2021 Wildlife Corridor Analysis

Methods Summary & Results

Submitted to:
City of Bellingham, Public Works Dept.
Natural Resources Division
July 13, 2021, Updated November 15, 2022

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ACKNOWLEDGEMENTS

The authors would like to thank City staff and community members who contributed to this analysis by providing guidance, direction and feedback including:

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- Kim Weil, Environmental Planner, City of Bellingham
- Sara Brooke Benjamin, Environmental Coordinator, City of Bellingham
- Scott Havill, Mitigation Coordinator, City of Bellingham
- Joel Ingram, Area Habitat Biologist, WA Dept of Fish and Wildlife
- Jeremy Porter, NW Region Community Assistance Forester, WA Dept of Natural Resources
- Chris Danilson, Region Biologist, WA Dept of Natural Resources
- Glen Kalisz, Habitat Connectivity Biologist, WA Dept of Transportation
- Stephen Nyman
- Vikki Jackson
- Rob Rich

1.0 Introduction

The City of Bellingham is a community of more than 90,000 residents that stretches over 28 square miles, with an additional 8 square miles of Urban Growth Area (UGA). The City manages an expansive urban forest which includes several thousands of acres of forest and thousands of street trees. Bellingham's urban forest is a valued asset within the community, as recognized in the City's Comprehensive Plan vision and its Tree City USA status.

In this context, the City is creating an Urban Forestry Management Plan (UFMP) as a strategic plan to help maintain a healthy and desirable urban forest through well-coordinated, consistent, efficient, and sustainable long-term urban forest management. The UFMP will encompass all trees, in forests and elsewhere, within City limits and the Urban Growth Area (UGA).

The City of Bellingham has worked with Diamond Head Consulting (DHC) to complete a wildlife corridor analysis as part of Phase 1 (Assessment) of the City's UFMP. The purpose of the wildlife corridor analysis was to help identify important terrestrial habitat hubs, wildlife corridors and breaks within the City limits and urban growth area (UGA). The analysis builds on the 2003 City of Bellingham Wildlife Habitat Assessment (Nahkeeta Northwest 2003) and the 2015 Bellingham Habitat Restoration Technical Assessment (ESA 2015). Wildlife habitat connectivity in Bellingham was modeled using the software package Conefor Sensinode (hereafter, Conefor). This model quantifies the relative importance of habitat areas and links for maintaining or improving connectivity for each selected focal species of wildlife. This report provides a summary of the process used to carry out this analysis as well as results.

2.0 Methods

The methods used to model wildlife habitat connectivity in Bellingham consisted of five main steps:

1. **Identifying Focal Species:** Three focal species were chosen in consultation with the City that represent the types of wildlife that inhabit Bellingham.
2. **Defining Habitat Types and Patches**: Habitat types and patches for each of the three focal species were created from City supplied data and a 2021 forest structure layer that defined the approximate age, height and structure class of forest patches throughout the city.[1]
3. **Rating Habitat Quality:** Habitat quality ratings were assigned to each of the focal species' patches. These consider conditions such as urban influences, recent disturbances, and riparian habitat.
4. **Habitat Patch Links:** Species habitat patches were used to create links among patches for each of the three species. Wildlife crossing information provided by the City was incorporated into the link files.
5. **Conefor Modelling:** Habitat patches and links were input into the modeling software Conefor 2.6 to create network models for each.

More detailed descriptions of each step are provided in the sections below.

[1] See the Bellingham Canopy and Forest Structure Report Draft (2021) for additional information on how this layer was developed.

2.1 Identifying Focal Species

Three focal species were selected to use in the connectivity model. These were chosen in collaboration with City staff, local wildlife consultants, the Washington State Department of Fish and Wildlife Area Habitat Biologist, the Washington State Department of National Resources Region Biologist, and Washington State Department of Transportation Habitat Connectivity Biologist.

The focal species were chosen to represent guilds of terrestrial species that require similar habitat characteristics. Together they represent a broad range of habitat requirements and life history characteristics. Focal species were from three broad classes: Birds, Mammals, and Amphibians/Reptiles. Median and maximum dispersal and minimum patch size are the parameters required for Conefor modelling. In general, a combination of natal (dispersal from birth to breeding) and foraging dispersal distances, home range, and territory size were used to calculate the quantitative modelling parameters (Table 1). Dispersal limitations were identified and help identify barriers that would make some networks unusable.

Table 1. Modeling and life history parameters considered for the wildlife corridor analysis

Modelling Parameters				
Median Dispersal (m)	Max. Dispersal Distance (m)	Min. Patch Size (ha)	Dispersal road-limited? (Y/N)	Dispersal water-limited? (Y/N)

In selecting the species, consideration was given to the typical habitat types and sizes that exists across the City. The size of the City was a consideration in choosing the species. Species with large dispersal distances were avoided because the results would dilute the prioritization of habitat within an area the size of Bellingham. For this study species with medium or short (<500 m) dispersal distances were selected. A complete list of the species considered is provided in Appendix 2. The three species that were chosen for this model include:

- Red legged frog (*Rana aurora*)
- Douglas-squirrel (*Tamiasciurus douglasii*)
- Brown Creeper (*Certhia americana*)

For each of the three focal species, life parameters were identified including preferent habitat types, maximum and minimum dispersal distances, minimum patch size, and dispersal limitations. The life requirements and modeling inputs are summarized in Table 2 and Appendix 2.

A network of high value habitat areas was identified for each species using the parameters listed in Table 2. Buffers of habitat along roads were erased for species that are sensitive to urban barriers. Rivers and other watercourses were also accounted for as a form of barrier, preventing dispersal for the species that cannot fly and without a water component of their life history strategy.

Table 2. Summary of modeling parameter used for the three focal species

Species Common Name	**Median Dispersal (m)**	**Max distance (m)**	**Min patch size (acres)**	**Habitat Summary**	**Disp. Road limited?**	**Forest habitat**	**Non-forest hatbiat**	**Med. Dispersal**	**Sensitivity to barriers**	**Sensitivity to development**	**Min patch sizes**
Red-legged frog	100	5,000	0.5	Moist mixed and coniferous forest, with condition modifiers for riparian sites. Medium median dispersal and small min. patch size.	Yes	Y	Y	medium	medium	high	small
Douglas squirrel	65	822	1.0	Prefers older coniferous forest. Uses mixed forest, but restricted to coniferous dominated stands in this study. Medium median dispersal and small min. patch size.	Yes	Y		medium	high	high	small
Brown Creeper	88	2,110	5.7	Mature and old forest only, condition modifiers for woodland, riparian, and wetland sites. Medium median dispersal and medium min. patch size.	No	Y		medium	low	medium	medium

2.2 Defining Habitat Types and Patches

Habitat types were defined to represent the most favorable habitat for the guild of species represented by each focal species. Patches of each habitat type were created in GIS using the City's forest structure layer[2] and City supplied data to derive:

1) Forest within 30 m of streams, wetlands and freshwater bodies were used to identify riparian areas
2) Buffered roads that were erased from the final patches prior to running Conefor
3) Habitat patches that met the description of habitat types A, B and C (see descriptions below), and that were filtered by area to remove those which were smaller than the species' minimum required patch size

The City reviewed the draft habitat patches for each species and all comments from the City were incorporated before running Conefor. This section summarizes the habitat types identified and notes some of the other species in the guild that are expected to rely on these habitat types as well.

2.2.1 Habitat A – Forest and shrub connected to fresh-water bodies. Focal species = northern red-legged frog (*Rana aurora*)

Forest and shrub connected to fresh-water bodies is a habitat type required by amphibians that need a combination of water for breeding and terrestrial habitat for cover and forage (COSEWIC 2004). Suitable habitat includes a range of young and mature forest types as well as natural shrub areas. Terrestrial patches must be connected to water or wetland areas to be in this habitat type and include areas known to have standing water for much of the year allowing for breeding of amphibians. Examples of other species that rely on this type of habitat include Pacific treefrog, Northwestern salamander, Long-toed salamander and Roughskin newt. Suitable patches can be small (min. patch size 0.5 acres). Median and maximum dispersal distances are 100 m and 5,000 m respectively[3] (Hayes *et al*. 2008, Grand *et al*. 2017, NatureServe 2.0). Quality ratings favor mature forested areas that are riparian and in close proximity to wetlands and ponds.

