While only one small case study, this project shows the potential for least cost pathway (LCP) analyses to prioritize land parcels based on perceived conservation opportunity. At the most basic level, LCP modeling can be quite simple to employ and produce important knowledge not otherwise easily obtained. Similar projects adapted for this or other study areas would not require intensive modification of methods or extensive research into new products for geospatial analysis to produce meaningful outcomes. However, to make future work like this more impactful over large landscapes, such as in the case study, communication and interorganizational planning needs to take place. Conservation easements, and factors related to their implementation, were the focus of the methods for this project. But the same approach would be useful for fee simple purchase prioritization or even stewardship practices.

If biodiversity is to be maintained utilizing corridor protection of different sorts around the world, more studies like this need to be completed. Bringing together the immense knowledge bases within the fields of wildlife movement modeling and habitat protection is key to realizing actual on-the-ground benefits. Moving into the future, the need for more conservation action will only increase, just as the available resources for that action will continue to be stretched further and further. When used together with collaborative planning at a landscape level, this study's blueprint and methods hold the potential to save time, money, and energy in the difficult work of conserving our natural world.

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