Exploring the Relative Effects of Different Wetland Restoration Sites on Functional Connectivity for the Northern Red-Legged Frog (*Rana aurora*)

by
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Abstract

Amphibian species are globally at risk, with a leading cause of decline attributed to habitat loss and fragmentation. The northern red-legged frog (NRLF) is one such species and listed as a Species of Special Concern by the Species at Risk Act. The Sunshine Coast Wildlife Project is creating new wetland habitat on the Sechelt Peninsula. In this research, I provide a tool to explore the relative effects on the functional connectivity of different potential restoration sites. A habitat suitability model (HSM) was created to describe the landscape in terms of conductance, or ease of movement for NRLF. Using this conductance map, I analysed the functional connectivity between wetlands by using Circuitscape, a software grounded in circuit theory. Three potential restoration options were compared against the existing landscape. Of the three options, one had a much greater effect in increasing the overall wetlands and its connectivity to the existing network of wetlands.

Keywords: Functional connectivity; wetland habitat restoration; northern red-legged frog (*Rana aurora*); habitat suitability model (HSM); circuit theory; Circuitscape

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List of Acronyms

asl	Above sea level
BC	British Columbia
BC Env.	British Columbia Ministry of Environment, Lands and Parks
Bd	*Batrachochytrium dendrobatidis*
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CW	Coarse Wood
CDF	Coastal Douglas-Fir
CWH	Coastal Western Hemlock
MH	Mountain Hemlock
DEM	Digital Elevation Model
Env. & C.C. Canada	Environment and Climate Change Canada
HSI	Habitat Suitability Index
HSM	Habitat Suitability Model
LCP	Least-Cost Path
NDVI	Normalized Difference Vegetation Index
NRLF	Northern red-legged frog (*Rana aurora*)
RISC	Resources Inventory Standards Committee
SARA	Species at Risk Act
SCWP	Sunshine Coast Wildlife Project
TEM	Terrestrial Ecosystem Mapping

1. Introduction

1.1. Context

Amphibians have suffered greatly in the past decades. Their entire class is at risk. Globally, it is estimated that over 70% of extant species are undergoing population declines (Abney et al. 2019). Anthropogenic land use and habitat modification are some of, if not the leading causes of decline in amphibian populations (Brown et al. 2012; Stuart et al. 2004). They are inherently vulnerable to habitat fragmentation because they are dependent on both aquatic and terrestrial habitats to complete their life cycles and have low dispersal capabilities (Decout et al. 2010). Fragmented habitat can reduce their reproduction success and increase their susceptibility to other stressors, such as introduced predators, disease and climate change (Brown et al. 2012).

The northern red-legged frog (*Rana aurora*) (hereafter NRLF) is one of three listed frog species that live here on the Sunshine Coast of British Columbia (BC), Canada. Their distribution ranges from northern California to southwestern BC. They are listed as a species of concern within most of that range, except in the state of Washington (Bunnell et al. 2016). In BC, NRLF was designated as a Species of Special Concern by The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 1999, and reconfirmed its status in 2002, 2004, and 2015 (COSEWIC 2015). As a result, it was put on the *Species at Risk Act* (SARA) in 2005 as a Schedule 1 Species of Special Concern. In BC, the provincial Conservation Data Rankings lists the NRLF as blue-listed and given a rank of S3, meaning a species of special concern vulnerable to extirpation or extinction (Env. & C.C. Canada 2017). For more details on their legal status, see the Species Account in Appendix A.

While NRLF populations currently appear to be stable, their numbers have greatly declined since the 1960s (Env. & C.C. Canada 2017). In BC, NRLF is of special concern because their distribution is confined to highly populated areas of coastal southern BC, including the Lower Fraser Valley, Vancouver Island, the Sea-to-Sky corridor, and the Sunshine Coast. Very little of its natural habitat remains; most has been converted to urban or agricultural landscapes, and much of their remaining forested landscapes are under active logging pressures (Env. & C.C. Canada 2017).

1.2. Species Profile

The integrity of NRLF habitat requires three overarching habitat components:

1) Aquatic habitat that is structurally complex with still or slow-moving waters of at least 30 cm depth (Storm 1960; Licht 1969) and abundant emergent vegetation such as sedges and cattail (Adams et al. 2011);
2) Forest habitat with a closed canopy cover, abundant coarse wood (CW), and an thick layer of leaf litter (Aubry 2000; Chan-McLeod 2003);
3) An appropriate spatial configuration and connection of these different habitats (Grand et al. 2017; Env. & C.C. Canada 2017).

Wetlands are used for breeding, raising their embryos and larvae, and as thermal refugia for adults during both the summer and winter (Licht 1969). The embryos and larvae of NRLF have the lowest critical thermal range of any frog species in North America and ranges from 4-21° Celsius (Licht 1971). Egg masses are placed in areas with high sun exposure at a depth ranging from 30 cm to 1.5 m and attached to stalks of sturdy vegetation like sedges (*Carex spp.*), cattail (*Typha latifolia*), water lilies (Nymphaeaceae), or submerged sticks and willow (*Salix spp.*) branches (Licht 1969). Tadpoles feed on algae and detritus (Licht 1974). While NRLF are found in larger permanent ponds, ephemeral ponds are important breeding habitat for NRLF as they lack the presence of predatory fish and other competing species that are associated with permanent ponds (Adams 1999).

Upland forests are used for foraging, dispersing by adults and juveniles, and can also be used as thermal refugia during the winter. Adult NRLF are highly terrestrial, may spend up to 90% of their time on land (Haggard 2000) and have been found up to 4.8 km away from any breeding ponds (Schuett-Hames 2004). They forage in damp, shaded areas and are more active at night, especially on warm rainy nights (Storm 1960).

When considering the long-term viability of a species, all life cycles must be considered, especially its specific breeding and dispersal behaviour (Brown et al. 2012). The species requires an adequate spatial configuration allowing adults to move between different habitat types, critical to the completion of all their life cycles and for the long-term persistence of the species (Grand et al. 2017). Bunnell et al. (2016) conducted a long-term monitoring study of NRLF in Surrey, BC and found that wetlands were much more productive when more than 10% of the shoreline was forested. Another study found odds of extirpation decrease as the proportion of forested shoreline increases (Adams et al. 2011). Furthermore, NRLF eggs are in high abundance in wetlands where adults are found in high numbers in the surrounding landscape. As for adults, they are found in greater abundance where the forest has at least 60% canopy cover (Bunnell et al. 2016). In Washington State, pond-breeding amphibians like the NRLF were strongly correlated with quantity of forested habitat within 1 km of the wetlands' edge (Adamus 2014). Another study in Washington found a strong relationship between the breeding population size in wetlands and the percent canopy cover of the surrounding forest. The correlation peaked at 450 m but remained high up to 5 km from breeding pond, which was the furthest distance analyzed in the study (Grand et al. 2017). Therefore, isolated patches of wetlands with the minimum legal requirement of a 30-m border of riparian vegetation (Riparian Areas Protection Act 2019) are likely not enough to sustain a healthy population for the long term (Hayes et al. 2008). For full species account, see Appendix A.

1.3. Threats

Habitat loss and fragmentation

Habitat loss is one of the main threats to NRLF in BC. This is because most of their range occurs in the densely populated regions of the Fraser Valley and southern and eastern parts of Vancouver Island. Furthermore, human population is expected to continue growing in the coming years, with a continued expansion of urban centers (COSEWIC 2015).

Development projects and forestry-management practices are required to maintain a 30-m riparian buffer around wetland ecosystems (Riparian Areas Protection Act 2019, Forest Range and Practices Act 2004). Wetlands are, however, only legally recognised and, therefore, protected when greater than 0.5 ha in the Coastal Douglas-fir (CDF) and Coastal Western Hemlock (CWH -xm, -dm, and -ds) biogeoclimatic zones, and greater than 1 ha in all other biogeoclimatic zones in the lower mainland (Tschaplinski & Pike 2010). In spite of being important breeding habitat, small wetlands are not legally recognized for protection.