2.2.2 Habitat B - Coniferous tree dominated forests. Focal species = Douglas-squirrel (*Tamiasciurus douglasii*)

Coniferous tree dominated forests is a habitat type required by bird and small mammal species that rely mainly on coniferous forests and do not require aquatic habitats as part of their life cycle. Examples of other species that rely on this type of habitat include creeping vole, Townsend's chipmunk, pine grosbeak and red breasted sapsucker. Suitable patches can be small (min. patch size 1.0 acres). Median and maximum dispersal distances are 65 m and 822 m respectively (Lee and Rudd 2003, NatureServe

[2] See the Bellingham Canopy and Forest Structure Report Draft (2021) for additional information on how this layer was developed.
[3] Stephen Nyman, personal email communication with Analiese Burns on 12/3/2020

2.0, Penteado 2021, Government of British Columbia 2014). Quality ratings favor large patches of conifer dominated forest that are away from the influence of urban development.

2.2.3 Habitat C – Large, intact forest areas. Focal species = brown creeper (*Certhia americana*)

Large, intact forest areas are a habitat type required by birds and mammals that inhabit a range of young and mature forest types, and forest in riparian and wetland areas. Examples of other species that rely on this type of habitat include Pacific wren, Hairy woodpecker, Warbling vireo, Red-breasted nuthatch and Masked shrew. Suitable patches must be large (min. patch size 5.7 acres). Median and maximum dispersal distances are 88 m and 2110 m respectively (NatureServe 2019, Geleynse *et al*. 2016, Timossi and Barret 1995, Poulin 2011). Quality ratings favor large, forested natural areas as well as wetlands and riparian areas.

2.3 Rating Habitat Quality

Quality ratings are on input used in the model to determine the importance of patches and corridors. Quality rating were applied to each species habitat patch based on the broad definitions provided below:

- Low (1): Urban, highly disturbed areas. Generally smaller, narrow and fragmented areas <5 acres with high edge influence. Many of these include long and narrow bands of habitat that are influenced by urban development on both sides. Areas that are dominated by maintained grass were included in this category.
- Medium (2): Semi-natural, moderately disturbed areas. Areas generally 5 to 20 acres in size with some urban influence. These areas may support some species that are intolerant of human impacts.
- High (3): Highest quality natural areas, little disturbance. Areas generally > 20 acres in size forming continuous natural areas with little urban influence. These habitat areas provide interior forest that is away from the influences of urban development.

Some larger habitat patches had both high value interior forest as well as edges that were impacted by urban development. In these cases, the polygons were assigned a quality rating based on the majority of the polygon area. It was difficult to confirm the condition of each patch, so these were inferred based on their proximity to urban development and indicators of recent disturbances.

2.4 Habitat Patch Links

Links - Euclidean (straight-line) distances between patches - up to the maximum dispersal distance were created using ArcGIS 9.3 extensions for Conefor:

- Habitat A - Red-leg frog: 107,327 links created
- Habitat B - Douglas squirrel: 807 links created
- Habitat C - Brown creeper: 48,352 links created

For Northern Red-legged frog and Douglas squirrel, all links that intersect with known wildlife crossing records provided by the City were marked as "yes" = 1 in order to be kept, then all links that intersect with roads that have wildlife crossing records = 0 were removed. Finally, the links were reviewed manually to make sure the wildlife crossing information were incorporated appropriately.

2.5 Conefor modelling

The Conefor Sensinode 2.6 software package was used to run a network analysis for each of the three focal species habitat types (habitats A, B and C). Habitat mapping, life requirements and quality ratings were used as inputs to create network models for each species resulting in the following outputs:

1. Overall connectivity index reported using:
    a. Probability of Connectivity (PC) - This can be interpreted as the probability that "...two animals randomly placed within the landscape fall into areas that are reachable from each other" (Saura & Pascual-Hortal, 2007a p.93). The PC metric describes the amount of reachable habitat within a landscape both between and within patches, and
    b. Integral Index of Connectivity (IIPC) - IIC is recommended as the best **binary index for overall connectivity** analysis of a landscape, and ranges from 0 to 1 increasing with improved connectivity.
2. Patch importance metrics reported using:
    a. dPC - is a metric that measures the effect of patch removal on overall network connectivity. dPC combines within-patch and between-patch connectivity to determine overall patch importance.
    b. dPC-connect - This is the measure of a patch's importance for connecting *other* patches together.

Appendix 1 provides a glossary of the Conefor terms. Appendix 3 provides a more detailed description of the key metrics and the formulas that are outputs of Conefor.

Important **habitat hubs** and **stepping stones** were identified based on frequency distribution of dPC and dPCconnect. Hubs are the habitat areas that the model identified as being most important for each species. The model also identifies stepping stones for maintaining connectivity across a landscape. The removal of stepping stone patches would have a disproportionally large negative effect on connectivity with nearby patches. Typically, the top 10% of patches were selected in the analysis; however, this was adjusted to up to 30% for Douglas squirrel as it had a low number of suitable habitat areas in the City. For Douglas squirrel, retaining only the top 10% of patches would have resulted in a very low number of important habitat hubs and stepping stones compared to the other focal species and therefore diluted the importance of Douglas squirrel habitat in the combined analysis.

Preliminary results were provided to the City Public Works Natural Resources staff, City Environmental Planners, the Whatcom County Wildlife Advisory Committee, the Washington State Department of Fish and Wildlife Area Habitat Biologist, the Washington State Department of Natural Resources Region Biologist, and the Washington State Department of Transportation Habitat Connectivity Biologist for their review. Comments were incorporated into the final analysis results and report.

3.0 Modeling Results

3.1 Overall Connectivity Indices

PC/IIC values for each species represent overall landscape connectivity of habitat. Higher values indicate a higher level of connectivity with a potential range of 0 - 1. The results show that the Douglas squirrel habitat is the least connected followed by the red-legged frog and brown creeper networks. The low absolute values of these PC/IIC results are similar to the results recently complete for a similar study in Metro Vancouver, BC, Canada (Diamond Head Consulting & Metro Vancouver, 2021).

Table 3. Connectivity Indices for Probability of Connectivity (PC) and Integral Index of Connectivity (IIC)

Focal Species	PC	IIC
Brown creeper	0.245	0.092
Northern Red-legged frog	0.058	0.034
Douglas squirrel	0.014	0.009

3.2 Patch Importance Metrics

The importance of any given patch in a network was measured by the metric dPC, calculated as the percent contribution of that patch to the overall Probability of Connectivity for the network, with a potential range of 0 - 100. In other words, dPC reflects the importance of a patch for maintaining or improving overall habitat connectivity. Therefore, the higher the dPC value, the greater the importance of that habitat patch.

dPC itself is the sum of three other patch importance metrics: d*PCintra,* which measures within-patch connectivity; *dPCflux,* which measures how connected a patch is to the rest of the network; and *dPCconnector,* which measures how important a patch is for connecting *other patches* together (see Appendix 3 for more details). It should be noted that, although the patch importance metrics were calculated as percentages, their sum will often be greater than 100. Due to the fact that we used area-weighted quality as the patch attribute for modelling, wetlands and riparian areas with small total area had lower dPC values than larger areas. Large forest patches that were well connected to surrounding natural areas had the highest dPC values (e.g., large, forested areas in the southern part of the City). The maximum dPC value for a single patch was 51%. The metric dPC is illustrated for each habitat type in the following maps (Figure 1 – 3).

