Technical report for

Permeable landscapes for climate change adaptation in and around Boulder and northern Jefferson Counties

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Incompatible land uses, compounded by recent and likely future climate change have impacted our natural habitat types and reduced the permeability of open space and park lands in Boulder and northern Jefferson Counties by roughly two-thirds. A primary climate-smart strategy to conserve biodiversity is to allow species to adapt to habitat change by ensuring a connected landscape. As such, this project was designed to inform decision making about opportunities to maintain, protect, restore, and manage for wildlife connectivity. Potential opportunities to facilitate movement within and surrounding the open space and parks, habitats, and landscapes were identified by mapping "hot spots" across four major habitat types using spatial modeling of landscape permeability. This can help inform management by identifying:

- restoration or management activities to facilitate wildlife movement;
- protection of additional adjacent or nearby lands to complement the existing system of protected lands;
- partnering opportunities with adjacent land managers; and
- subsequent analyses to evaluate conservation strategies and for specific situations.

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B. Anacker, W. Keeley, H. Swanson: *City of Boulder Open Space & Mountain Parks*
C. Beebe, H. King: *Jefferson County Open Space*

Abstract

This research was designed to inform decision making about the opportunities to maintain, protect, restore, and manage open space and park lands to ensure wildlife connectivity across Boulder and northern Jefferson Counties, Colorado. A primary strategy to address the impacts of climate change on natural systems and biodiversity is to allow ecological systems to adapt to climate change by ensuring a connected landscape. One approach to understanding landscape connectivity is to model climate-induced habitat shifts for specific wildlife species, yet this is challenging because limited data are available on species-specific life history characteristics, sensitivity to new climate conditions, and capacity to adapt. Moreover, there is high uncertainty in future climate predictions at management relevant scales, especially in a landscape that contains numerous habitat types and diffuse ecotones. As a result, this project measured connectivity using an indicator called landscape permeability, which characterizes the ability of wildlife to move through a landscape while avoiding developed areas with high human activity and ecological processes to function naturally. Overall, permeability has declined by two-thirds from "natural" (no humans) conditions. Not surprisingly, upper and lower montane habitats are much more permeable than lower elevation grassland/shrublands, while permeability in riparian/valley bottoms is variable. The resulting maps were analyzed to identify potential opportunities ("hot spots") to facilitate movement through: (a) restoration or management activities; (b) protection of additional adjacent or nearby lands to complement existing protected lands; and (c) partnering with adjacent land managers. Also, the datasets can be analyzed in a variety of ways to evaluate additional conservation strategies and for specific situations.

Keywords: wildlife connectivity, landscape permeability, climate adaptation, habitat types

Introduction

The goal of this project was to inform decision making about wildlife connectivity on open space lands in and adjacent to Boulder County, which includes lands managed by Boulder County Parks & Open Space (POS), the City of Boulder Open Space & Mountain Parks (OSMP), and Jefferson County Open Space (OS). A primary strategy to adapt to climate and land use change is to maintain and restore ecological connectivity (i.e. for wildlife movement, plant dispersal, ecological processes such as disturbances like wildfire, and gene flow; Lawler 2009). This project informs POS, OSMP, and OS decision makers and managers by providing information about landscape-level permeability, as an important way to adapt to climate change effects on habitat types in and around Boulder and northern Jefferson counties. The terms "protected areas" or "system of protected lands" are used below to refer to the open space, parks, and other properties owned or managed by POS, OSMP, and OS, and by adjacent agencies (e.g., US Forest Service, National Park Service, etc.).

A few climate change adaptation strategies have emerged from the scientific literature (Schmitz et al. 2015; Keeley et al. 2018; Thurman et al. 2020), which are roughly grouped into modeling *functional* or *structural* connectivity. Functional connectivity recognizes the behavioral response of species to the structure of the landscape (Theobald 2006; Kindlmann and Burel 2009) and is used typically to characterize the shift in habitat use by single-species due to climate change. Modeling functional connectivity can be challenging because of a paucity of data about species-specific life history characteristics, the sensitivity to new climate conditions, and the adaptive capacity of a given species. In addition, there is high uncertainty in future climate projections, particularly at management relevant scales, which is compounded in a highly heterogeneous landscape that contains numerous habitat types. *Structural* connectivity, on the other hand, is based on the spatial arrangement of habitats on a landscape and characterizes broader ecosystem and landscape naturalness to understand the "stage" on which species' movements occur (Anderson and Ferree 2010). The functional and structural strategies are considered to be complimentary.

For this research we chose to use a structural, coarse-filter conservation approach (Noss 1990) because it recognizes the relatively high uncertainty about how future wildlife and broader habitats will evolve with climate change in the coming decades; the limited biological data for individual species, particularly at management-relevant scales; and that a functional approach requires up to a order of magnitude more resources. Briefly, structural, coarse-filter conservation is rooted in the idea that ecological systems operate within landscapes and are typically understood in terms of composition, structure, and function (Noss 1990). A landscape with high ecological integrity supports and maintains a community of organisms and ecological processes that are comparable to natural habitats within a region (Parrish et al. 2003). Central to landscapes with high ecological integrity is connectivity, which is commonly defined as the degree to which a landscape facilitates movement of species, populations, and genes among resource patches (Taylor et al. 1993). Providing connectivity is the most common strategy recommended for ecological adaptation to climate change (Heller and Zaveleta 2009; Keeley et al. 2018).

In this project, we will measure connectivity by modeling landscape permeability, which is defined as an indicator of how easily wildlife can move across the landscape while avoiding human modified areas (Theobald et al. 2012). Permeability is particularly valuable in situations and landscape contexts that have high biogeographic variability and a mixture of management agencies involved (Spencer et al. 2010; Theobald et al. 2012). Permeable landscapes are needed to maintain ecological processes, genetic diversity, and the potential for communities and populations of species to adapt as the climate and land use change (Anderson et al. 2016). Recently, Keeley et al. (2018) found that evaluating for climate change adaptation provides a practical approach as a proxy for movement patterns of a wide range of species that has relatively low uncertainty. By mapping the permeability of the landscape, insight and understanding can be gained about how natural ecosystems adapt to climate change impacts (Keeley et al. 2018).

The central premise of this work is that *landscapes with higher permeability will allow wildlife and plant communities to adapt more easily to the effects of climate and land use changes to the landscape*. Mapping and assessing landscape permeability then is intended to inform landscape planning and management by identifying potential protection, mitigation, and/or restoration actions to maintain or improve habitat connectivity patterns and corridors, and to understand potential priorities and opportunities when collaborating with adjacent land owners/managers. Landscape permeability is a trans-boundary approach, recognizing that the dynamics of the ecological systems transcend political and administrative boundaries. This work potentially benefits all land management agencies in the study area because adaptation to climate change will likely require wildlife movement and ecological flows that cross political boundaries.

This report describes the: (1) study area composed of open space and surrounding lands; (2) spatial data used to map open space and parks (and other managed natural lands) and the degree to which lands are natural (i.e. are have less urban or residential use, lower road density, etc.); (3) modeling of the landscape permeability indicator; (4) potential management applications (i.e. scenarios) to explore the gaps, vulnerabilities, and opportunities to maintain, protect, or mitigate; and (5) key results and a brief discussion with recommendations. Because the maps are numerous and detailed, a basic map viewer is available to view the data online at: https://davidtheobald8.users.earthengine.app/view/landscape-permeability-bojeffco.