Pond-breeding amphibians such as NRLF are especially vulnerable to the fragmentation of their habitat because they depend on both aquatic and terrestrial habitat (COSEWIC 2015). When these habitats are cut off from each other, NRLF cannot complete their life cycles which can lead to population decline, and sometimes even extirpation of the species. Furthermore, many amphibian species exist within larger metapopulations where some populations periodically “wink-out” due to environmental stochasticity. The long-term persistence of local populations requires immigration of individuals from other breeding sites (Marsh & Trenham 2001). While this is a natural process, fragmentation of the landscape, or even an increased distance separating wetlands due to the loss of small wetlands, can impede the “rescue effect” within the metapopulation. This is caused by the interaction of a reduced overall population size and an increased distance among wetlands (Semlitsch & Bodie 1998). A population could be extirpated from the fragment in a single bad year (Wind 2000). Therefore, even when both terrestrial and aquatic environments remain within a fragment, the isolation of a population from its metapopulation can have deleterious impacts by restricting the gene flow and prohibiting new migrants to augment the population.

Logging

Much of the remaining forested landscape within NRLF range is subjected to extensive forestry activities. Forestry companies are obliged to maintain a 30-m riparian buffer around lakes, streams, and legally recognized wetlands (i.e.: those large enough to be classified, as described above; Forest Range and Practices Act 2004). However, cutblocks and associated roads reduce the quality of the habitat and hinder NRLF movement through the landscape, which can lead to the isolation of populations.

Adult NRLF occur in lower abundance in clearcuts and young forests than rotational-aged forests (80 years old and the oldest age class of the study; Aubry 2000). Recent cutblocks are harsh environments for NRLF as the lack of vegetation makes them vulnerable to desiccation and predation (Chan-McLeod 2003). Amphibians were not observed during terrestrial surveys conducted by the SCWP within these landscapes (L. Riahi 2020, SCWP, personal communication). A study using radiotelemetry-tagged frogs concluded that cutblocks create a barrier to NRLF movement (Chan-McLeod 2003). They were only able to travel through recent cutblocks when there had been two to three consecutive days of rain. When experimentally placed in a cutblock, NRLF moved towards the largest forest patch in the vicinity. Effects were greater in very recent cutblocks (2 and 3 years) than in a cutblock 11 years post-harvest (Chan-McLeod 2003), indicating that effects on NRLF movement subside once the trees are tall enough to provide some shelter. Another study showed NRLF adults preferentially moved away from small (<0.3 ha) remnant forest patches left within a cutblock to larger patches (>0.8 ha), unless a stream was nearby. These findings indicate that negative effects of logging can be mitigated if logging practices leave large (>0.8 ha) forest patches (Chan-Mcleod & Moy 2007).

It is unclear whether breeding ponds in these landscapes provide quality habitat or actually act as a population sink (Wind & Dunsworth 2007). Logging practices change the hydrology of a landscape. Loss of trees can cause water levels in wetlands to fluctuate causing either increased runoff or earlier dry conditions (Adamus 2014). While these effects subside in time as the vegetation recovers (Adamus 2014), on the short-term, premature drying of wetland habitat can impact tadpoles that have to yet metamorphosed and emerged, leading to mortality (Abney et al. 2019). Furthermore, having high breeding-site fidelity, NRLF will continue to breed in small ephemeral ponds, even if the surrounding forest has been harvested. If these ponds are unbuffered, it increases the likelihood of drying out before emergence (Wind & Dunsworth 2007). However, the increased sun exposure from the loss of surrounding canopy can also increase primary production in the wetland (Adamus 2014), which can benefit tadpoles by providing greater food source.

Although NRLF are found in all forest seral stages, they tend to be in greater abundance in older and mature forest stands (>80 years), than in younger stands (<75 years; COSEWIC 2015). They are less common in open-canopy sites than closed-canopy forests (Adamus 2014) and negatively correlated with variable retention logging practices (Wind & Dunsworth 2007). While NRLF prefer a closed-canopy forest with a complex understory, a thick layer of leaf litter and CW, the loss of these habitat features due to logging are constrained to a relatively short term, with habitat conditions improving and NRLF abundance increasing in forests 40 years post-harvest (Aubry 2000).

Other effects, however, permanently change the landscape, having long-term impacts on NRLF populations. Logging and the construction of roads reduce occurrences of wetlands by homogenizing the landscape. Small wetlands can have increased sedimentation due to the increase in runoff, soil erosion and input of CW (Adamus 2014). Furthermore, small, non-classified wetlands (<0.5 ha) and ephemeral ponds are important breeding habitat (Adams 1999) but are often infilled during road construction (Adamus 2014). While logging practices have been refined to reduce their impact on wildlife and hydrology (Forest Range and Practices Act 2004), much of the Sunshine Coast has been logged repeatedly over the past century (VRI BC Data Catalogue 2020). This legacy has undoubtedly changed the natural morphology and hydrology of the landscape, with ultimately less wetlands than the pre-logging era.

Introduced Species

Another factor exerting pressure on NRLF populations is the presence of introduced species, notably American bullfrogs (*Lithobates catesbeianus*) and non-native fish used for sport fishing. Studies show that non-native fish like centrarchids have negative effects on the survival of NRLF tadpoles through predation (Adams 2000; Pearl et al. 2005). Data shows mixed results on the effects of introduced bullfrogs. American bullfrog adults, and occasionally larvae, predate upon NRLF tadpoles (Kiesecker & Blaustein 1997) and are strong competitors for resources (Govindarajulu 2004). Studies show that presence of bullfrog adults and tadpoles increases time required for NRLF tadpoles to reach metamorphosis and reduces their mass at metamorphosis (Kiesecker & Blaustein 1998) which can, in turn, increase the likelihood of desiccation of juveniles (Chan-McLeod 2003).

However, it is unclear whether NRLF decline in some areas is directly cause by the presence of bullfrogs, or if there are other underlying drivers causing their decline. Other studies show NRLF and bullfrogs co-existing and breeding abundance similar in wetlands with and without the presence of bullfrogs (Grand et al. 2017; Adams et al. 2011; Pearl et al. 2005). Research shows that tadpoles were more affected by the presence of bullfrogs when they were newly introduced, but had adapted their behaviour in locations where bullfrogs had been present from many years (<60 years; Kiesecker & Blaustein 1997). Bullfrogs have not yet been observed on the Sechelt Peninsula of the Sunshine Coast. While, their range is expected to increase (Govindarajulu 2004; COSEWIC 2015), it has been suggested that focusing on habitat features is a better management strategy than direct control of bullfrogs (Adams & Pearl 2007; Adams et al. 2011).

Diseases

Amphibians worldwide have been affected by the chytrid fungus *Batrachochytrium dendrobatidis* (Bd). Bd infects the skin of amphibians. Given that amphibians breathe and osmoregulate through their skin, severe infection leads to mortality (Fisher & Garner 2020). As of 2019, Bd was confirmed in 54% of tested species (Fisher & Garner 2020). Throughout the province, NRLF have tested positive for Bd, but with a low prevalence ranging from 4-6% (Richardson et al. 2014; Govindarajulu et al. 2013). The SCWP maintains an active monitoring program for this fungus. Any amphibian found dead and showing signs of disease (i.e.: white spots or discolouration) is sent to a lab for analysis (L. Riahi 2020, SCWP, personal communication).

Climate Change

Climate change is of increasing concern. Although the nature of climate change is unpredictable, the Pacific Northwest is projected to have overall increasing temperatures, as well as wetter winters and dryer summers than currently experienced (Mote & Salathé 2010). This could have significant impacts on amphibian communities. By the 2080s, it is estimated that approximately 45% of NRLF range within BC could experience temperatures above their thermal optima (Gerick et al. 2014). As summers get drier, small wetlands and ephemeral ponds, important breeding habitat for many amphibians, can prematurely dry out, killing the tadpoles still inhabiting them (Abney et al. 2019). While predicting exactly how our changing climate will affect NRLF populations on a local scale is impossible, it is likely that the variable climate will be detrimental to NRLF by (a) causing ephemeral ponds to dry prematurely, (b) increasing the occurrence of erratic late-season frost events that can harm the eggs or tadpoles, and (c) warming water temperatures, which both decreases NRLF breeding productivity and increases the risk of invasion by alien predatory frogs (Abney et al. 2019).

Other studies have indicated NRLF may benefit from warmer temperatures which increases primary productivity, improving food availability for tadpoles (O'Regan et al. 2014). The development of NRLF tadpoles quickens with higher temperatures. Therefore, if the hydroperiod is sufficient and the pond does not dry out before emergence, warming temperatures may benefit NRLF tadpoles (O'Regan et al. 2014). However, temperatures above 21 degrees Celsius kills tadpoles (Licht 1971).