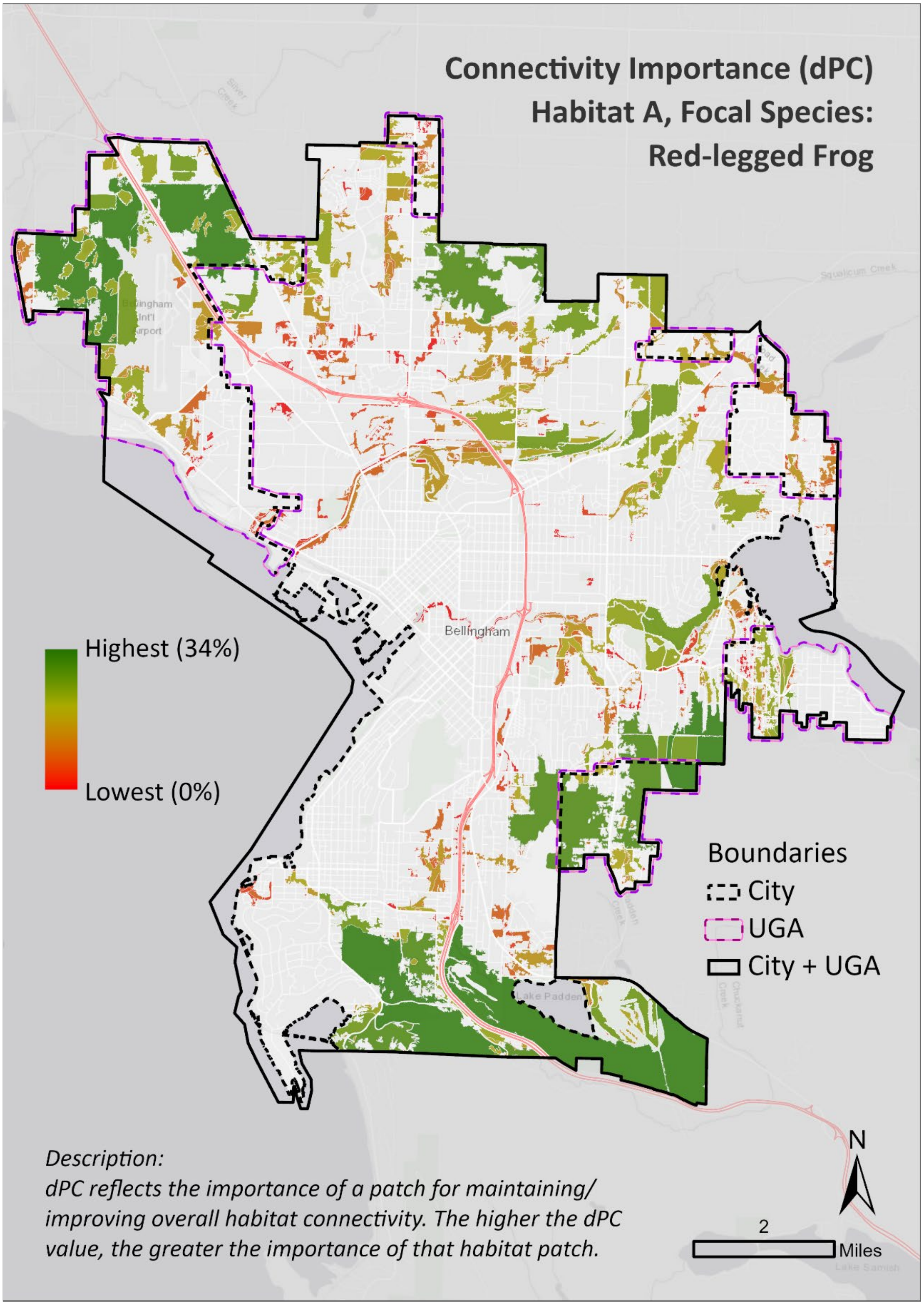

Figure 1. Habitat connectivity importance (dPC) for Habitat type A.

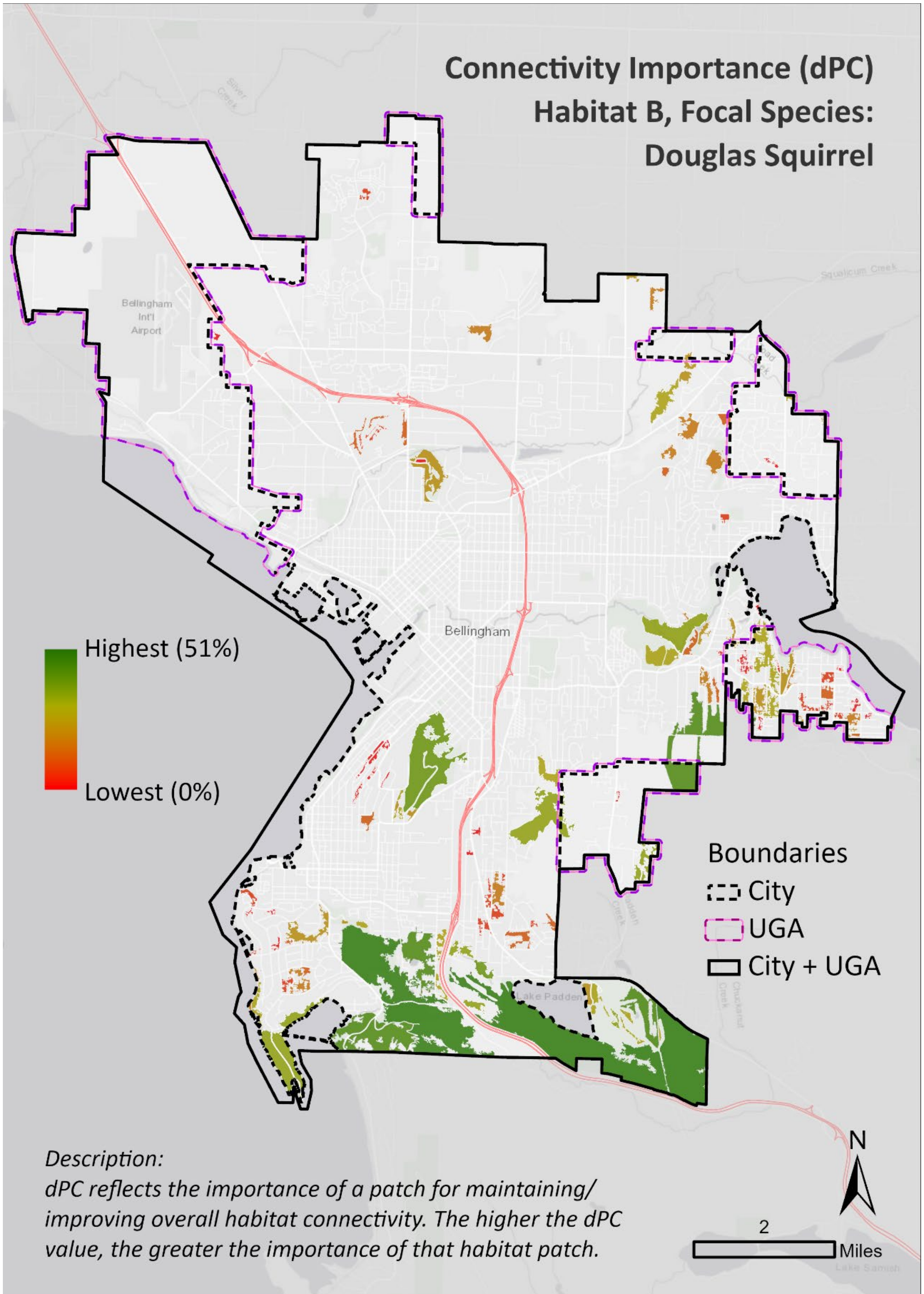

Figure 2. Habitat connectivity importance (dPC) for Habitat type B.