Methods

Study area

The core of the study area was defined as all lands (open space and adjacent privately-owned areas) within Boulder County and northern Jefferson County, Colorado (Figure 1a). Based on discussions with the technical advisory team, the study area was extended north to approximately US 34 and south to US 6 and I-70. To account for cross-boundary wildlife movement and ecological flows to and through the complex of city, county, and adjacent parks and open space lands, lands within roughly 5 miles of the core area were included in the study area. The analysis of landscape permeability naturally applies to lands beyond this study area, though is bounded here in an attempt to balance the trade-offs between extent (more inclusive of surrounding lands) and resolution (features relevant to management).

Table 1 provides a summary of the spatial data compiled and used to represent habitat types, designated protected areas with a legal guidance to protect natural qualities, and land use pressures such as built-up areas, roads, croplands, and energy development. A map of the overall study area, major habitat types (i.e. life-zones), designated protected lands (e.g., open space, parks, conservation easement), and land use patterns (e.g., built-up areas, roads, etc.) are provided in Figure 1.

Modeling permeability

This study follows a common framework to analyze landscape connectivity that identifies: the purpose, features to be connected, resistance to movement, movement process or model, output indicator, and evaluation. Permeability was measured by connecting within protected lands (i.e. OSMP, POS, OS, US Forest Service and National Park Service lands) and out into adjacent areas, for the full study area and then separately for four habitat types (roughly analogous to "life zones"). Separate permeability analyses were conducted for each habitat type to provide habitat-specific results for the upper montane, lower montane, grassland/shrubland, and valley bottom (riparian) habitat types (Table 2, Figure 1b). To map the four habitat types, we grouped individual biophysical settings into one of the four habitat (or life-zone) types (Landfire v1.4 www.landfire.gov; Appendix 1). For example, *Southern Rocky Mountain Ponderosa Pine Woodland* was placed into the lower montane habitat class. Note that valley bottoms were mapped directly from the Landfire land cover classes that typically represent large, perennial rivers and some smaller order (~2nd) streams, so that riparian systems narrower than 30 m are not represented. Modeling all of habitat types together as a landscape within the full study area provides an overall perspective, and complements habitat type-specific results -- particularly because habitat types will likely shift (e.g., higher) in elevation with future climates and hence habitat in the future may occupy different locations than they do currently.

We characterized movements and ecological processes in response to human modification -- that is, assuming that movement is restricted by more intense land uses and increased human activities -- (i.e. a "naturalness" approach; Theobald et al. 2012; Keeley et al. 2018). To represent human land use, we used a map of the degree of human modification (Figure

1d), which is a comprehensive representation of human stressors, organized as a parsimonious list that includes estimates of uncertainty and combined using a robust formula to generate a map of overall modification values that range from 0.0 to 1.0 (Theobald 2013; Kennedy et al. 2019; Theobald et al. 2020). Primary stressors mapped here include: built-up areas, roads, croplands, and human accessibility/use (see Appendix 2 for a full list). This modeling approach accounts explicitly for the footprint of land cover as well as the intensity of land use and human activities. Note that data and analyses of trails and visitor use was not investigated here due to pragmatic constraints.

Movements into adjacent habitats are assumed to incur additional resistance beyond the originating habitat type (e.g., species that use lower-montane habitat would avoid moving through grasslands because of lack of cover). The ratio of the length of shared boundary between habitat types was used to adjust the resistance weights on the non-originating habitat type (Appendix 3). In addition, we incorporated energetic costs of movement by assuming that moving across steeper slopes is avoided (Appendix 4). Note that the results for the full landscape are different than if all habitat types were simply combined, because the probability values are max-normalized and specific to each habitat type.

To model landscape permeability, we used a gradient-based application of the least-cost distance method (Theobald 2006; Theobald et al. 2012). This method calculates cost-distance across a resistance surface that reflects the degree of human modification and topography, with higher accumulated "cost distance" in areas of higher modification and/or slope, where natural and flat locations are equivalent to simple euclidean distance (see Appendix 4). The cost-distance values were converted to a "dispersal" probability assuming an exponential function reflecting typical dispersal distances of 5, 10, and 20 km (Urban and Keitt 2001; Saura and Hortal 2007). The probabilities were then summarized (typically averaged) across habitat types, PAs, etc. A strength of this method is that results are easily interpreted, robust, and rigorous because they quantify permeability by modeling ecological processes using estimated probability rather than some ad hoc index or scoring system (Saura and Hortal 2007; Theobald et al. 2012; Cushman et al. 2014).

Because spatial and environmental data are very rarely normally distributed, the permeability indicator is calculated as the *median* of the dispersal probability values within the full study area and for each habitat type (along with the median absolute deviation, MAD, see Appendix 5). The main results presented below assume moderate movement ability (10 km median distance) and moderate sensitivity to human land use/activities (see Appendix 6 for a sensitivity analysis).

Identifying adaptation opportunity areas

Three applications of the landscape permeability maps were conducted to identify locations with high opportunity to maintain landscape connectivity (i.e. for wildlife and other processes):

1. "hot spots" or key locations within the system of protected lands that are critical to maintain landscape permeability;
2. locations that are currently not part of the system that are key to landscape permeability; and
3. opportunities to coordinate and partner with managers of adjacent lands.

To highlight “hot spots”, the permeability values were normalized using a z-score, calculated using the median and MAD statistics. These results and datasets support a variety of additional management and policy questions through subsequent analysis of the datasets.

Results

Landscape permeability within and between the protected lands varies substantially across the study area, with values occuring across the full range of possible values (0.0 to 1.0). Figure 2 shows the pattern of permeability across the entire study area, and that the upper and lower montane areas generally have high permeability values while grassland/shrubland areas have much lower values. The median value for the landscape permeability representing current conditions was 0.224 (MAD=0.212; Table 3). This is significantly lower than the permeability indicator for a “natural” landscape with no human modification included, which was 0.777 MAD=0.306 (shown in Figure 3a). Figure 3b shows where permeability has been “lost” due to current land uses (human modification) as compared to the natural scenario.

Figure 4 shows the landscape permeability results that were modelled separately for each habitat type. The median of the degree of human modification for the upper-montane, lower-montane, grasslands, and riparian/valley bottom habitat was 0.236, and was 0.068, 0.197, 0.724, and 0.568 respectively. Permeability values were reasonably consistent with the degree of human modification values, but permeability provides critical information about the landscape context and pattern of connectivity beyond the general patterns of land use. Appendix 7 provides summary statistics specific to each of the protected area properties.

Adaptation opportunity areas

To identify potential opportunities where management of currently protected lands could focus to increase or maintain permeability on protected areas, z-scores of the permeability values for the protected areas were calculated (Figure 5a). This helps to highlight key locations within the system of protected lands that may be valuable beyond their in-situ level of naturalness (Figure 5b). Figure 6 shows the z-scores for each of the four habitat types, and Table 4 provides the median values for the properties of OSMP, POS, and OS.

To identify key potential opportunities to add additional protected lands to the system of currently protected lands that aim to maximize permeability among the protected lands, for example through acquisition or easement, highly permeable non-protected lands (mostly privately owned) are shown in Figure 7.

To identify key potential opportunities to coordinate and partner with managers of adjacent protected lands, Figure 8 shows permeability values along the shared boundaries of land managers, and the z-score maps provide visuals of “hot-spot” locations.

Discussion

Not surprisingly, human modification has strongly fragmented the landscape of Boulder and northern Jefferson Counties, reducing permeability by two-thirds compared to a landscape prior to European settlement. Also not surprising is that the upper- and lower-montane habitats have higher permeability than the lower elevation habitats. It is somewhat surprising, however, that there remain vestiges of well connected and fairly natural areas. One of those areas is the headwaters of the north St. Vrain and West Fork of the Little Thompson river, with very high permeability values (>0.8) and z-scores (>2.2). Some fragmentation is indicated along Highway 36 just southeast of Estes Park (in Larimer County) and around Allenspark on Highway 7. Another cluster of permeable lands of note is south of Coal Creek canyon along Drew Hill road, with key “bridging” locations just south of Rollinsville on 119, and between Centennial Cone Park and Douglas Mountain Study area. Another important permeable area crossing the lower montane and grass/shrubland habitat is along US 36 between Altona and Lyons.