Cumulative Effects

Cumulative effects occur when different stressors interact in ways that their overall impacts are greater than the sum of their isolated effects (Brown et al. 2013). The continued human population growth and subsequent land conversion to an urban-agricultural matrix is expected to increase. The presence of invasive competitors and predators like the American bullfrog is also increased in degraded habitat. Therefore, their occurrence can be expected to increase along with land conversions (Govindarajulu 2004; COSEWIC 2015). Furthermore, introduced bullfrog populations in BC carry Bd and can act as vectors for the disease (Garner et al. 2006).

Climate change will likely exacerbate other stressors, and vice versa (COSEWIC 2015). In a mesocosm experiment, NRLF exposed to Bd were more vulnerable to negative effects on their body condition and immune functions when exposed to varying temperatures (Hamilton et al. 2012). It is probable then that the increasing climate instability will exacerbate the effects of Bd on NRLF. Furthermore, increasing temperatures may give a competitive advantage to other native sympatric species like the Pacific chorus frog (*Pseudacris regilla*; Hamilton et al. 2012).

The unstable climate will likely increase the probability of populations plummeting during extreme climatic events (Abney et al. 2019). As previously discussed, the extirpation of populations from wetlands is a common occurrence within larger metapopulation dynamics (Marsh & Trenham 2001). However, the possibility of affected populations being rescued by surrounding populations is limited when the total amount of wetlands has been reduced through habitat loss, fragmentation, and logging, thereby increasing the distance between remaining wetlands (Semlitsch & Bodie 1998). Therefore, the risk of permanent extirpation from extreme climatic events is greater in fragmented landscapes where there is no possibility for outside individuals to boost the population or to recolonize extirpated patches.

1.4. Project Partner

The Sunshine Coast Wildlife Project (SCWP) was created in 2006 with the mandate to enhance and create more habitat for local wildlife at risk (SCWP n.d.). In 2016, they slowly began to reverse the historical tendency to infill wetlands by creating new wetlands to benefit a range of different species from amphibians and birds, to small and large mammals. The SCWP is particularly concerned about the unpredictable but exacerbating effects of climate change on amphibian communities as a whole. One of SCWP's goals is therefore to increase the overall resilience of the amphibian community towards a changing climate by creating a range of new breeding habitat for them (M. Evelyn 2020, SCWP, personal communication). The SCPW chose NRLF specifically as the focal species because of their use of both terrestrial and aquatic habitat. Promoting their well-being will, therefore, benefit other animals and plants of the region (M. Evelyn 2020, SCWP, personal communication).

The Sunshine Coast, to date, is free from many of the stressors affecting NRLF in other locations. Although the species seems to be currently stable, strengthening the NRLF populations on the Sunshine Coast would help secure the long-term persistence of the species by acting as a stronghold on BC's mainland. Furthermore, a thriving NRLF metapopulation indicates a healthy ecosystem with strong landscape connectivity and high habitat value for many other species (Hayes et al. 2008; COSEWIC 2015). Due to amphibians' relatively small dispersal range, SCWP want future constructed wetlands to be accessible by expanding and connecting the network of existing wetlands, thereby increasing the likelihood of colonization of new or restored wetlands (M. Evelyn 2020, SCWP, personal communication).

1.5. Project Objectives

The SCWP's wish for the likelihood of colonization of new wetlands to be maximized, providing the greatest benefits possible to NRLF, motivated the following research question:

> "Where are the most strategic locations to restore breeding habitat for the northern red-legged frog (*Rana aurora*) on the Sechelt Peninsula of the Sunshine Coast, BC, to help increase their population size and promote their resilience?"

To answer this question, my research goal and objectives were as follows:

Overarching project goal:

Promote the resilience of NRLF populations on the Sechelt Peninsula by increasing the amount of wetland habitat for NRLF, while ensuring the spatial configuration of the restored habitat is adequate and accessible to NRLF.

Research objectives:

1. Create a habitat suitability model (HSM) to describe the landscape in terms of its ease of movement for NRLF.
2. Use the HSM to analyse the functional connectivity between the wetland habitats and explore the relative effect of different potential restoration sites on the functional connectivity of wetland habitat for NRLF.
3. Provide the SCWP with a tool with which they can continuously explore future potential restoration sites.

Resiliency and redundancy are two components vital to a species' survival. Resilience is when a population has the capacity to bounce back from disturbances (Walker 1992). A resilient population must have suitable habitat that allows for proper reproductive success and gene flow within the metapopulation. Redundancy means the population is large enough to lose some individuals without affecting the metapopulation (Walker 1992). Redundancy therefore leads to greater resiliency within a species. These components will become critical when facing the challenges of climate change. Increasing the overall area of breeding habitat, as well as establishing complexity in the landscape, will provide NRLF with a variety of habitats acting as refuge throughout different climatic conditions. The best way to promote resilience to climate change is to provide a complex network of wetlands that span a range of types and hydroperiods, which will buffer the effects of varying weather patterns and permit some frogs to persist throughout extreme climatic events. Redundancy within metapopulations will also permit NRLF metapopulations to persist, in the case of severe and/or unusual climatic events (like wildfires, persistent droughts, or late frost events to name a few possibilities), in spite of losing individuals from certain ponds. The remaining individuals will contribute to rebuilding the population.

Although the SCWP's restoration efforts are focused on creating wetlands, NRLFs require both quality wetland and upland forest habitats to complete their life cycles. An adequate special configuration (or connection) of these habitats is important when considering the conservation of this species (Schuett-Hames 2004; Hayes et al. 2008). This may be vital in maintaining metapopulation dynamics by buffering against stochastic events and temporal variations in productivity, allowing different wetlands to act as population source in different environmental conditions (Maxcy 2004). Therefore, to achieve the goal of promoting the resilience of NRLF populations, we must ensure the new and restored wetlands are well connected within the greater network of wetlands by promoting landscape connectivity.

It is, however, important to note that before connecting a patch of habitat to the network, the habitat's quality and ability to support all life cycles of NLRF must be evaluated. Enhanced connectivity is generally considered beneficial. However, the opposite effect can occur where some ponds may be colonized by NRLF while in fact be acting as a population sink in their metapopulation dynamics. A wetland could potential be behaving as an ecological trap by attracting individuals to breed in habitat that cannot support the development of the offspring (D. Ransom 2020, BCIT, personal communication). This can occur when the pond dries up too early in the season, before the offspring are able to emerge from the wetland. Increased connectivity could also lead to invasions of undesirable species. Active monitoring must continue to identify whether undesirable species such as the American bullfrog or non-native fish are present. If this is not evaluated, it could open a healthy part of the landscape to harmful invasive species.

As the term “landscape connectivity” has come to be used in many different ways, for the purpose of my project, I am defining it as:

> “the degree to which the landscape facilitates or impedes movement among resource patches” (Taylor et al. 1993).

Furthermore, the majority of the landscape of interest (see section 1.6 below) is continuous (or is not fragmented by impassible barriers like highways and urban areas). Rather, it is forested landscape under different forestry tenures. Despite being non-fragmented, this does not mean it is accessible to, or suitable for, NRLF. Therefore, it is of greater value to this research to use functional connectivity as opposed to structural connectivity. Where structural connectivity only considers physical characteristics of habitat and how they are connected, functional connectivity transforms the landscape in terms of suitability to the specific animal and includes a certain degree of behavioural responses to the landscape (Taylor et al. 2006).

My research consists of a predictive model used to determine areas to prioritize wetland restoration for a maximum benefit to NRLF populations. These sites must have suitable conditions to hold a wetland but must also be accessible to NRLF populations. They should be well connected to existing wetlands, possibly even contributing to strengthening the connections between exiting wetlands. Creating more breeding habitat that is easily accessible to NRLF, and therefore are more likely to be colonized, will increase the redundancy, and consequently the resiliency, of NRLF populations on the Sunshine Coast.

The final results of this project are not only to provide a map of areas to prioritize restoration efforts, but moreover to provide a tool that can be used to explore the relative effects of different potential restoration sites being considered in terms of functional connectivity within the landscape for NRLF. The results will evolve as new wetland habitat is restored and added to the data. This predictive and dynamic model can also be refined as more data is gathered and input with each passing field season.

1.6. Study Area

The priority area for restoration has been identified by the SCWP: a 423-ha patch of forest that was severely burned by a wildfire in 2015 (Figure 1). The fire occurred approximately 6 km northwest of the town of Sechelt, on crown land leased to the Sunshine Coast Community Forest. The Sunshine Coast Community Forest have agreed for SCWP to create and enhance wetlands in this area and will leave the minimum recommended riparian boarders, regardless of the minimum size requirements for legal recognition.