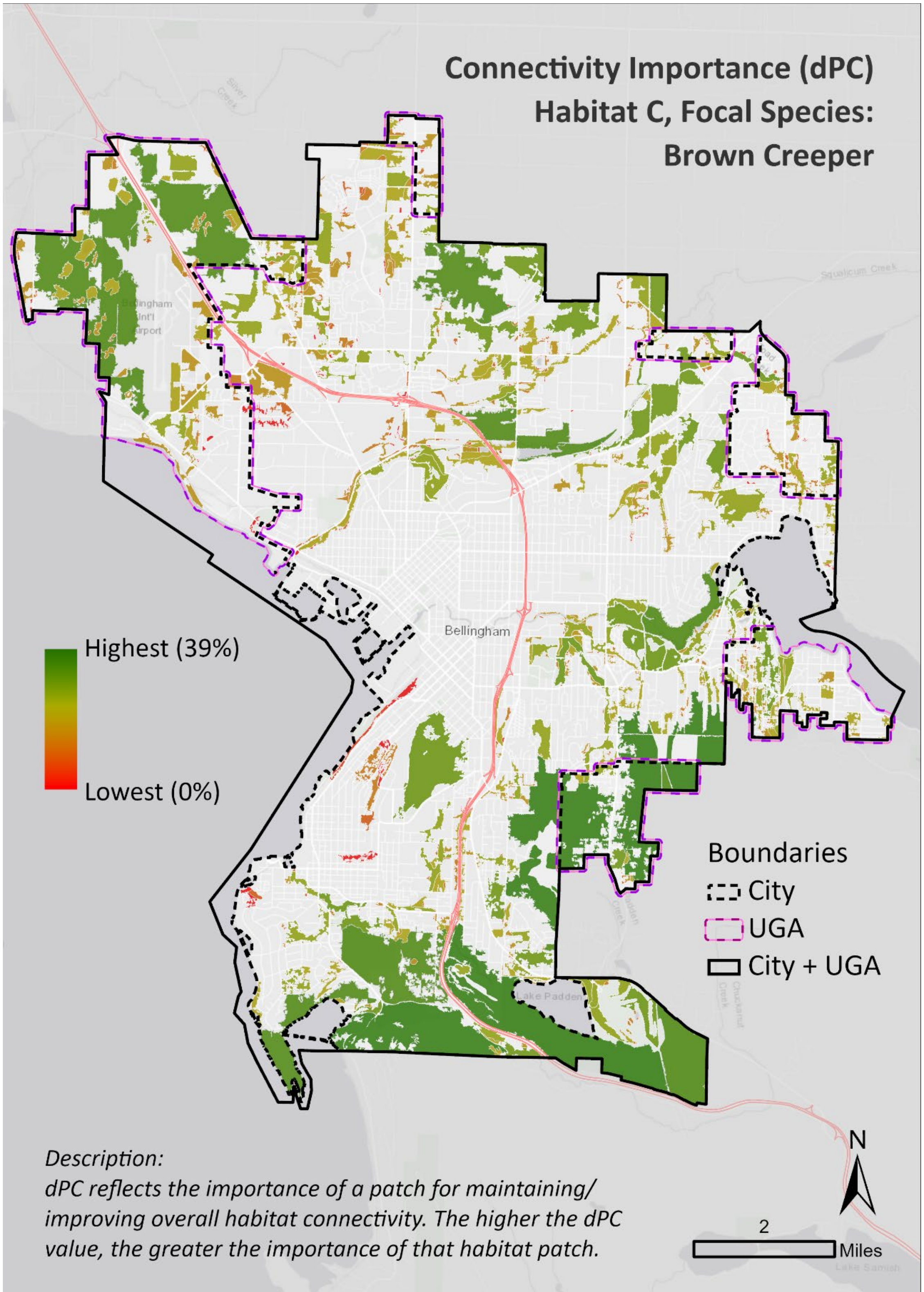

Figure 3. Habitat connectivity importance (dPC) for Habitat type C.

Habitat type C, represented by brown creeper, had the highest sum dPC values compared to the two non-bird species. This reflects the greater range of habitat conditions preferred by brown creeper compared other focal species. Birds can also take better advantage of the smaller, more urban, less connected features throughout the landscape.

The larger continuous forested habitat areas provided important habitats for all three focal species. These areas had few limitations to travel, provided access to a variety of habitats and provided refuge areas that are further away from the influences of humans. These large natural areas were most important for preserving biodiversity.

The fragmented habitat areas that extended into urban areas provided habitat for fewer species and habitat that was less important at the citywide scale. Fragmented habitats increased in importance when they were closer to large natural areas. Smaller natural areas fragmented on their own did provide habitat but only for the species that tended to be more tolerant of human disturbance. Birds in particular are able to make use of these fragmented areas because they can access other nearby habitat and intermix with landscape level populations.

3.3 Important habitat hubs

The distribution of patches classified as important habitat areas (**hubs**), **stepping stones**, as well as any remaining patches, are illustrated in Figure 4 – 6. See section 2.5 for a more detailed description of hubs and stepping stones. The distribution of important habitat areas mirrored the distribution of dPC values. The important habitat areas were the most important patches in the network, as they provided critical habitat on their own, while also linking the network as a whole. These areas are likely to be sources of species emigrants to other nearby patches.

The important habitat hubs for red-legged frog included the larger forest areas that were connected to wetlands and freshwater breeding habitat. The importance of habitat areas reduced as they became more fragmented by barriers in the urban development areas. The model identified some important stepping stone areas that are highly fragmented.

The Douglas squirrel had fewer important habitat patches within the city. The largest and most connected patches were identified as being important habitat hubs. These included the continuous coniferous forests that extend south of the city. Only one patch was identified as providing a more important role as a stepping stone.

The brown creeper had more important habitat hubs throughout the city because the species had fewer barriers to movement. The largest habitat patches were generally identified as the most important areas. More stepping stone patches were considered important in urban areas compared to other focal species.

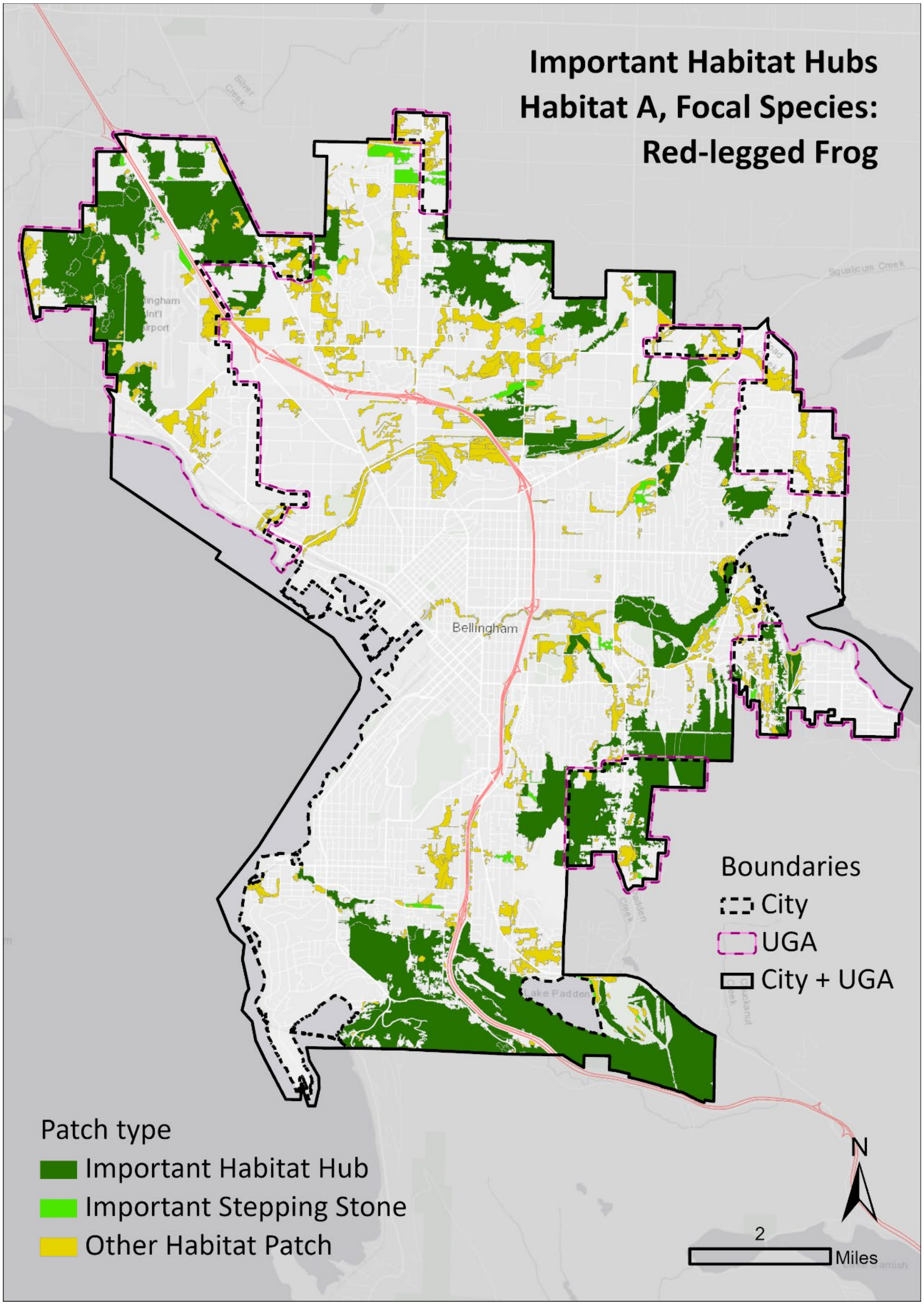

Figure 4. Important habitat hubs and stepping stones for Habitat A. The habitat areas not identified as important are shown as "Other habitat patches" for reference.