Recommendations and next steps

The novel results generated in this study provide guidance on specific opportunity areas to protect, mitigate, restore, and manage for wildlife connectivity to maintain a permeable landscape. This information, complemented with other data on high biodiversity areas, forest structure and condition, etc., would provide a strong platform to inform conservation planning activities with relevant partners. There are numerous opportunities to overlay and summarize these permeability datasets with other data layers, for example, to understand how other maps that have identified important wildlife habitat compare, particularly when those maps did not consider landscape-level connectivity in their designations (e.g., drawing habitat polygons). Subsequent refinement of this work would include higher resolution (~10 m) datasets of habitat types and human modification to result in a minimum mapping unit smaller than the current ~1 ha.

Further analysis would be valuable, specific to riparian areas at a higher resolution (e.g., 10 m) with more detail on cover, species composition, and current and future upstream flow conditions to help refine and bolster the analysis conducted here, particularly for the riparian/valley bottom habitat type. Although the study boundary transcends a number of political and ecological boundaries, potential future studies should expand on the study boundary and identify the study boundary more strongly based on ecological processes, such as the Protected Area Centered Ecosystem approach (Hansen et al. 2011). Also, including potential impacts of visitor use on wildlife connectivity in an analysis would be valuable to inform open space management and decision making. This issue was explored initially, and here we recommend that more consistent and detailed data on visitation patterns (e.g., on and off-trail use) coupled with more detailed habitat data are needed. Inclusion of wildlife fencing in the permeability modeling was also explored, but because of time constraints was not fully examined. Also, a more thorough and consistent dataset on fencing location, type, height, etc. is needed.

The resulting maps of landscape permeability (and connectivity in general) remain challenging to evaluate and test, particularly for structural connectivity models that aim to be more general for conservation planning. A brief overlay analysis of the permeability surfaces with elk and mule deer corridors, migration patterns, and highway crossings did show largely consistent patterns. Subsequent work should seek additional ways to quantify the results of the model, or to use the results to identify locations for which additional data (especially field-collected) could be collected to test the permeability results.

This report was focused on investigating the connectivity among protected lands in the study area. Three additional scenarios would be valuable to explore to complement this work: connecting known important wildlife habitat areas (e.g., using Potential Conservation Areas from Colorado Natural Heritage Program), connecting large blocks of land with high ecological integrity (e.g., Theobald et al. 2012), and incorporating climate change data to map riparian climate corridors (Krosby et al. 2018) as another key climate-wise adaptation strategy.

Incompatible land uses, compounded by recent and likely future climate change, have impacted our natural ecosystems and reduced the permeability of open space and park lands and the broader landscapes. The results of this project were designed to inform decision making about opportunities to maintain, protect, restore, and manage for climate adaptation through wildlife connectivity across landscapes. Potential opportunities to facilitate movement within and surrounding the open space and parks, habitats, and landscapes were identified by mapping "hot spots" across four major habitat types using spatial modeling of landscape permeability. We believe that analyses provided here, and subsequent analyses of the datasets as well, will be valuable to inform management by identifying restoration and management activities to facilitate wildlife movement; protection of additional adjacent or nearby lands to complement the existing system of protected lands; and partnering opportunities with adjacent land managers.

Literature cited

Anderson, M.G. and Ferree, C.E., 2010. Conserving the stage: climate change and the geophysical underpinnings of species diversity. *PloS one*, 5(7), p.e11554.

Anderson, M.G., Barnett, A., Clark, M., Olivero-Sheldon, A., Prince, J. and Vickery, B. 2016. *Resilient and Connected Landscapes for Terrestrial Conservation*. Report from The Nature Conservancy.

Cushman, S.A., J.S. Lewis, and E.L. Landguth 2014. Why did the bear cross the road? Comparing the performance of multiple resistance surfaces and connectivity modeling methods. *Diversity*, 6(4), pp. 844-854.

Hansen, A.J., Davis, C.R., Piekielek, N., Gross, J., Theobald, D.M., Goetz, S., Melton, F. and DeFries, R., 2011. Delineating the ecosystems containing protected areas for monitoring and management. *BioScience*, *61*(5), pp.363-373.

Heller, N.E. and Zavaleta, E.S., 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation*, 142(1), pp.14-32.

Keeley, A.T., Ackerly, D.D., Cameron, D.R., Heller, N.E., Huber, P.R., Schloss, C.A., Thorne, J.H. and Merenlender, A.M., 2018. New concepts, models, and assessments of climate-wise connectivity. *Environmental Research Letters*, 13(7), p.073002.

Kennedy, C.M., Oakleaf, J.R., Theobald, D.M., Baruch‐Mordo, S. and Kiesecker, J., 2019. Managing the middle: A shift in conservation priorities based on the global human modification gradient. *Global Change Biology*, 25(3), pp. 811-826.

Kindlmann, P. and Burel, F., 2008. Connectivity measures: a review. Landscape ecology, 23(8), pp. 879-890.

Krosby, M., Theobald, D.M., Norheim, R. and McRae, B.H. 2018. Identifying riparian climate corridors to inform climate adaptation planning. *PloS ONE*, 13(11), p.e0205156.

Lawler, J.J., 2009. Climate change adaptation strategies for resource management and conservation planning. *Annals of the New York Academy of Sciences*, 1162(1), pp. 79-98.

McGarigal, K., S. Tagil, and S.A. Cushman. 2009. Surface metrics: an alternative to patch metrics for the quantification of landscape structure. *Landscape Ecology* 24, 433–450.

Noss, R.F. 1990. Indicators for monitoring biodiversity: a hierarchical approach. *Conservation Biology* 4(4):355–364.

Parrish, J.D., D.P. Braun, and R.S. Unnasch. 2003. Are we conserving what we say we are? Measuring ecological integrity within protected areas. *BioScience* 53(9):851–860.

Saura, S. and L. Pascual-Hortal. 2007. A new habitat availability index to integrate connectivity in landscape conservation planning: comparison with existing indices and application to a case study. *Landscape and Urban Planning*, 83(2-3), pp. 91-103.

Saura, S., L. Bastin, L. Battistella, A. Mandrici, and G. Dubois. 2017. Protected areas in the world's ecoregions: How well connected are they? *Ecological Indicators*, 76, pp. 144-158.

Schmitz, O. J., J.J. Lawler, P. Beier, C. Groves, G. Knight, D.A. Boyce, J. Bulluck, K.M. Johnston, M.L. Klein, K. Muller, D.J. Pierce, and D.M. Theobald. 2015. Conserving biodiversity: practical guidance about climate change adaptation approaches in support of land-use planning. *Natural Areas Journal*, 35(1), 190-203.

Spencer, W.D., P. Beier, and K. Penrod. 2010. *California essential habitat connectivity project: a strategy for conserving a connected California*. Prepared for California Department of Transportation, California Department of Fish and Game, and Federal Highways Administration.

Taylor, P. D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. *Oikos* 68, 571–573.

Theobald, D.M., 2006. *Exploring the functional connectivity of landscapes using landscape networks.* CONSERVATION BIOLOGY SERIES-CAMBRIDGE-, 14, p. 416.

Theobald, D.M., S.E. Reed, K. Fields, and M. Soule. 2012. Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the US. *Conservation Letters* 5(2):123–133.