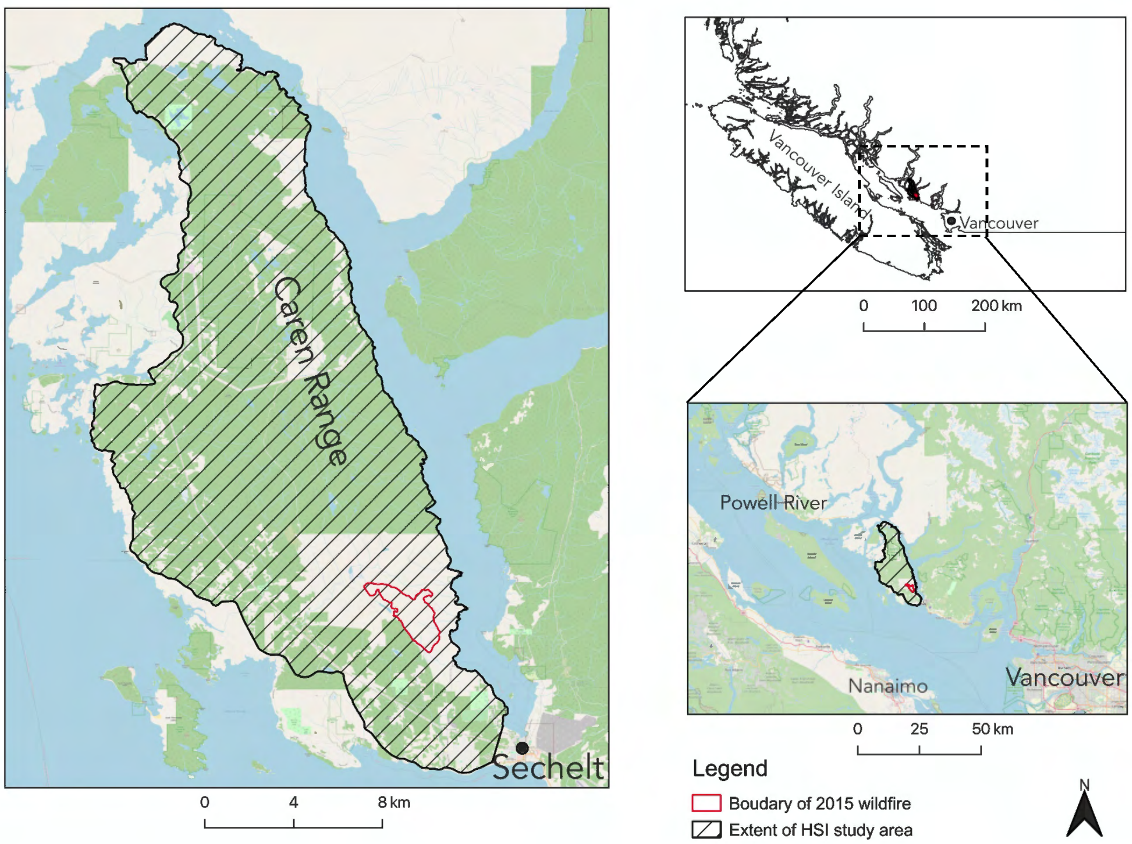


Figure 1. The study area is delineated by the hashed area which spans most of the Sechelt Penninsula, British Comlumbia. The red polygon shows the location of the 2015 wildfire identified by the SCWP as a priority restoration area. Panes on the right show general location within BC. Map made in QGIS 3.10.13 using basemap from OpenStreetMap.

As previously mentioned, NRLF populations on the Sunshine Coast are free from many of the pressures threatening NRLF populations globally. Exotic species have not yet reached the region, there has not been any chytrid fungus detected, and urban development and agricultural fields are constrained to a strip west of the Sunshine Coast Highway (Highway 101) along the shore, with most of the inshore land remaining forested. The greatest pressures on NRLF populations within the study area are logging and, in coming years, climate change (although the metapopulation level effects of climate change are still unknown; COSEWIC 2015). These forests are actively being logged and have been since the end of the 19th century (SC Museum & Archives n.d.). The site's history of logging has likely led to the homogenization of the landscape, with fewer small wetlands available for NRLF and other wetland species. Although it is impossible to precisely predict the effects of climate change on the Coast, the increasingly inconsistent weather patterns will likely cause stress to NRLF populations.

Site Description

The Sechelt Peninsula of the Sunshine Coast, BC, lies within the Pacific Northwest. It is surrounded by the Georgia Straight to the west, Earl's Cove to the north, and the Sechelt Inlet to the west. Its only tie to the Mainland is in the southeast, where the current town of Sechelt lies. The Caren Range dominates the interior of the Peninsula, with slopes mainly stretching from northwest to southeast. The highest point on the Peninsula is Caren Peak at 1,259 m asl (Caren Peak 2014).

This area lies in the Georgia Straight Lowlands. During the last glacial period, glaciers covered the entire regions (McCammon 1977). The glaciers left behind a veneer of surficial material. Regions 300m above sea level (asl) have many exposed rock outcrops or a shallow layer of till. Areas below this elevation are characterized by unconsolidated materials of glacial, glaciomarine, marine and fluvial origins. Post-glacial marine deposits reach an elevation of 180 m asl (McCammon 1977).

Being within the Pacific Northwest, the Peninsula is characterized by the heavy precipitation and mild temperatures of the coastal temperate rain forest (SCCA 2012). It lies within the Georgia Depression ecoregion and has biogeoclimatic zones ranging from Coastal Douglas Fir (CDF moist maritime (mm)) on the southwestern coast, Coastal Western Hemlock (CWH very dry maritime (xm1), dry maritime (dm), and very wet maritime (vm)) covering most of the Peninsula and becoming more wet with increasing elevation, and Mountain Hemlock (MH, moist maritime (mm)) clustered on the highest peaks of the Caren Range (SCCA 2012). This area lies in the range shadow of the mountains on Vancouver Island and causes the lower elevation and southwest slopes to be drier than the surrounding landscape, as evident by the CDFmm, CWHxm and -dm biogeoclimatic zones that only occur on the leeward side of Vancouver Island (Meidinger & Pojar 1991).

The CDF zone is the smallest in BC and created by the rain shadow of Vancouver Island and the Olympic Mountains (Meidinger & Pojar 1991). It is drier, warmer, and sunnier than the surrounding CWH zone with a mean annual temperature of 9.8° Celsius and a mean annual precipitation of 1000 mm, as opposed to the average 2200 mm received in the CWH zone (CFCG n.d.). Douglas-fir (*Pseudotsuga menziesii*) is the most commonly occurring species in this zone and are accompanied by western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), grand fir (*Abies grandis*), bigleaf maple (*Acer macrophyllum*), red alder (*Alnus rubra*), and Balsam poplar (*Populus balsamifera*) on moister sites, and Garry oak (*Quercus garryana*) and arbutus (*Arbutus menziesii*) and the drier sites (Meidinger & Pojar 1991). Most of this zone, however, occurs west of Highway 101, with only very small fragments occurring in the study area.

The CWH zone covers much of the area west of the Coast Mountains. It has a mild climate and is the rainiest zone in BC (Meidinger & Pojar 1991). Its mean annual temperature and mean annual precipitation range from 9.3° Celsius and 1420 mm in the very dry maritime (xm1) subzone to 4.8° Celsius and 3020 mm in the very wet maritime (vm) subzone (CFCG n.d.). Although western hemlock is the most common tree species in this zone, western redcedar is also very common. Other dominant species vary among subzones with Douglas-fir mainly occurring in drier subzones (e.g.: xm1) and Amabilis fir and yellowcedar (*Xanthocyparis nootkatensis*) on wetter sites (e.g.: vm) (Meidinger & Pojar 1991). The area that lies within the fire-burned patch identified as priority for restoration is of the CWH very dry and dry maritime subzones (xm1 and vm).

The MH zone occurs at high elevations, above the CWH zone (Meidinger & Pojar 1991). It covers most of the Coast Mountains, but only occurs in small patches at the highest elevations of the Caren Range within the study area. It is the coldest zone within the region with a mean annual temperature of 3.5° Celsius and heavy snowfall in the winter. Its mean annual precipitation is 3500 mm on the windward side of the Coast Mountains (CFCG n.d.). Old-growth ecosystems are common here due to the infrequent occurrence of disturbances. Mountain hemlock (*Tsuga mertensiana*) is the dominant species accompanied by western redcedar and white pine (*Pinus monticola*) (Meidinger & Pojar 1991).