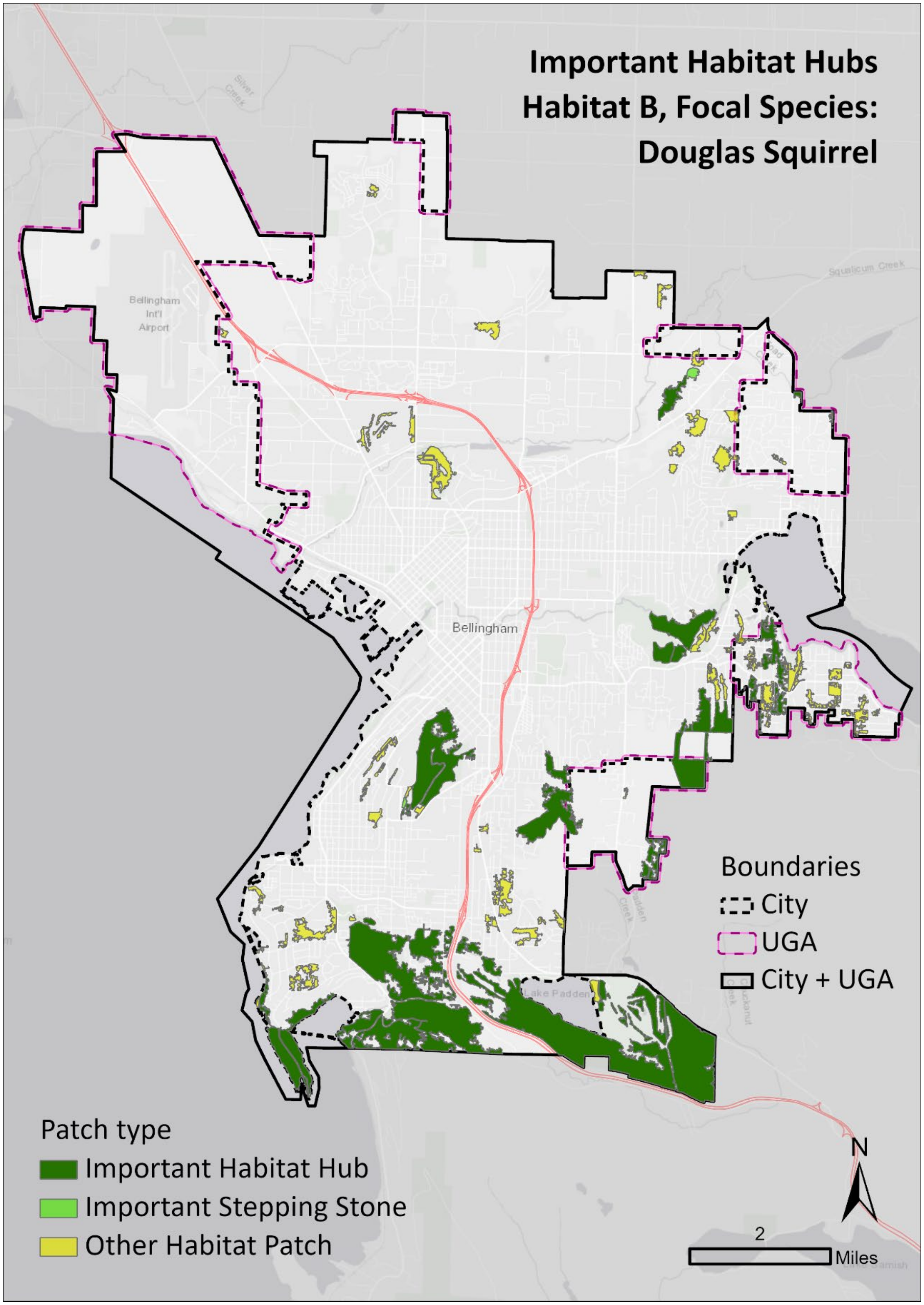

Figure 5. Important habitat hubs and stepping stones for Habitat B. The habitat areas not identified as important are shown as "Other habitat patches" for reference.

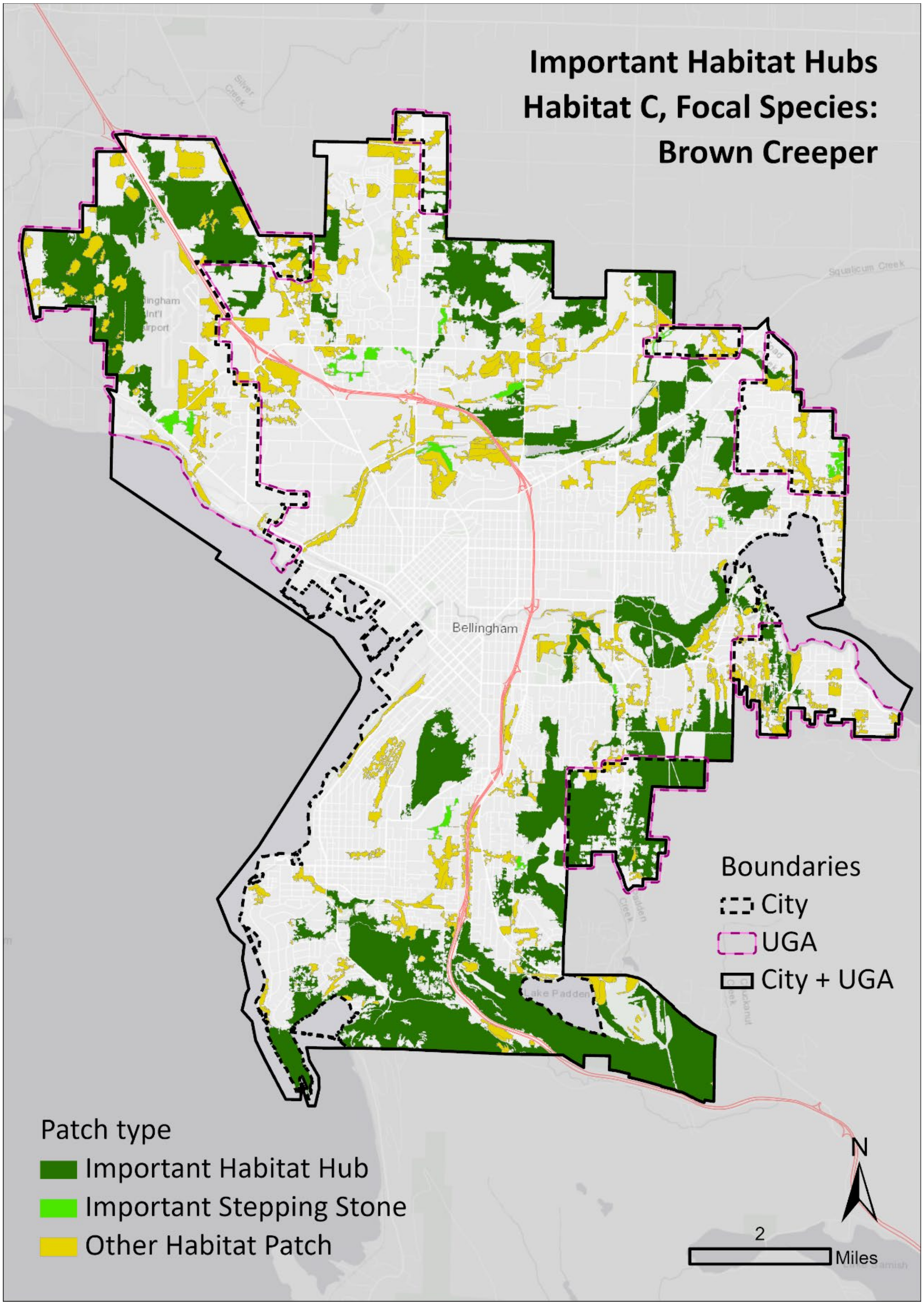

Figure 6. Important habitat hubs and stepping stones for Habitat C. The habitat areas not identified as important are shown as "Other habitat patches" for reference.

3.4 Multi-species Overlap Areas

The important habitat hubs for all species were overlaid (Figure 7) to identify hubs important for habitat connectivity to two or more of the focal species. Overlapped important habitat hubs were sites of high functional connectivity and high conservation priority for the focal species.

This combined map provides a high-level output to illustrate the most important terrestrial habitat areas in the City. Marine and freshwater habitat are not represented in this analysis and therefore corridors that extend to the marine foreshore rated as lower importance for the terrestrial species represented in the model.