Theobald, D. M. 2013. A general model to quantify ecological integrity for landscape assessments and US application. *Landscape Ecology*, 28 1859–1874.

Theobald, D. M., C. Kennedy, B. Chen, J. Oakleaf, S. Baruch-Mordo,and J. Kiesecker. 2020. Earth transformed: detailed mapping of global human modification from 1990 to 2017, *Earth Systems Science Data* 12, 1953–1972.

Thurman, L.L., Stein, B.A., Beever, E.A., Foden, W., Geange, S.R., Green, N., Gross, J.E., Lawrence, D.J., LeDee, O., Olden, J.D. and Thompson, L.M., 2020. Persist in place or shift in space? Evaluating the adaptive capacity of species to climate change. *Frontiers in Ecology and the Environment*, 18(9), pp. 520-528.

Urban, D., T. Keitt, T. 2001. Landscape connectivity: a graph-theoretic perspective. *Ecology* 82 (5), 1205–1218.

Table 1. Spatial datasets compiled and used in the landscape permeability analysis.

Group	Name	Source	Scale
Priority conservation	Important habitat areas	CNHP Potential Conservation Areas v4, 2019 (link)	1:24,000
Habitat types	Biophysical Setting	LANDFIRE v2.0 (2014)	30 m
Designated protected lands	Management area designations	City of Boulder OSMP (link); downloaded 7/27/2020	1:10,000
	Open space	Boulder County (link); downloaded 10/15/2020	1:10,000
	Land use classification	Jefferson County (link); downloaded 7/29/2020	1:10,000
	State and federal protected lands	USGS PAD-US v2.0 (link); downloaded 5/7/2019	1:100,000
Land use pressures	*Degree of human modification (2016)	See Theobald (2020) for methods. Datasets used include: built-up and impervious surfaces from National Land Cover Dataset (2016); agriculture from USDA Cropland Data Layer (2018); transportation (roads and railroads from Census TIGER 2018); energy infrastructure (powerlines, night-lights); and human intrusion	30 m
	Visitor use - trails**	OSMP (link); downloaded 7/27/2020; BCPOS (link), downloaded 7/27/2020; JCPOS (link); 8/10/2020	1:10,000
Wildlife movement features	Fences**	OSMP; downloaded 8/10/2020	1:10,000
	Wildlife fences**	OS fences (from CPW); downloaded 7/29/2020	1:10,000

*See Appendix 2 for more details.

**Results in this report do not include these data due to limited project scope.

Table 2. Summaries for each of the ecosystem types by area, proportion, and median elevation, for full study area and for just Boulder County. Elevation is measured as the median value in feet.

	Study area		Core area		Boulder County		
Ecosystem	**Acres**	**Percentage**	**Acres**	**Percent age**	**Acres**	**Percentage**	**Elevation**
Upper montane	488,171	31.00%	289,025	26.50%	126,450	26.60%	10,170
Lower montane	480,206	30.50%	414,687	38.00%	158,426	33.40%	7,586
Grass/shrub	513,970	32.60%	325,868	29.90%	157,771	33.20%	5,240
Riparian/valley bottoms	92,069	5.80%	61,646	5.60%	31,996	6.70%	5,273
Total	1,574,416	100.00%	1,091,227	100.00%	474,643	100.00%	7,339

Table 3. Summaries of the landscape permeability indicator calculated from protected areas (e.g., open spaces) within the study area, for the four habitat types and all four combined. “Natural” permeability is calculated to reflect the natural permeability of the landscape devoid of human land uses (but does include energetic costs of movement), while “modified” incorporates the additional resistance to movement due to human modification of the landscapes. “Natural” permeability scores <1.0 result from the interaction of the spatial distribution of habitat types in relation to the current location of open space lands, as permeability is calculated with reference to (starting from) open space lands.

	"Natural" permeability		**"Modified" permeability**		**Human modification**	
Ecosystem	**Median**	**MAD**	**Median**	**MAD**	**Median**	**MAD**
All combined	0.7773	0.3066	*0.2245	0.2129	0.2363	0.1895
Upper montane	0.5508	0.4511	0.2402	0.2325	0.0682	0.0096
Lower montane	0.6054	0.2753	0.1855	0.1465	0.1972	0.0957
Grass/shrub	0.2851	0.2226	*0.0005	0.0007	0.7246	0.1543
Valley bottoms	0.4492	0.2168	*0.0605	0.0601	0.5682	0.2989

*Statistically significant difference with “natural” permeability results.

Table 4. Summaries of metrics for the protected lands for City of Boulder (OSMP), Boulder County (POS), and Jefferson County (OS). Human modification (H) characterizes the land use and human activities, naturalness is the complement of human modification (1-H), and the landscape permeability indicator for the full study area and the four habitat types. Note that naturalness and permeability values are not directly comparable.

Metric	City of Boulder				Boulder County				Jefferson County			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Human modification	0.644	0.154	0.239	0.978	0.501	0.233	0.036	1.000	0.601	0.256	0.155	0.956
Naturalness	0.356	-	0.761	0.022	0.500	-	0.964	0.000	0.399	-	0.845	0.044
Permeability (overall)	0.052	0.044	0.000	0.179	0.124	0.137	0.000	0.782	0.068	0.071	0	0.2455
Permeability (upper montane)	0.000	0.000	0.000	0.000	0.058	0.115	0.000	0.647	x	x	x	x
Permeability (lower montane)	0.026	0.047	0.000	0.174	0.178	0.152	0.000	0.798	0.093	0.076	0	0.237
Permeability (grass/shrub)	0.086	0.091	0.000	0.391	0.084	0.097	0.000	0.506	0.322	0.052	0	0.266
Permeability (riparian/valley)	0.033	0.603	0.000	0.214	0.080	0.115	0.000	0.550	0.007	0.015	0	0.069