2. Methods

There are two main components involved in this analysis. First, I created a habitat suitability model (HSM). The HSM was used to predict locations where NRLF are expected to be present based on biological and physical attributes of the landscape (BC MoE 2008). Second, I used Circuitscape (Circuitscape v. 4.0.5, McRae BH, Shah VB & Mohapatra TK), an open-access software grounded in circuit theory, to analyse the spatial configuration of wetland habitat in terms of functional connectivity for NRLF. The functional connectivity analysis was used to explore and compare the relative effects among different potential restoration sites. By comparing the different options, we can hypothesise which one will most efficiently increase NRLF breeding habitat and enhance connectivity within the existing network of wetlands.

2.1. Habitat Suitability Model

2.1.1. Model Description

As defined in BC's Wildlife Habitat Rating Standards:

> "a species-habitat model describes the habitat requirements of a species and the ecosystem attributes that provide these requirements" (BC MoE 1999).

The HSM is a deductive modelling approach that uses published literature and existing expert knowledge on a species' ecology to determine their distribution. The model output is a habitat suitability index (HSI) map that estimates locations NRLF could be present. It does not, however, confirm their presence (BC MoE 2008). The general species suitability index is calculated as:

(1)

$$S = \sum_{i}^{n} wC \prod_{j}^{m} r$$

Where *S* is the suitability index, *w* is the weight given to each criterion, *C* is the criterion for suitability, and *r* the restrictions. This is a weighted overlay where each layer is given a specific weight and added together to produce a final suitability index for each cell within the raster grid. The restrictions are represented by a value of 0, so that when the sum of the weighted criteria is multiplied by the product of all the restrictions, the final suitability index map retains cells where the suitability is 0. These represent complete barriers to NRLF movement.

Habitat suitability modelling is an iterative process that begins with a preliminary model that uses knowledge of the species' requirements. The model is then validated and calibrated using field observations (BC MoE 1999).The model was created in QGIS (QGIS, v.3.10.13 – A Coruña. QGIS Association.) in such a way to be able to change the input files or model parameters and re-run the model. Due to technical problems explained in Appendix C, the HSM was built as a series of sub-models with some intermediary steps required. See Appendix C for a guide to using the model with the sub-model, as well as a more in-depth guide to each step required in creating the model without using the sub-models.

2.1.2. Model Parameters

The parameters of the HSM were chosen based on features identified through my literature review of NRLF ecology and habitat requirements. The details of this literature review can be found in Appendix A. The four criteria used to create the HSM include elevation, slope (both derived from a digital elevation model (DEM); BC Data Catalogue 2012), terrestrial ecosystem mapping (TEM) data (BC Data Catalogue 2019), and the normalized difference vegetation index (NDVI) (Copernicus Sentinel 2 data 2020).

In BC, NRLF are found mainly at lower elevations. They have never been observed above 1,040 m above sea level (asl) in BC (COSEWIC 2015). Therefore, elevation was used for prioritizing lower elevations and as the upper limit of their range, with a 60 m buffer. Anything above 1,100 m was determined to be a restriction, or a barrier to their movement. NRLF are negatively correlated with increasing slope and, as such, found in greater abundance in relatively flat habitat (Adams 1999; COSEWIC 2015). While adult NRLF can move through a gentle to moderate slope, its is very energetically costly for them to travel in steep slopes. Therefore, steep slopes were deemed a restriction. The upper limit was set at 32° and was based on Adams (1999) and NRLF occurences. The TEM dataset provides general information on habitat types such as plant indicator species and soil moisture regimes. For instance, whereas sword fern (*Polystichum munitum*) generally indicates drier upper-slopes, skunk-cabbage (*Lysichiton americanus*) indicates wet swampy habitat where NRLF can often be seen (L. Riahi 2020, SCWP, personal communication; and personal observations). Finally, the NDVI is used as a proxy for vegetation cover. NDVI values ranges from -1 to 1. Negative values generally indicate bodies of water, while values ranging between 0.6 and 1 indicate dense vegetation cover. Values around 0 to 0.2 indicate barren or urban lands, and values ranging from 0.2 to 0.4 indicate sparse or unhealthy vegetation (USGS n.d.). While the NDVI can only inform the model on general vegetation cover rather than specific canopy cover, it is useful to associate a low rank to areas of the landscape matrix with little to no vegetation which are unfavourable habitat for NRLF. More specifically, it can reduce the suitability of recent cutblocks or urban areas. The NDVI was calculated from satelite imagery taken with the Sentinel 2 satelite using the following expresion:

(2)

$$NDVI = \frac{(\,NIR - Red)}{(\,NIR + Red)}$$

Where NIR refers to near-infrared (band 8) and red refers to red light (band 4). Both have a resolution of 10 m (GIS Geography 2021).

Each criterion was ranked on a four-tiered ranking scheme from 0 to 3. It describes the specific criterion's suitability for NRLF with 0 representing hostile environments or complete barriers, 1 representing a less favourable or unsuitable environment, 2 representing somewhat favourable habitat, and finally 3 representing high NRLF habitat suitability (for any life stages, not just breeding habitat). A separate raster file was created combining all the restrictions (a rank of 0). These criteria were then combined using the weighted overlay described in equation (1). Details on the specific ranks attributed to values of each criterion, the weigh attributed to each criterion, as well as the rationale for each are stated in Appendix B.

Known NRLF occurrences from iNaturalist (GBIF.org 2021) and SCWP data (SWCP unpublished data) were used to help corroborate the ranked values. The data were used to indicate presence/not detected. These data served to calibrate the restrictions where NRLF have been sighted, and therefore could not be classified as a restriction. While the priority area for restoration lies in the fire-damaged patch, due to the resolution of the data layers used to inform the HSM (see Section 2.1), all of the Sechelt Peninsula east of the highway was used to develop the HSM. This larger area was required to see more patterns between data layers used as suitability criteria and NRLF occurrence. It allowed me to better calibrate the model for greater forecast capability.

The highway was chosen as the cut-off because it acts as a barrier for NRLF movement. Large roads, like the Sunshine Coast Highway, are a source of mortality for amphibians (COSEWIC 2015). Therefore, while the occasional individual may cross the highway, I am assuming the populations on each side of the highway are isolated, in which case, only the landscape east of the highway is of interest for the purposes of this project.

The output of the HSM produces a raster file with a HSI for each cell in the raster grid. A file containing the breeding habitat patches (or focal regions) was created using all mapped lakes and wetlands. The HSI is then used in the next step to represent the ease of movement for NRLF in each grid cell and calculate the functional connectivity between the wetland patches (or focal regions). Explanations of this process are provided below (Section 2.2). Shown in Figure 2 is a simplified representation of the HSM workflow to prepare files for the connectivity analysis. For the full layout of the steps in the HSM, see Appendix B.

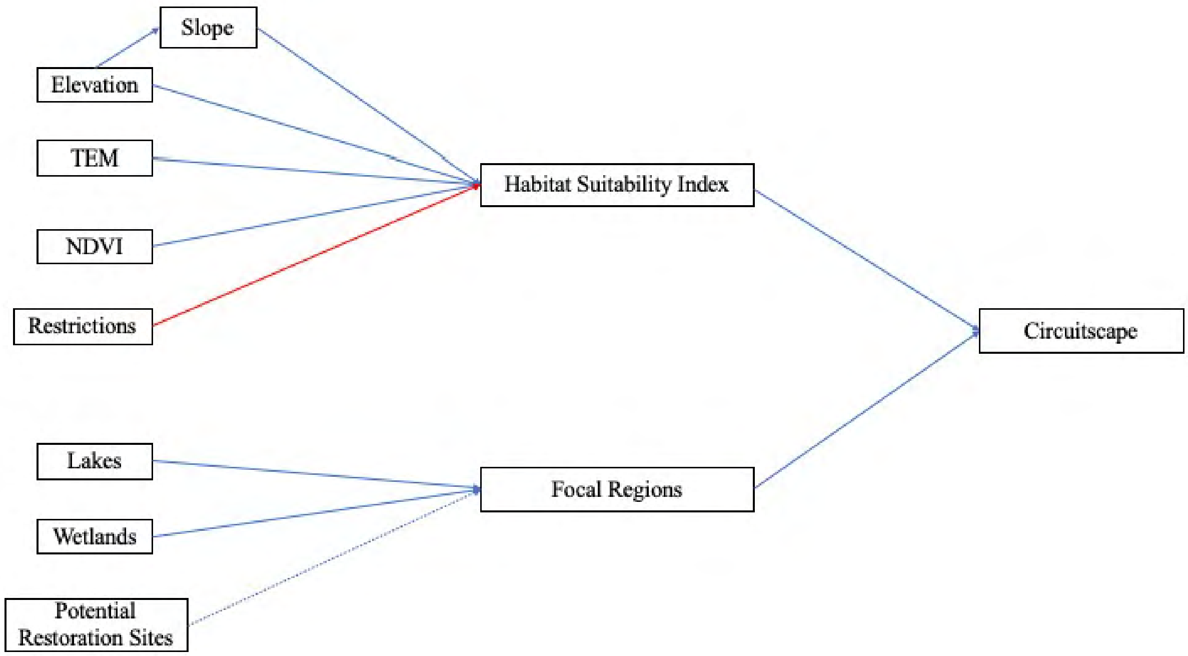


Figure 2. Simplified view of habitat suitability model (HSM) workflow showing the four criteria used to produce a habitat suitability index. This flowchart also shows the layers required to produce the focal regions file.