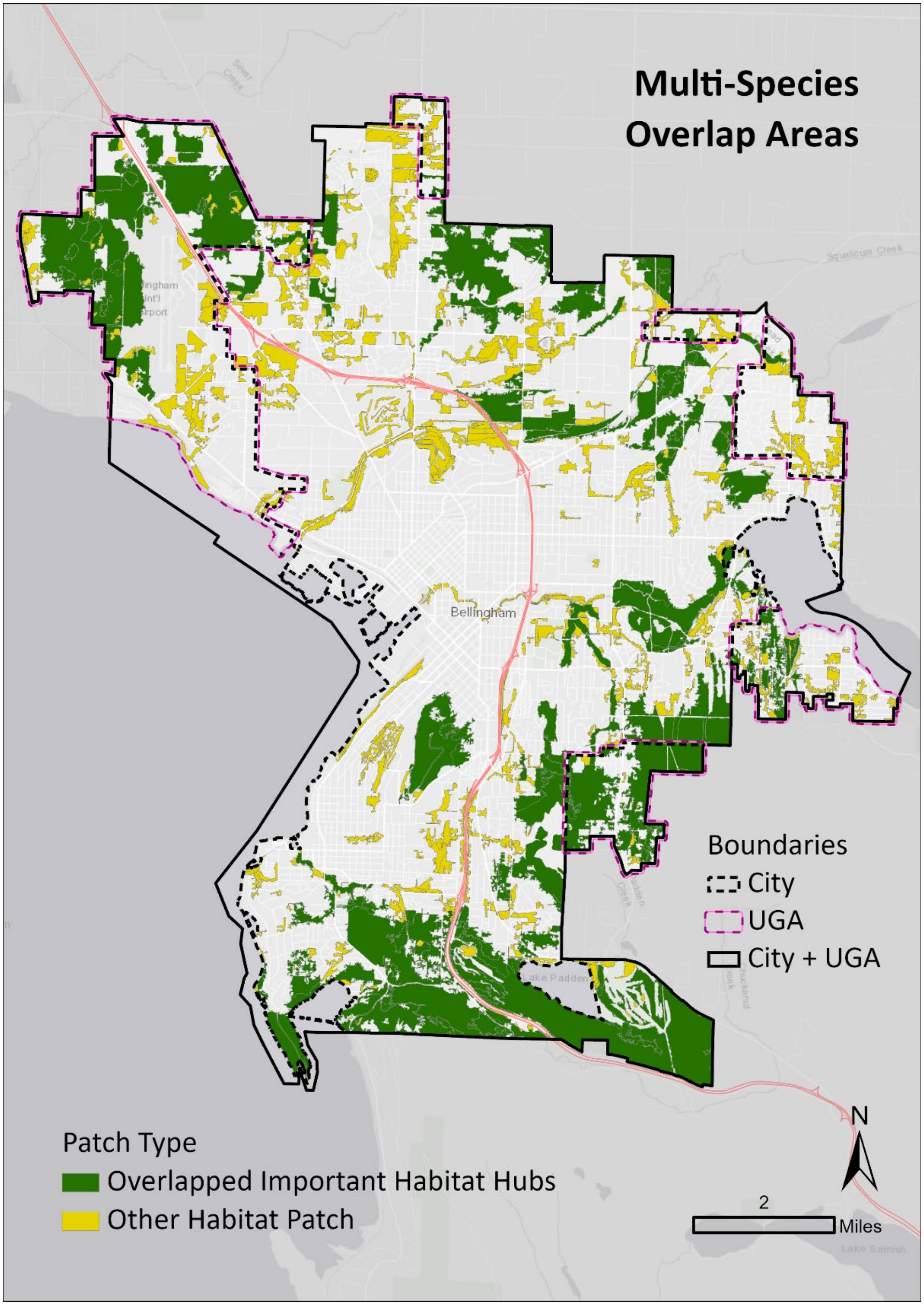

Figure 7. Multi-species overlap areas of important habitat hubs. The habitat areas not identified as important are shown as "Other habitat patches" for reference.

3.5 Terrestrial Wildlife Habitat Network

The outputs from this analysis were used to identify a Terrestrial Wildlife Habitat Network Map for the three focal species. Larger important habitat hubs that are expected to support the greatest diversity and number of wildlife species have been grouped together. These hubs tend to include areas that have a variety of habitat types and provide natural areas away from the influences of urban development.

Wildlife movement corridors were identified to connect these larger hubs together. Corridors are generally narrow with lower habitat value, however they could support the movement of a diversity of wildlife species. There are however a variety of barriers to movement that exist along many of these proposed corridors. These include non-natural features such as roads and developed properties, as well as natural barriers to many terrestrial species such as rivers. Wildlife species will respond differently to these barriers depending on their tolerances and capabilities. Interstate 5 is considered a significant movement barrier because it is wide and supports a high volume of traffic. Known locations of wildlife conflicts along this interstate were considered.

This Terrestrial Wildlife Habitat Network Map (Figure 8) is based on the outputs for the terrestrial focal species modeled. However, these species do represent a broader range of terrestrial wildlife species that are expected to make use of these corridors and habitat areas. This analysis does not consider habitat and movement corridors for aquatic species.

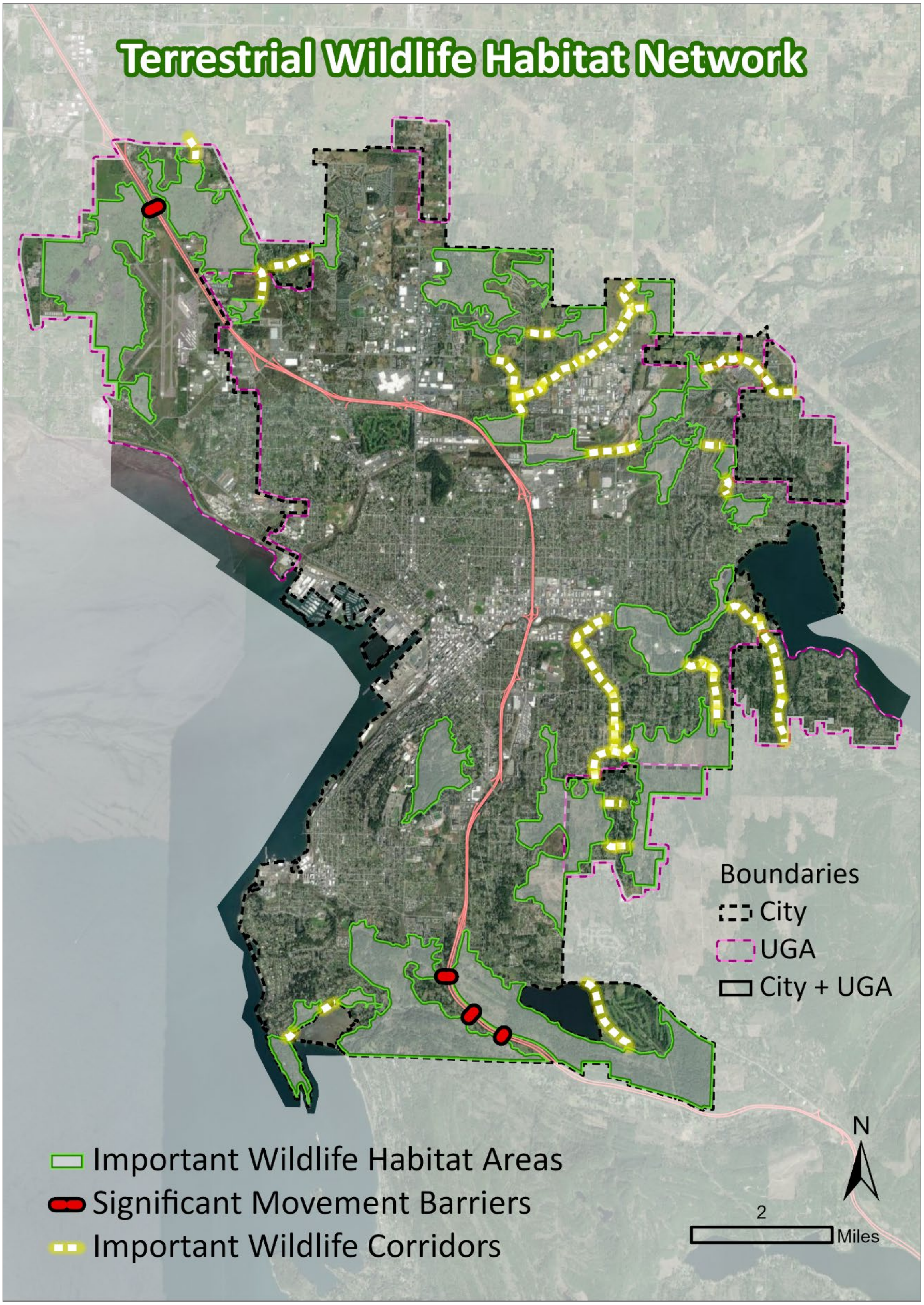

Figure 8. Terrestrial Wildlife Habitat Network. This analysis does not consider habitat extending outside of the City boundary, or habitat for marine or freshwater fish.