- not calculated
x - no data

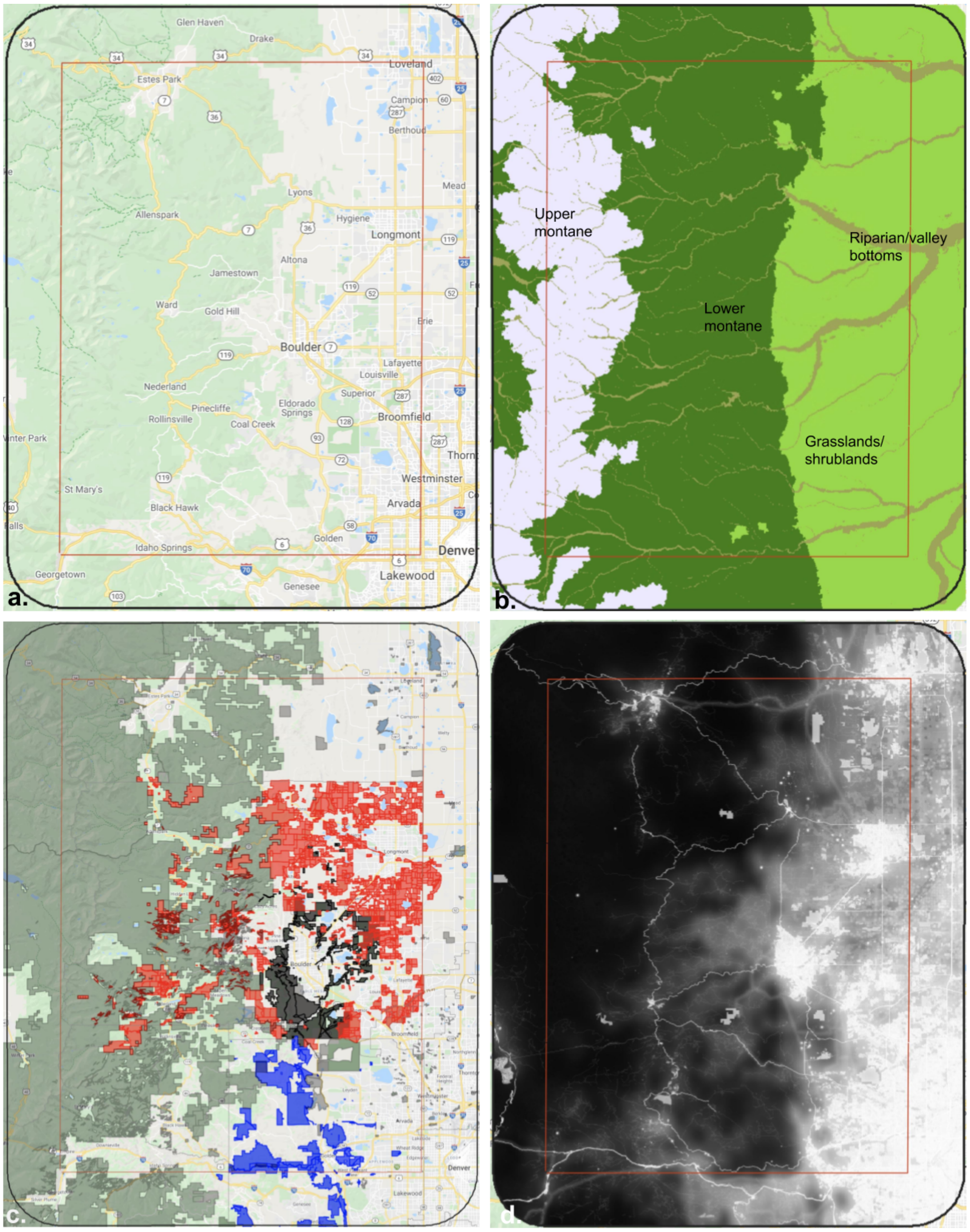

Figure 1. The study area of this project is defined on the northern Front Range of Colorado, focused on Boulder County and adjacent areas. Specifically, this figure shows (a) the “core” of the study area inside the red rectangle, with a 2 mile buffer to minimize artifacts in model results due to edge effects; (b) major habitat types: upper montane, lower montane, grassland/shrublands, and riparian/valley bottoms; (c) open space and park lands including the City of Boulder OSMP (black), Boulder County (red), Jefferson County (blue), and other state and federal lands in grey; (d) the degree of human modification (black low, white high).

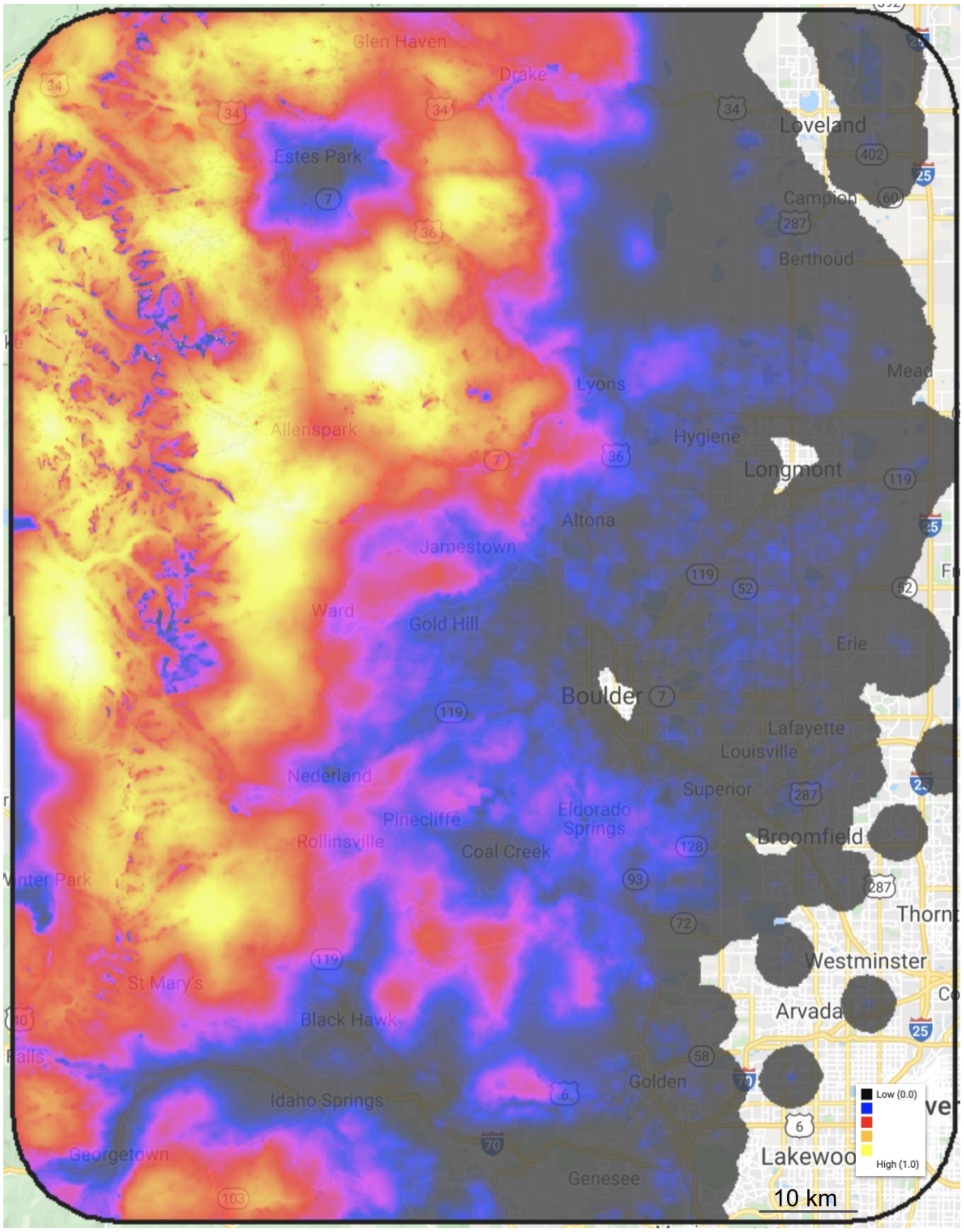

Figure 2. A map of the landscape connectivity of the City of Boulder, Boulder County, and Jefferson County open space and parks, and other formally protected lands. Connectivity is quantified here as the permeability of movement across the landscape, which is reduced in locations with high human development and activities, and higher in more "natural" areas. Upper and lower montane habitat types are generally more permeable, with some reduced permeability nearing highways. Grass and shrubland habitat in the lower elevations have very low permeability. Values can range from 0 to 1.0, and the median value is 0.22 (MAD=0.21) for the full study area. The detailed data underlying this map can be analyzed to identify potential opportunities for various conservation actions, such as potential "corridors" to connect open space and park lands.