Map Scale

Data layers produced at a scale of 1:20,000 was used as they show specific ecosystem units and displays area in km^2. This scale allows amphibian mobility to be evaluated at the population level, and on a monthly timescale (BC MoE 1999). The SCWP is looking to create new breeding habitat, which will need to be colonized by NRLF individuals. This will occur during their spring migration while they are moving towards their breeding ponds. Therefore, 1:20,000 scale data is able to evaluate seasonal and migratory movement to and from their breeding sites (BC MoE 1999).

2.1.3. Field Surveys – *Ground Truthing*

Field surveys were conducted to validate the information described in the TEM dataset based on dominant plant species and indicator species of specific site series. However, I needed to increase the size of the study area to see more patterns better the data layers used and NRLF occurrences and calibrate the HSM (as described in Section 1.6). Therefore, the data points collected were no longer significant. There were too few data points in too small an area to meaningfully ground truth the TEM data. As a result, the HSM I created is a preliminary model and should be validated through field surveys. The data collected were nonetheless published on an online database as open access so that anyone may have access to the data for future reference (McInnis 2021a and b).

Sample Design

Using standardized methodologies is especially important when conducting wildlife inventories and ecosystem mapping because of the large temporal and spatial scales needed to get meaningful insights on long-term patterns and population trends across a species' entire distribution (BC MoE 1998a). The methods used were informed by those recommended by the BC government's Resources Inventory Standards Committee (RISC) on "Species Inventory Fundamentals" (BC MoE 1998a) and "British Columbia Wildlife Habitat Rating Standards" (BC MoE 1999). These methods were adapted based on recommendations made by Doug Ransom (2020, BCIT, personal communication).

From the TEM data, I randomly selected different sections of the study area to survey. We performed ground truthing at two levels of intensity: reconnaissance and vegetation surveys. Because my research focus is on NRLF breeding habitat, full vegetation surveys were only conducted at wetland sites. Where there were no wetlands, we conducted reconnaissance-level surveys where we scouted the general area and took photos and notes on the landscape features, such as presence of rock outcrop, site dryness, and presence of dense or sparse understory. The data were recorded in the Avenza mobile application (Avenza Maps v.3.14, Avenza Systems Inc., Toronto, ON) which records georeferenced data points, photos, and comments on a map of my study area.

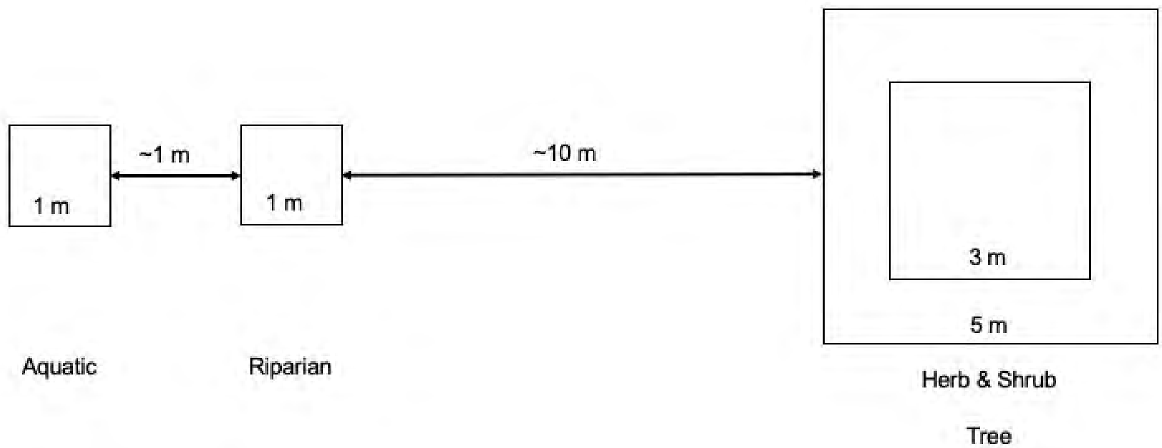


Figure 3. Approximate layout of the vegetation transects used in the field surveys.

Where wetlands were present, we conducted thorough vegetation surveys. Specific sites were selected based on accessibility by road and trail networks. We would drive as far as possible, then walk into the wetland. We conducted our 1-x1-m aquatic quadrat first, usually walking on logs to get further away from the shoreline, then walked back to the shoreline in as much of a straight line as was possible. Next, we conducted a 1-x1-m survey of the riparian vegetation. Finally, we walked approximately 10 m into the upland forests to survey a 3-x3-m quadrat of the herb and shrub layer nested within a 5-x5-m tree quadrat (Figure 3). While the size of the quadrats was constant, the distance between each quadrat varied depending on the specific terrain. We planned to conduct more systematic surveys of the wetlands' different vegetation communities, but this proved impossible due to physical barriers or dense vegetation, making many areas inaccessible. I used an overlapping percent cover scheme to estimate the presence of specific species and their relative abundance. Any areas with open water deeper than 2 m were excluded from surveys.

Considerations for COVID-19

My field assistant Leila Riahi and I both had our own respective gear and did not share or switch throughout the day. Most of the time was spent outdoors, other than while carpooling when we wore our masks. Furthermore, Leila and I were part of each other's "social bubble."

2.2. Functional Connectivity Analysis in Circuitscape

2.2.1. Model Description

The next step involved analysing the HSI map created by the HSM in the previous step (Section 2.1). This was done using Circuitscape, an open-access software based on electrical circuit theory. Circuit theory was originally developed in electrical engineering but has since been applied to many other fields (McRae 2006). When applied to landscape ecology, the landscape is displayed as a raster grid with each cell having a resistance (or a reciprocal conductance) value. A simplified representation of a landscape in terms of a grid and a circuit can be seen in Figure 4. The resistance value is attributed to the cell's suitability for the focal animal. Here, I describe the landscape in terms of its conductance given that higher values indicate greater suitability. Circuitscape then analyses how the electrical current (interpreted as an animal's movement) moves through the board and between focal regions (important habitat patches). It produces a current map that shows areas of higher conductance where the animal can move through the landscape and among habitat patches easily and, inversely, areas of greater resistance to movement (McRae et al. 2008). Henceforth, I use the terms "current" and "movement" interchangeably as the current is a measure of, or proxy for, the animal's probability of moving through any given location.

While the model may seem similar to a least-cost path (LCP) method in which the landscape is also described in terms of resistance to the animal's movement through the landscape based on a habitat suitability ranking scheme, circuit theory has two main differences from LCP that offer clear advantages for my purpose. First, circuit theory is able to evaluate the contributions of multiple pathways to the overall flow of movement in the landscape (McRae et al. 2008). Although LCP identifies movement corridors that offer the path of least resistance, it does not take into account the cumulative effects of multiple pathways connecting habitat patches. Therefore, it does not identify when a single corridor is present and possibly leading to a bottleneck, or a pinch point. In circuit theory, when the same amount of voltage is passing through multiple pathways, it is subjected to a lower overall resistance. This allows more current to effectively pass through the grid than if the same amount of electrical current is forced into a single pathway with the same resistance (McRae et al. 2008).