4.0 Limitations and Assumptions

The following limitations and assumptions apply to the analysis results:

- The Conefor model only accepts certain types of input variables can be used and it does not identify or prioritize degraded areas that could be restored to improve connectivity.
- The scope of this model exercise was focused on terrestrial habitats, which were a data gap in previous studies including the Bellingham Habitat Restoration Technical Assessment (Environmental Science Associates, 2015). Marine habitat was not considered since they have been analyzed in detail in previous studies such as:
    - WRIA 1 Nearshore & Estuarine Assessment and Restoration Prioritization Plan (Coastal Geologic Services, 2013)
    - City of Bellingham Marine Nearshore Habitat Connectivity Study (Environmental Science Associates, 2014)
- Freshwater species that inhabit the streams that run through the City were not considered since they have been analyzed in detail in previous studies including studies by state and tribal entities as well as the City of Bellingham Habitat Restoration Technical Assessment (Environmental Science Associates et al., 2015).
- This analysis does not represent all wildlife species and does not identify all habitat areas and corridors.
- Results are limited by the accuracy of the input habitat mapping, the focal species chosen, and understandings of their life requirements. The lifecycle characteristics of each species were based on available scientific studies. It was difficult to derive a single metric that best represented the minimum habitat patch size and dispersal limitations of a species. There is variability among individuals and populations of a species as well as the data available in scientific literature.
- Scope and budget available were limited to choosing three species and focusing on terrestrial habitat connectivity to generate terrestrial connectivity information to support the Urban Forestry Management Plan.
- The model results are relevant for the three focal species, and the similar species they represent, chosen for this analysis. They represent three types of habitat requirements for terrestrial species. The riparian corridors that extended through urban areas did not connect large habitat patches required by these three species and therefore did not rank high in relative importance. This model is not suitable for modeling the movement of aquatic species does not consider the importance of the marine foreshore as habitat. The City boundary was used as the limit of this analysis. There are important habitat areas and corridors that extend out to adjacent areas which were not included in this analysis.
- This analysis was completed using prioritization software that provides an output that is not biased by professional judgement. However, the findings are derived directly from the focal species choice and their input variables which do involve professional judgement and may have

limitations in accuracy. The method used to prioritize the habitat areas is based on one theory of connectivity modeling.

- The scale of the analysis impacts the relative importance of habitats. At the citywide scale, the fragmented habitat that remains within urban areas is less important compared to the extensive natural areas in more rural neighborhoods.
- There are likely to be some differences between the modelled patches and the actual presence of species in those patches. Interspecific interactions can also affect how each species uses the landscape; this is especially true for territorial species and development-sensitive species. These uncertainties should be considered when interpreting the results of this study.
- This analysis was largely a desktop-exercise. Due to the restrictions on travel due to the COVID outbreak, biologists from Diamond Head were not able to travel to the City to complete field reviews of these areas. Instead, data and conclusions were reviewed by City staff and local wildlife experts.

5.0 Conclusion and Next Steps

Evaluating the importance of natural areas for the health of wildlife and biodiversity is complex. There are multiple variables that affect species from the scale of the population to the individual. The climate and ecosystems are dynamic and continually changing. This model attempts to prioritize important habitat for three terrestrial species and the rank the effect that patch loss would have on landscape level connectivity. The model provides a repeatable, quantitative assessment of habitat value while minimizing the influence of professional bias.

The City has completed detailed studies on wildlife habitat in and adjacent to Bellingham. The Terrestrial Wildlife Habitat Network results were compared with and found to be consistent with wildlife information contained in the following supplemental sources:

- Bellingham Habitat Restoration Technical Assessment (ESA, 2015)
- Wildlife Crossing Site Selection in Whatcom County, draft (LaFever *et al*., 2020)
- Deer carcass data mapped by the Sierra Club (Sierra Club, 2018)
- Priority Habitats and Species (PHS) (Washington Department of Fish and Wildlife, 2021)
- Natural Heritage Program (NHP) Washington Wetlands of High Conservation Value (Washington Department of Natural Resources, 2021)

The modeling results described in this report, together with future studies and local knowledge and expertise, could be used to establish a broader habitat network to inform land use, restoration, and protection decision-making. For example, secondary corridors that are important for aquatic species, such as the riparian areas along Squalicum Creek, Padden Creek, and Whatcom Creek, could be incorporated, and the network could be expanded to include areas outside but adjacent to the City boundary. Other considerations for a broader habitat network may include:

- Values beyond connectivity, such as land use designation or species at risk of extirpation or extinction based on local knowledge and values.
- The presence of sensitive habitat features and species at risk that rely on habitat types not represented, such as the intertidal foreshore areas, freshwater habitats or pollinator communities.
- Opportunities to improve connectivity through habitat enhancement including in areas that have value by nature of their location, but are currently developed (such as the foreshore). Many species will choose to travel through a highly disturbed area if it provides the closest connection point to two valuable habitat areas.

Appendix 1 Glossary

DHC: Diamond Head Consulting

Probability of Connectivity (PC): This can be interpreted as the probability that "...two animals randomly placed within the landscape fall into areas that are reachable from each other" (Saura & Pascual-Hortal, 2007a p.93). The PC metric describes the amount of reachable habitat within a landscape both between and within patches.

Integral Index of Connectivity (IIC): IIC is recommended as the best **binary index for overall connectivity** analysis of a landscape, and ranges from 0 to 1 increasing with improved connectivity.

dPC: This is a metric that measures the effect of patch removal on overall network connectivity. dPC combines within-patch and between-patch connectivity to determine overall patch importance.

dPCconnect: This is the measure of a patch's importance for connecting *other* patches together.

Important Habitat Hubs: These are the habitat areas that the model has identified as being most important for each species. These have been identified by selecting the top 10-30% rated habitat patches.

Important Stepping Stones: These are areas that are most important for each species as stepping stones for maintaining connectivity across a landscape. The removal of these patches have disproportionally large negative effect on connectivity with nearby patches.

Appendix 2 Candidate focal species

A list of candidate focal species was developed (Table 4) and researched (Table 6). Three were chosen for the final connectivity analysis that represent a range of habitat types, modelling and life history parameters (Table 5).

Table 4. Candidate focal species

Species Common Name	Median Dispersal (m)	Max distance (m)	Min patch size (ha)	Habitat Summary	Disp. Road limited?	Forest	Non forest	Med. Dispersal: short (<50), medium(50-500), long (>500)	Sensitivity to barriers (low, medium, high)	Sensitivity to development (low, medium, high)	Min patch sizes: small (< 0.5ha), medium (0.5-3ha), large (>3ha)
Red-legged frog	100	2,500	0.05	Moist mixed and coniferous forest, with condition modifiers for riparian sites. Medium median dispersal and small min. patch size.	Yes	Yes	Yes	medium	medium	high	small
Western Red-backed Salamander	1.0	36	1.0	Moist mixed and coniferous forest, with condition modifiers for old, mature, core and riparian sites. Terrestrial only. Short median dispersal and small min. patch size (Lee and Rudd 2003).	Yes	Yes		short	high	high	medium
Long Toed Salamander	200	3,200	30	Old and mature coniferous and mixed forest. Moist, not wet sites. Medium median dispersal and large min. patch size (NatureServe 2019).	Yes	Yes		medium	medium	high	large
Douglas squirrel	65	822	0.4	Prefers older coniferous forest. Uses mixed forest, but restricted to coniferous LC in pilot study. Medium median dispersal and small min. patch size.	Yes	Yes		medium	high	high	small
Southern Red-backed Vole	220	500	0.1	Restricted to riparian, old and mature forest only. Medium median dispersal and small min. patch size (Lee and Rudd 2003, Santini *et al.* 2013, South Coast Conservation Program 2011).	Yes	Yes		medium	high	high	small
Townsend's Vole	6.4	42.8	0.1	Non-forest only, including shrub, agricultural and wetland areas. Thrives in wetlands and grasslands. Small median dispersal and small min. patch size (NatureServe 2019).	Yes		Yes	short	medium	medium	small
Brown creeper	88	2,110	2.3	Mature and old forest only, condition modifiers for woodland, riparian and wetland sites. Medium median dispersal, medium min. patch size.	No	Yes		medium	low	medium	medium
Muskrat	57	4,000	3.0	Wetland forest only; wetland, estuarine and intertidal grass-herb and soil only. Medium median dispersal and medium min. patch size (Santini *et al* 2013, Laurence *et al*. 2013).	Yes	Yes	Yes	medium	medium	medium	medium
Pileated Woodpecker	1,650	18,700	1.0	All forest, condition modifiers for old/mature forest. Long median dispersal, medium min. patch size (Lee and Rudd 2003, Sibleys 2003, Naylor *et al* 1996).	No	Yes		long	low	medium	medium
Pacific Wren	102	500	0.4	All forest and shrub, no non-forest. Riparian inclusive but not preferred. Medium median dispersal, min patch size small (NatureServe 2019, Lee and Rudd 2003).	No	Yes		medium	low	high	small
Rufous Hummingbird	31	2,000	0.3	All forest, condition modifiers for old and young forest, edge habitat, woodlands; shrub and grass-herb areas including riparian and wetlands, old fields and agricultural field. Short median dispersal and small patch size (Lee and Rudd 2003, Sibley 2003).	No	Yes	Yes	short	low	medium	small
Great Blue Heron ssp. fannini	2,000	10,000	1.0	Mature riparian and coastal forest (10km buffer) only, wet non-forest only except old fields. Long median dispersal. Medium (forest) and Large (non-forest) min. patch sizes (Butler 1999, COSEWIC 2008, Melvin 1999).	No	Yes	Yes	long	low	medium	medium and large