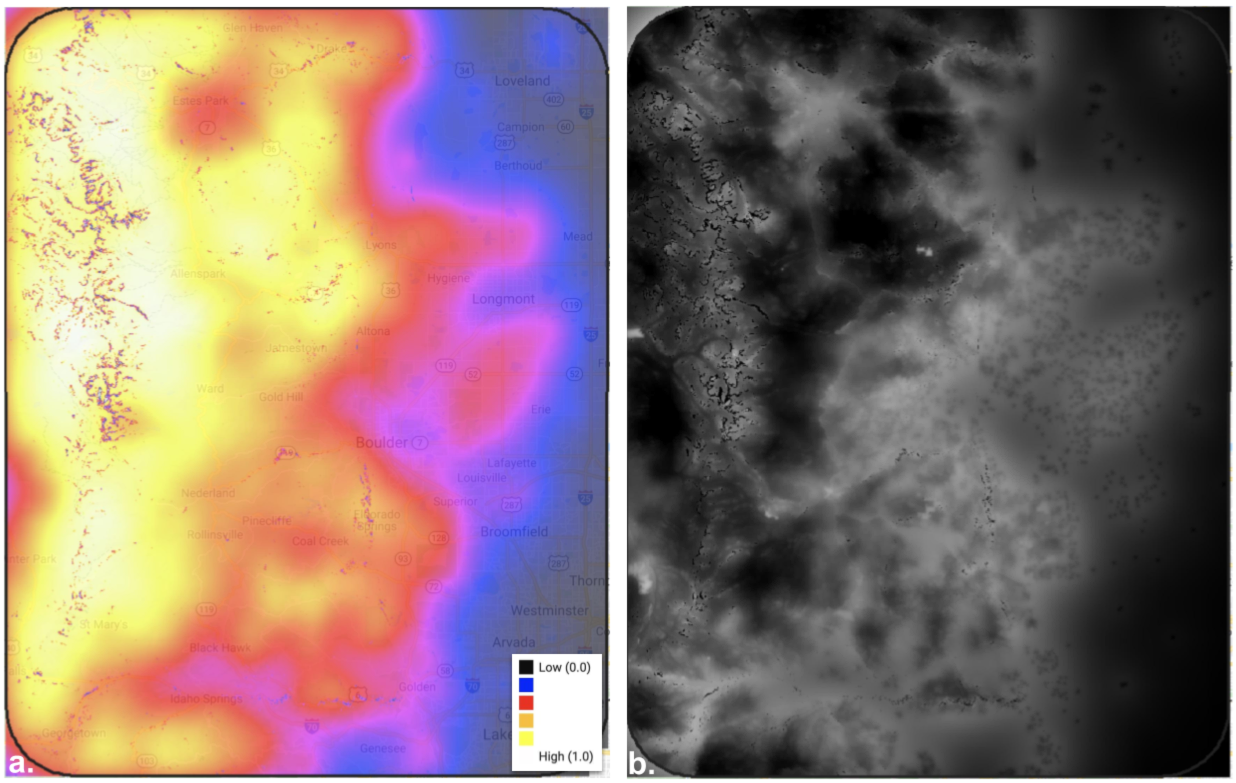

Figure 3. Landscape permeability reflecting “potential natural” conditions, that is devoid of human modification (a), and in (b) the landscape fragmentation or permeability “lost” due to human modification (black lower loss, white higher loss).

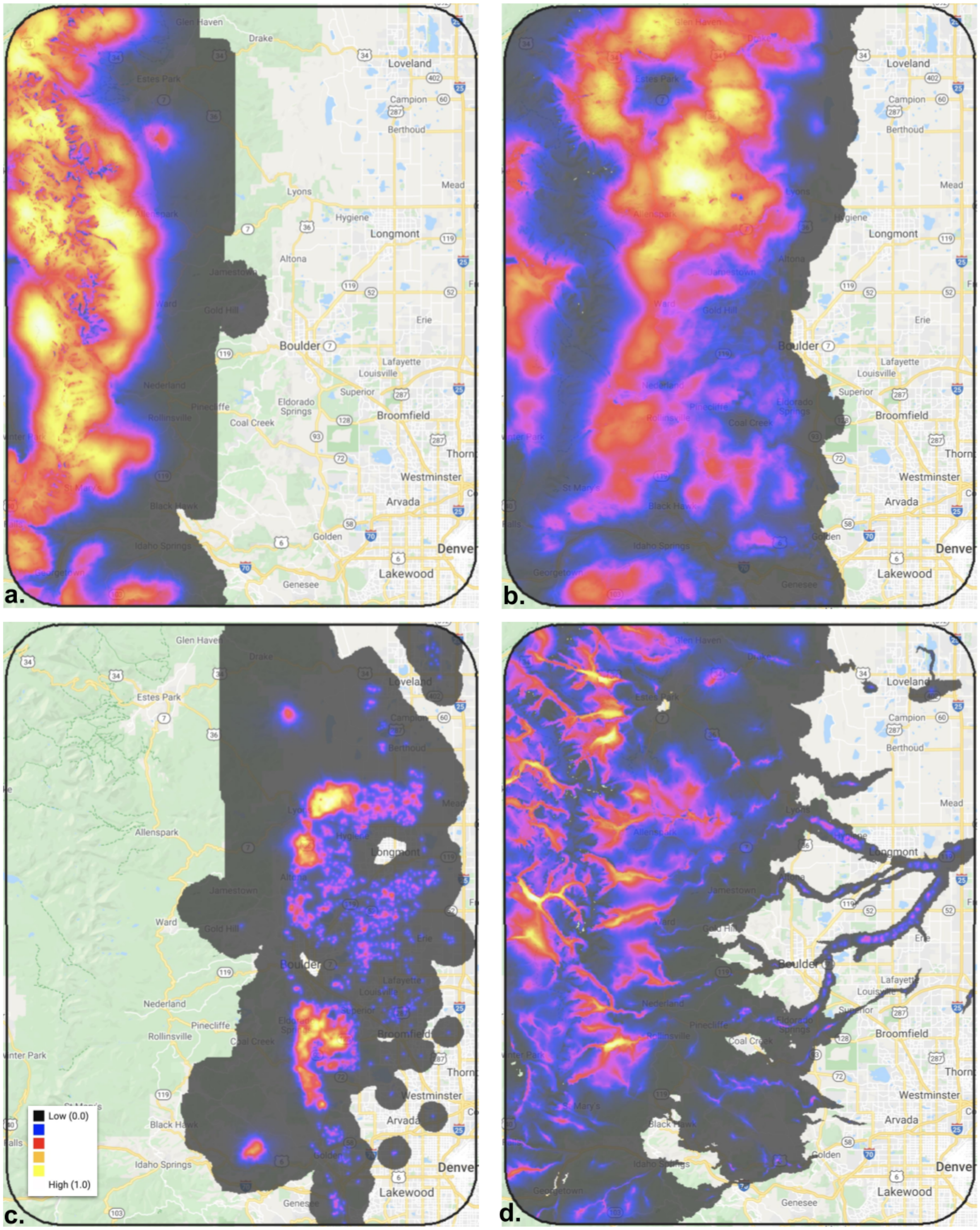

Figure 4. These maps show the landscape permeability values (similar to Figure 2), but modeled separately for each major habitat type: (a) upper montane, (b) lower montane, (c) grassland/shrublands, and (d) riparian/valley bottoms. Note that the permeability results shown here assume a 10 km maximum movement distance and moderate sensitivity to human land use, so connectivity can cross the ecotones between major habitat types.