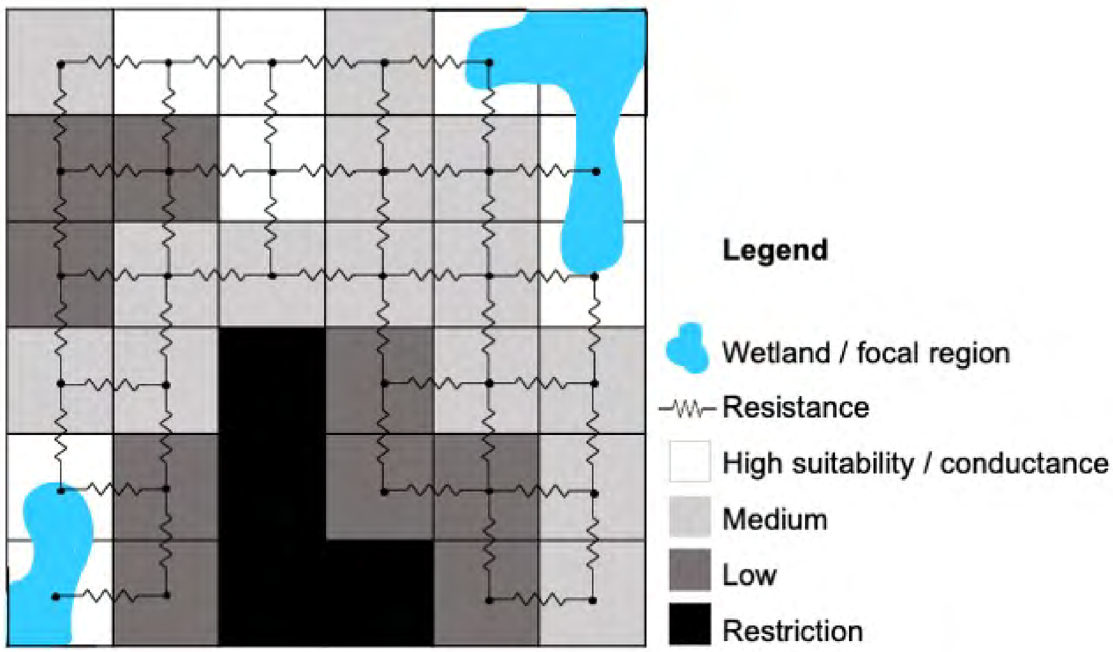


Figure 4. Simplified representation of the landscape in a raster grid with resistance values assigned to each cell. Black cell represents a complete barrier, while white cells represent high habita suitability. The flow of current it calculated between pair of focal regions, or wetlands (Image adapted from McRae et al. 2008).

Furthermore, circuit theory includes a component of random walk that, unlike LCP, does not assume the animal has previous knowledge of the landscape and can choose the path of least resistance. Random walk represents a 1% probability for each individual to stray off of the path of least resistance at each node and get “lost” while exploring the landscape. This current, or individual, is lost to the circuit board as it is not reaching a focal region and is assumed to be dead (McRae 2006). The effects of random walk are also reduced when there are multiple pathways available, because there is a greater probability of those individuals finding their way onto another pathway, which will ultimately lead them to a habitat patch (McRae et al. 2008). While LCP can be suitable for established migration routes where it is assumed the animal knows where that path of least resistance is connecting different usable habitat, circuit theory includes this element of randomness which represents a more exploratory behaviour from the animal, which is especially suitable for the dispersal of individuals to new habitat (McRae 2006).

By combining the cumulative effects of multiple pathways and of random walk, circuit theory includes a notion of redundancy (McRae et al. 2008) which, in ecological terms, is important for the resilience of a species, as stated in the introduction. Where there are more pathways, there is a higher probability of reaching the different habitat patches. It also means that if a disturbance occurs in one or some of these pathways, the animal still has many other options to reach the desired habitat.

Given the study area is forested and provides multiple pathways between breeding ponds, this is a vital component in analysing the connectivity in different regions of the landscape. When all else is equal, ponds with greater accessibility through more pathways are more likely to be colonized than an equivalent pond with fewer routes and access points. Furthermore, the component of random walk is a more realistic representation of individuals dispersing to new habitat, as is the ultimate goal of this project to promote the colonization of new wetland habitat. Circuit theory is therefore a better fit for my purpose as the SCWP will be creating new wetland habitat that is unknown to individuals and will need to be colonized by young NRLF unfamiliar with the landscape. In this sense, I am exploring the dispersal of NRLF to new breeding ponds, rather than a seasonal, recurring migration.

2.2.2. Model Parameters

The model inputs are two raster files: 1) the HSI produced by the HSM with resistance or conductance values attributed to each cell, and 2) a file with focal regions. The focal regions used were all lakes and wetlands (see Section 4.2. for further details on the selection of the focal regions).

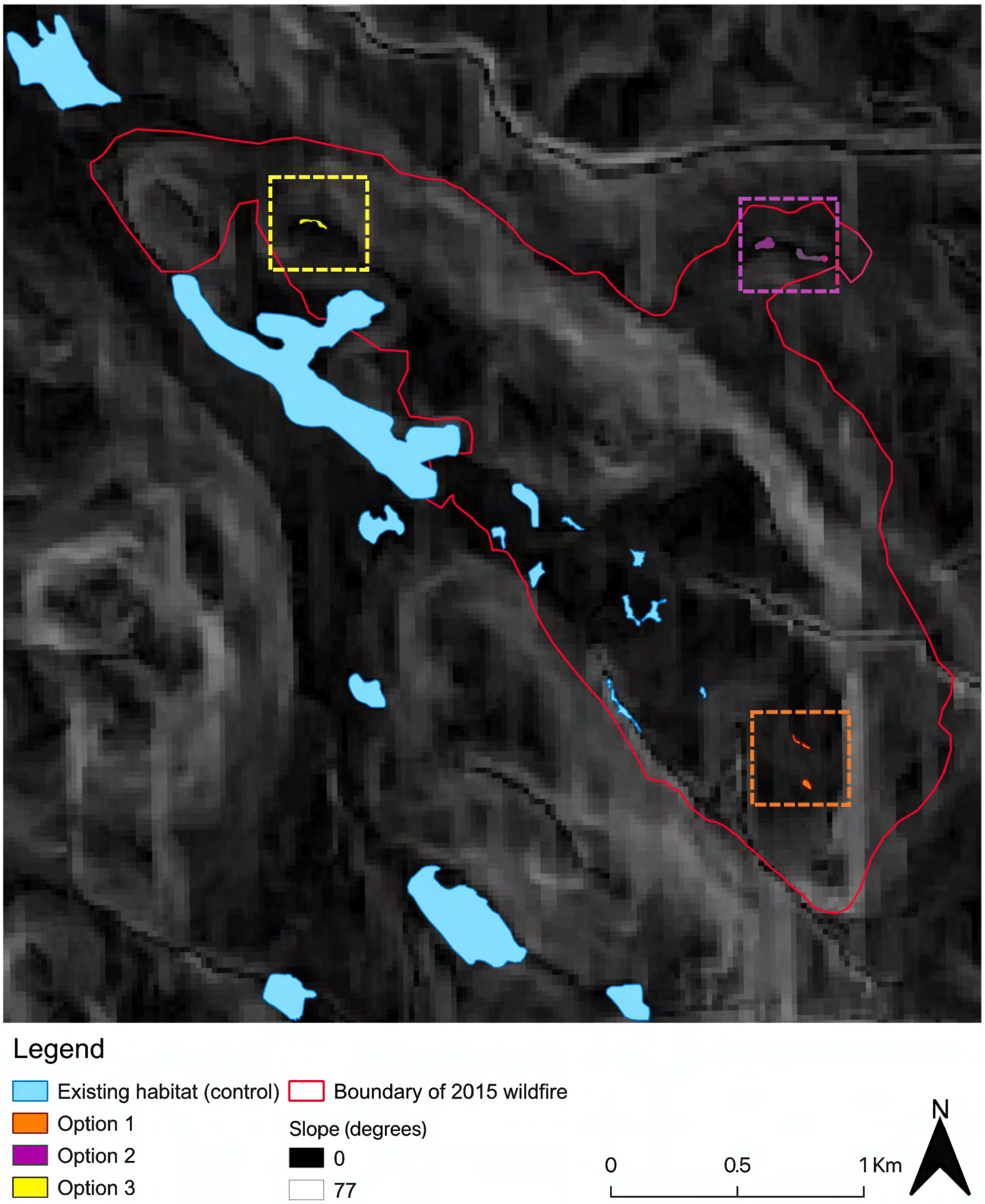
The ranking scheme I used for the HSI attributes higher values to greater suitability, in other words greater conductance. I therefore set the software's parameters to view the HSI raster in terms of conductance values. The software has multiple modes for analysing the connectivity between focal regions. For this project, I used the "pairwise" mode which evaluates the electrical conductance between each pair of focal regions. For *n* focal regions, a total of n(n-1)/2 calculations are conducted (McRae & Shah 2011). The model calculates the respective flow of the electrical current connecting these habitat patches for each grid cell. Each cell is connected to its second order neighbours, or the eight surrounding cells, to analyse the flow of current between them. The output is a raster file of a current map which can be read in QGIS or ArcMap.