Three focal species were used in the Conefor connectivity model. The three species were selected with consideration for the typical habitat types and sizes that exists across the City. Terrestrial habitat in the City typically includes forested ecosystems with few natural grass or shrub communities when left unmaintained. There are also numerous watercourses, wetlands and a marine estuarine area that play a large role in supporting biodiversity. The City is not large in area and dispersal criteria and minimum patch size should reflect this. From the list of potential species, three species were chosen by the City:

- Red legged frog (*Rana aurora*)
- Douglas-squirrel (*Tamiasciurus douglasii*)
- Pacific wren (*Troglodytes pacificus*) – substituted for brown creeper (*Certhia americana*)

The species selected should represent the diversity of terrestrial wildlife that inhabits Bellingham. Red legged frog and Douglas squirrel represent amphibians and small mammals and are supported by sound data regarding their life requirements. Pacific wren was originally chosen to represent forest birds; however, it had similar habitat requirements to Douglas-squirrel. The consultants recommended that brown creeper be substituted because it has larger minimum patch size requirements and would add a species with a different patch size requirement to the analysis. There were also more studies available for the habitat requirements of the brown creeper.

Table 5 and Table 6 summarize the inputs for the four species and the references used to select input metrics for the model. The City supplied references for studies of red legged frog that showed the max dispersal distance should be increased from 2,500 to 5,000m. The minimum patch size was kept small at 0.05 ha for this analysis to ensure that the small wetlands that exist across the City were identified as potential habitat for the frog. It should be noted that it is difficult to quantify exact dispersal ranges and minimum patch size from many references. While these studies provide metrics and observations of the characteristics of each species, the final numbers should be considered generalizations with the intention of yielding modeling outputs that reflect guilds of species with similar life requirements.

Table 5. Life requirements for focal species

Species Common Name	**Median Dispersal (m)**	**Max distance (m)**	**Min patch size (ha)**	**Habitat Summary**	**Disp. Road limited?**	**Forest**	**Non-forest**	**Med. Dispersal: short (<50), medium(50-500), long (>500)**	**Sensitivity to barriers (low, medium, high)**	**Sensitivity to development (low, medium, high)**	**Min patch sizes: small (< 0.5ha), medium (0.5-3ha), large (>3ha)**
Red-legged frog	100	5,000	0.05	Moist mixed and coniferous forest, with condition modifiers for riparian sites. Medium median dispersal and small min. patch size.	Yes	Y	Y	medium	medium	high	small
Douglas squirrel	65	822	0.4	Prefers older coniferous forest. Uses mixed forest, but restricted to all coniferous stands in pilot study. Medium median dispersal and small min. patch size.	Yes	Y		medium	high	high	small
Pacific Wren	102	500	0.4	All forest and shrub, no non-forest. Riparian inclusive but not preferred. Medium median dispersal, small min. patch size.	No	Y		medium	low	high	small
Brown Creeper	88	2,110	2.3	Mature and old forest only, condition modifiers for woodland, riparian, and wetland sites. Medium median dispersal, medium min. patch size.	No	Y		medium	low	medium	medium

Table 6. Metric research for focal species

Species	Source	Notes
Red Legged Frog	Metro Vancouver Indicator cited from O'Neil *et al*.	- Home range ≤ 1 km w/high site fidelity to summer and winter range
	Grand *et al*. 2017. Ecological Processes	- Migrates seasonally long distances (to at least 5 km) - Recaptured at 5 km straight line distances from breeding ponds - Relationship between breeding pop. size and % forest becomes important at 200 m, peaks at 450 m, but remains high to 5 km (furthest distance examined in this study)
	Hayes *et al*. 2008. Society for the Study of Amphibians and Reptiles Urban Herpetology	- <10 m daily movement in terrestrial habitat - Up to 80 m seasonal movement - Recaptured up to 4.8 km from breeding sites - Seasonal movements in the 1+ km range from breeding area - Movement scales that exceed 150 m - Can't do weighted average – no sample pop.
	NatureServe	- Several km movement but most individuals stay within few km of breeding site - Max distance between capture points is generally few km or less
	COSEWIC Report	- Northern Vancouver Island – individual radio tracked frogs were relatively sedentary remaining approx. 36 m or closer to edge of forest streams - In suitable conditions, frogs can be encountered on forest floor far from water - distances of 200-300 m have been noted - Oregon – adult frogs found during April-May 1.1 to 2.4 km straight line distance from capture points previous December - 2 frogs moved about 260 m along riparian channel, another moved perpendicular to stream at least 200 m
Pacific Wren	Ruan, X., J. Huang, S. Gergel, D. Williams, K. Harker, Y. Lu, N. Coops 2017. Metro Vancouver Regional District	- Weighted means through literature review
Douglas Squirrel	Metro Vancouver Indicator cited from O'Neil *et al*.	- Home range < 1 ha, highly territorial
	NatureServe	- Range extent 200,000 – 2,500,000 km^2 - Length 36 cm - Weight 300 g - 1-2 litters per/year, litter of 28 (usually 4-6) - Dispersal up to several tens of km, but usually not more than few km - Home range of 0.8 km
	Penteado 2020. Urban ecosystems	- Numbers used in dispersal model: Home range <0.6 ha, Dispersal <0.15 km
Brown Creeper	NatureServe	- Territories range from 2.3 to 6.4 ha: three study sites yielded 2.0 ha per pair, 1.5 ha per pair for 2 areas of swamp forest habitat, and 5.6 ha per pair in upland site (5.6 may be exaggerated by inclusion of inappropriate habitat away from streams) -
	D'eon *et al*. 2002 Conservation Ecology	- Estimated probable maximum dispersal ability 10.04 km, median dispersal ability 0.89 km - Estimated proportion of landscape accessible: median dispersers 15%, maximum dispersers 100%

Species	Source	Notes
	Timossi and Barrett 1995. California Wildlife Habitat Relationships Program	- Home range 2.3-6.4 ha - Dispersal distance 2,110 m
	Poulin and Villard 2011. Landscape Ecology	- 141 m radius as approximate size of territory

Appendix 3 Connectivity metrics

Table 7. Connectivity metrics calculated using Conefor, adapted from Saura and de la Fuente (2011).

Metric Name	Formula/Explanation	Description
Probability of Connectivity (PC)	$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \cdot a_{ij} \cdot p_{ij}^{*}}{A_L^2} = \frac{PCnum}{A_L^2}$	PC is the **probability that "... two animals randomly placed within the landscape fall into areas that are reachable from each other."** Probabilities between patches are based on median dispersal distances having a probability of 0.5. The patch attribute, *a*, is the area-weighted quality of a patch.
dPC	$dPC(\%) = \frac{PC - PC'}{PC} \times 100$ *and* $dPC = dPCintra + dPCflux + dPCconnector$	**Measures the effect of patch removal on overall network connectivity (PC).** dPC is the percent contribution of a patch (*k*) to PC. The value of PC after removing patch *k* (PC') is subtracted from the overall value of PC. The difference between the two values is then expressed as a percentage of PC. dPC is composed of three patch importance metrics explained below.
dPCintra	Available habitat provided by a patch (k) itself: $a_i \times a_j \; when \; i = j = k \; (a_k^2)$. Where *a* is area-weighted quality.	dPCintra is the percent contribution of a patch to **intrapatch (within-patch) connectivity**. It is not affected by number of links or link probabilities.
dPCflux	Area-weighted dispersal flux from a patch (k) to or from all other patches in a network: $a_i \times a_j \times p_{ij}^{*}$	dPCflux measures **how connected a patch is in the network.** dPCflux depends on the area-weighted quality of a patch and its position in the network. It differs from dPCconnector in that it doesn't measure how important a given patch is for connecting *other patches* together, but rather how connected an individual patch is itself to the rest of the network.
dPCconnector (Stepping Stone Importance)	Contribution of patch *k* to the connectivity of neighbouring patches. The sum of $a_i \times a_j \times p_{ij}^{*}$ for any number of pairs of patches, *i and j,* around a given patch *k.* Patch *k* must be part of the best path between *i* and *j.*	**dPCconnector is a measure of how important a patch is for connecting other patches together.** It can be thought of as stepping stone importance. dPCconnector is independent of a patch's area-weighted quality, and depends only a patch being part of the *best* path for dispersal (i.e. when $p_i \times p_j$ is highest).

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