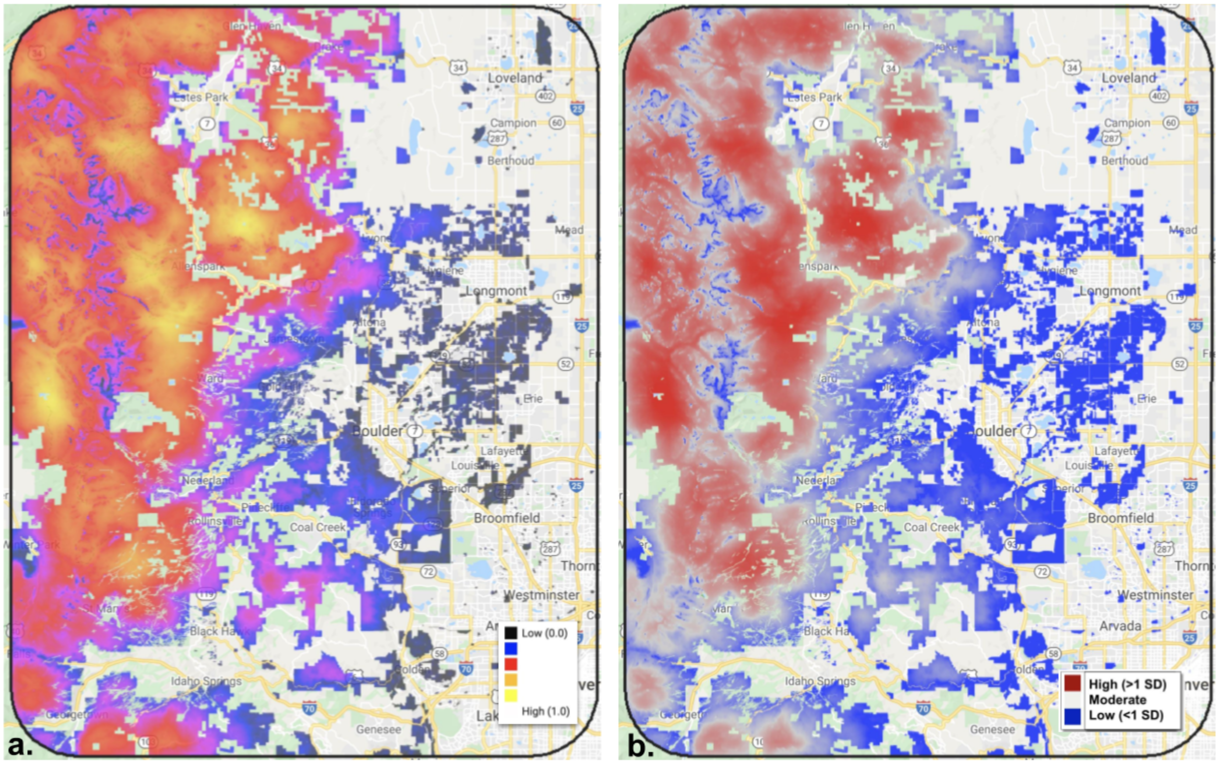

Figure 5. These maps show (a) the permeability values only for the protected lands of the City of Boulder (OSMP), Boulder County (POS), and Jefferson County (OS), and the z-scores normalized for the permeability just for the protected lands.

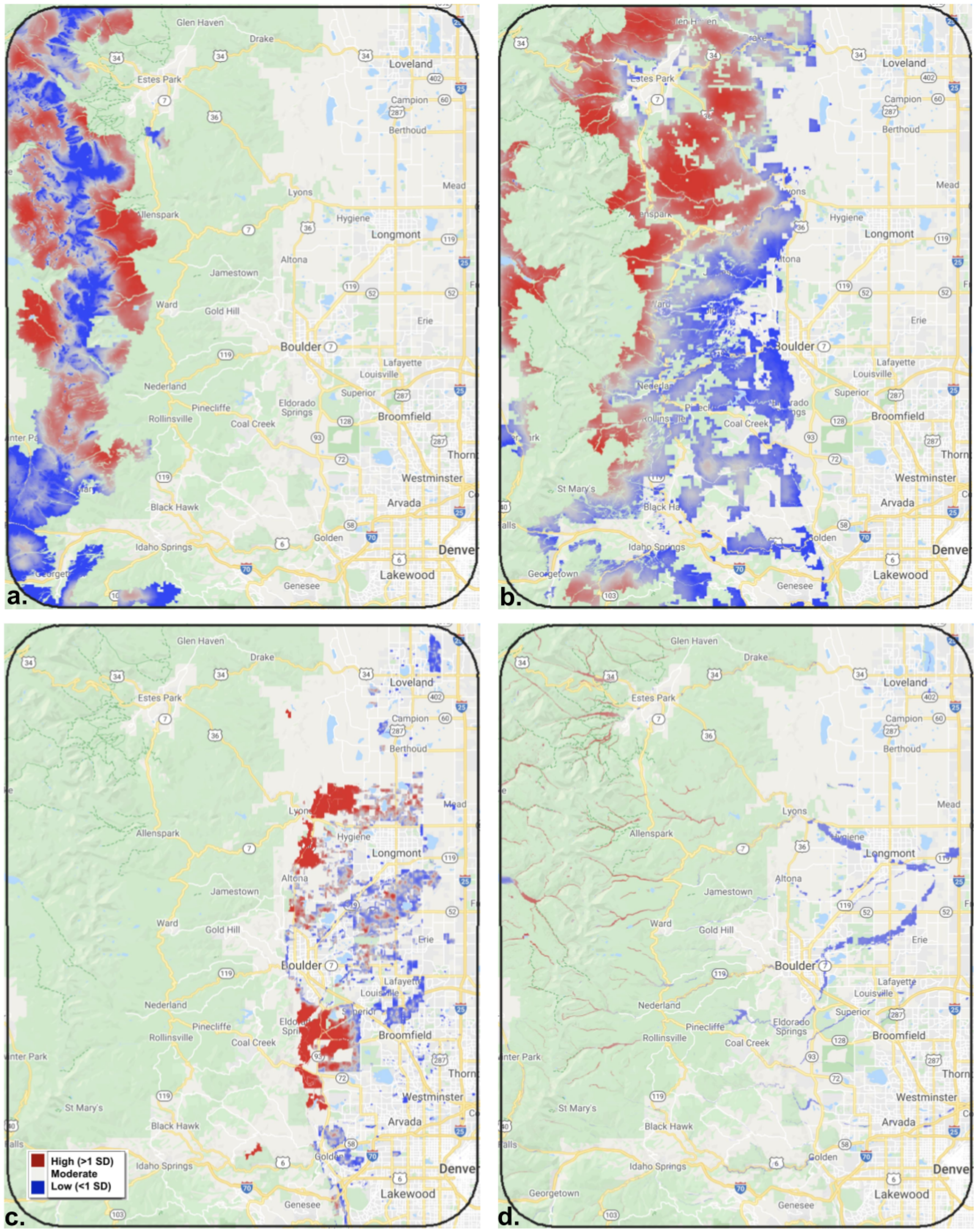

Figure 6. These maps show the “hot spots” or high values (in red), relative to the raw permeability values on protected lands within each major habitat type: (a) upper montane, (b) lower montane, (c) grassland/shrublands, and (d) riparian/valley bottoms. Locations shown in blue can be highly permeable -- but are relatively lower than the permeability values at other locations within a given habitat type.

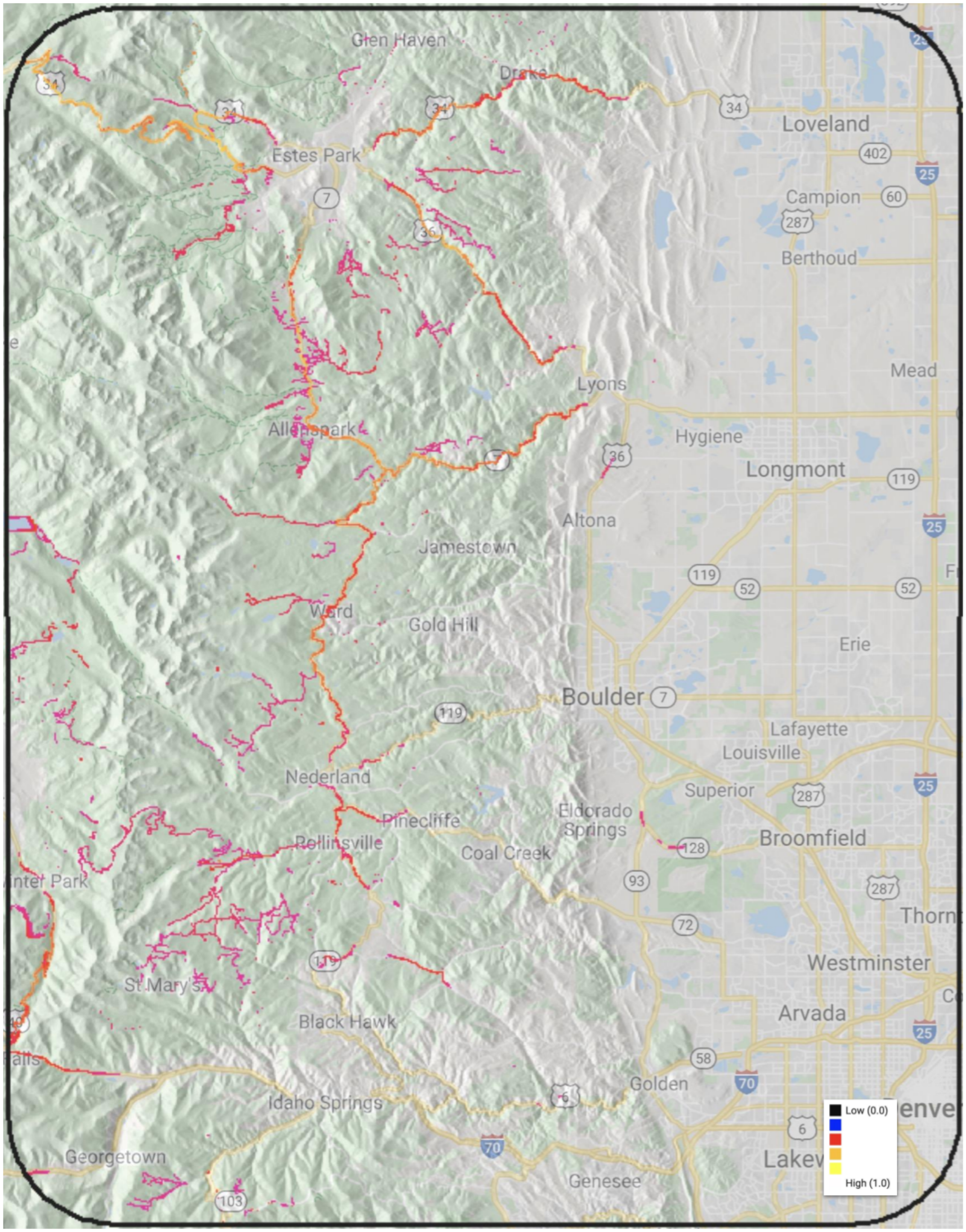

Figure 7. Identifying “crossing” locations that have low naturalness in-situ, but high permeability within 200 m radius. To simplify the visual presentation of this dataset, locations with larger contrast (approximately greater than H=0.4) are removed. The resulting hot spots” suggest areas with very abrupt differences, which are characteristic of, and dominated by linear features such as roads and other transportation and utility corridors. These results are best used to identify important locations to provide for crossing (i.e. orthogonal to a linear feature).

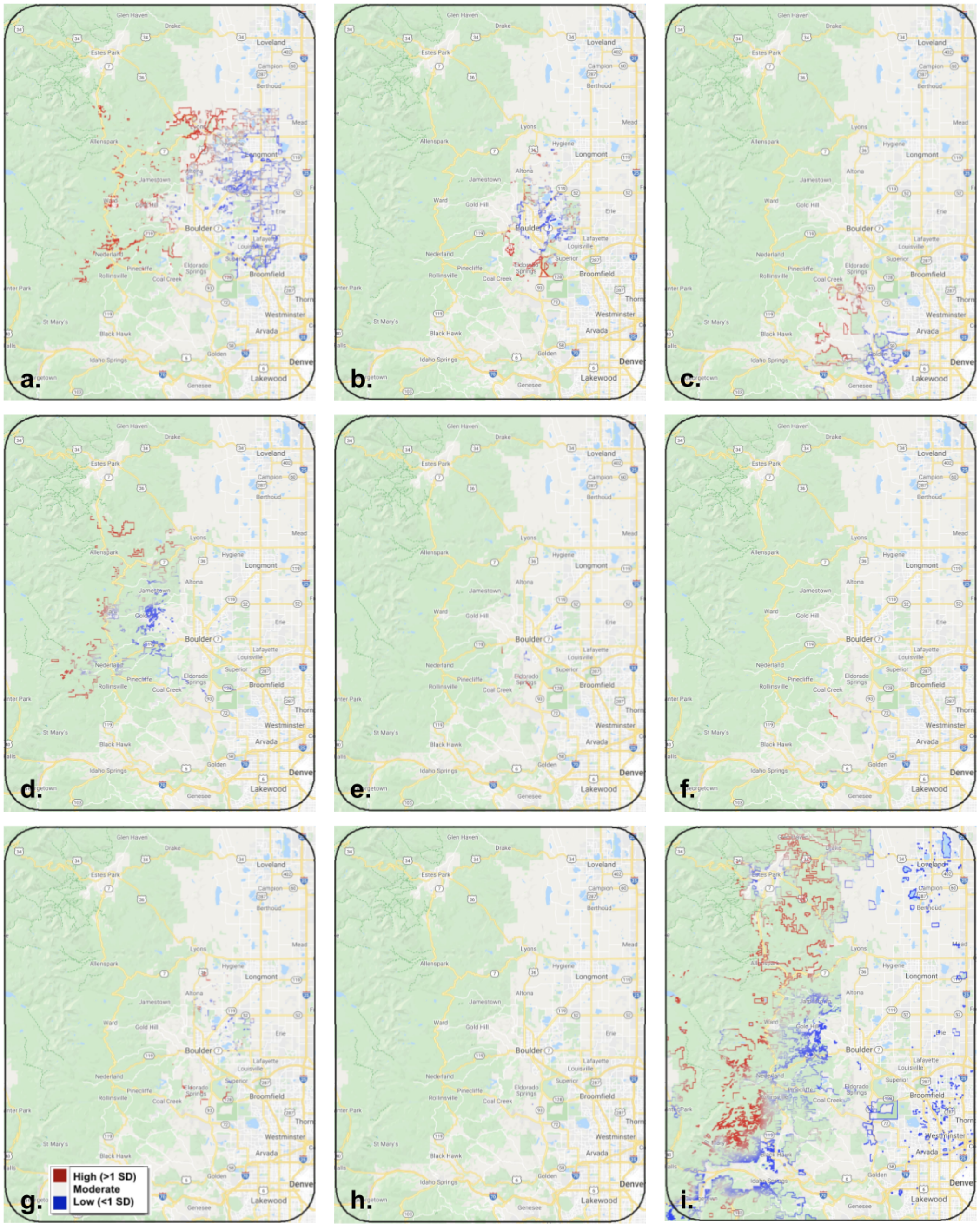

Figure 8. These maps show the z-scores of permeability values specific to the boundaries shared by the City of Boulder (OSMP), Boulder County (POS), and Jefferson County (OS). Z-scores are used to indicate statistically significant high or low values by normalizing the permeability values at a pixel with the mean of permeability values within 60 m of shared boundary, specific to a given combination of two entities: (a) POS and private lands; (b) OSMP and private; (c) OS and private; (d) POS and public lands; (e) OSMP and public; (f) OS and public lands; (g) POS and OSMP; (h) POS and OS lands; and (i) protected lands and private lands.