The connectivity analysis was done using the Circuitscape for ArcGIS tool within the ArcMap GIS environment (ArcGIS Desktop, version 10.8.1, ESRI, Redlands, CA, USA) to works around technical problems explained in Appendix C. Due to the high computational requirements to run a Circuitscape analysis, I decided to only analyse the southern half of the Sechelt Peninsula, which included the fire-burned patch, as well as a large buffer area. The fire-burned patch is bounded by natural and anthropogenic barriers on three sides: the inlet to the east, the town of Sechelt to the south, and the highway to the west. A buffer of just over 5 km was left to the north of the patch to consider the possible immigration of NRLF. They commonly travel 1.5 km to and from breeding and foraging sites but have been found as far as 4.8 km from breeding sites (Schuett-Hames 2004). The large buffer was also necessary as Circuitscape produces an edge effect where the border of the current map underestimates the current passing through because it does not see the focal regions outside the range. This region alone requires approximately 17 hours to run.

Once the initial map of connectivity is produced showing the current state of the landscape, trials can be run with the different potential wetland restoration sites to see how this influences the overall landscape connectivity. I ran connectivity analyses on four different analyses (Figure 5):

Control: The first analysis represents the landscape in its existing state and acts as a control on which to compare the other options of potential restoration sites.
Option 1: The first option includes a complex of three small wetlands in the south-eastern part of the fire-burned patch. The three patches amount to an area of 1,743 m^2.
Option 2: The second includes two patches in the north-east of the fire-burned patch. These two patches are 3,760 m^2.
Option 3: The third option contains one larger patch in the north-west of the fire-burned patch. This single patch is 1,687 m^2.

The wetlands in option 1 represent sites currently under assessment for restoration in the fall of 2021. Options 2 and 3 are hypothetical. I created patches where a topographic depression exists and could potentially hold water, as seen by the slope derived from the DEMs. However, we have not been there in person to assess the landscape for actual potential restoration sites. This is purely for the exercise of



comparing the relative effects to the functional connectivity and potential benefit of different options in Circuitscape.

Figure 5. This map shows the locations of the three restoration sites analysed for their relative effects on the functional connectivity for NRLF. Focal regions (or habitat patches) are overlain on a map of the slope (in degrees) which has a resolution of 10 m.

3. Results

Habitat Suitability Model

The HSM produced the map shown below (Figure 6). Each cell is 10x10 m and has an index value ranging from 0 to 3. The grey scale indicates the different suitability values, with white and lighter grey areas representing areas of high suitability, and conversely, dark grey areas indicating low suitability.

The HSI map indicates that a majority of the modeled area offers intermediary suitability for NRLF. Subsequently, a minority of places have the greatest suitability or are unsuitable and represent a barrier to their movement. The long, parallel black regions running north-south in the northern half of the Peninsula are caused by the steep slopes of the Caren Range. The other, more contiguous large-patched restrictions at the center of the map represent areas greater than 1,100 m asl. The southern half of the Peninsula has substantially less restrictive areas. There are some restrictions caused by slope, but this area is generally less steep than the northern reaches of the Peninsula. Locations in white, with the greatest suitability, are mainly where lakes and wetlands are present. The area within the fire-burned patch has generally lower suitability due to the lack of canopy. This will, however, change in time as the forest recovers from the wildfire and subsequent salvage lumber harvest.

Functional Connectivity Analysis

An overview of the current map was produced by overlaying the focal regions and the HSI conductance map in Circuitscape (Figure 7). Areas in red represent regions with high electrical current, with a maximum of 13 amperes moving through a cell, while areas in green represent lower current. The amount of current flowing through the landscape is analogous to the probability of an individual to move through the corresponding raster cell (McRae et al. 2008). The darkest shade of green show areas with no current (0 amperes) and represent the same restrictions, or NRLF movement barriers, displayed in the HSI map. The dark green area at the southern-most part of the study region also has no current passing through the landscape in spite of there being no explicit movement barriers. This is where the urban and suburban reaches of the municipality of Sechelt extend and there are no focal regions to “attract” the current.

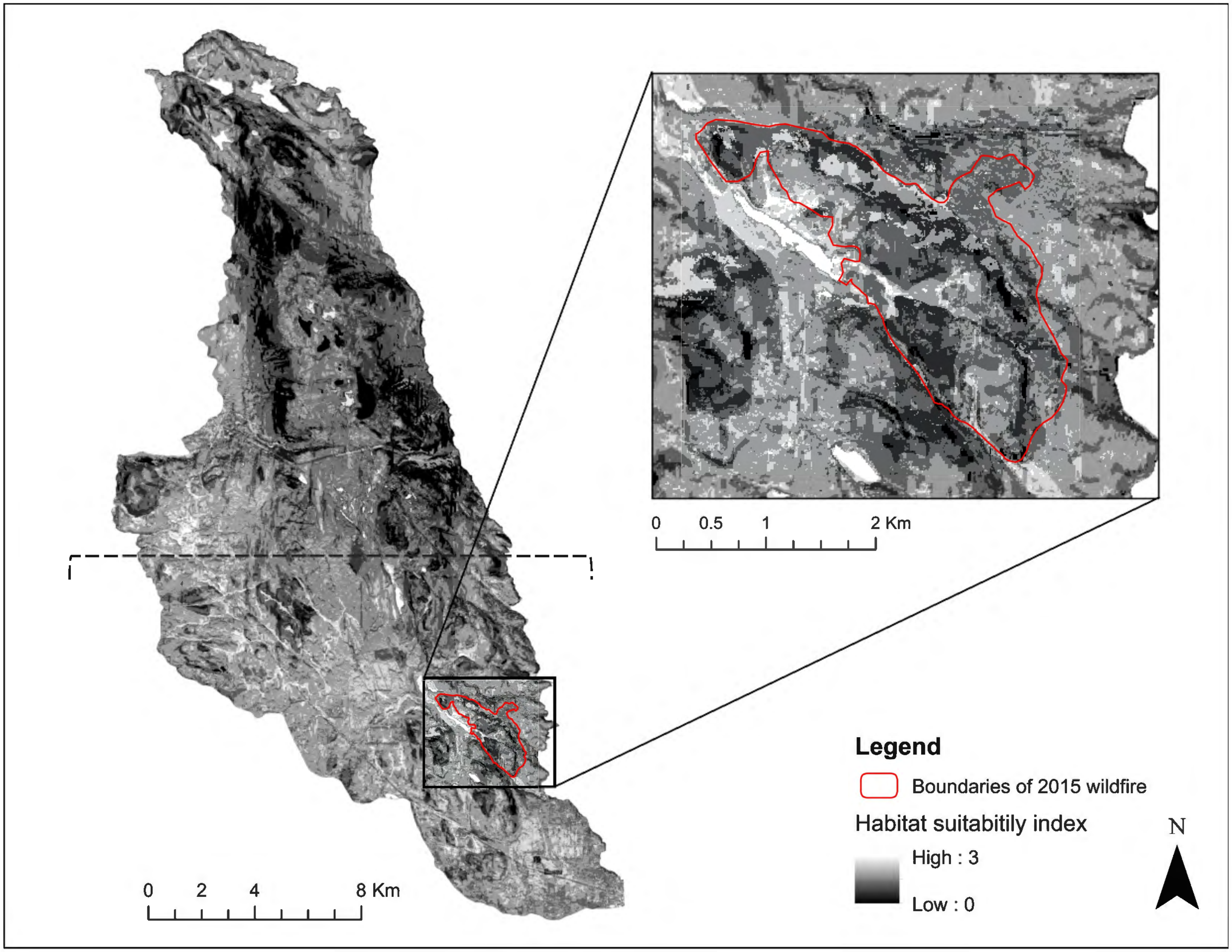


Figure 6. HSI map produced by the HSM. White and light grey show areas of greater suitability, while black areas show inhospitable areas that are treated as complete barriers to NRLF movement. Inset shows an enlarged view of the priority area that was burnt in 2015 by a wildfire, outlined in red. The dashed line shows the cutt-off used for the connectivity analysis. Map made in ArcMap v.10.8.1.

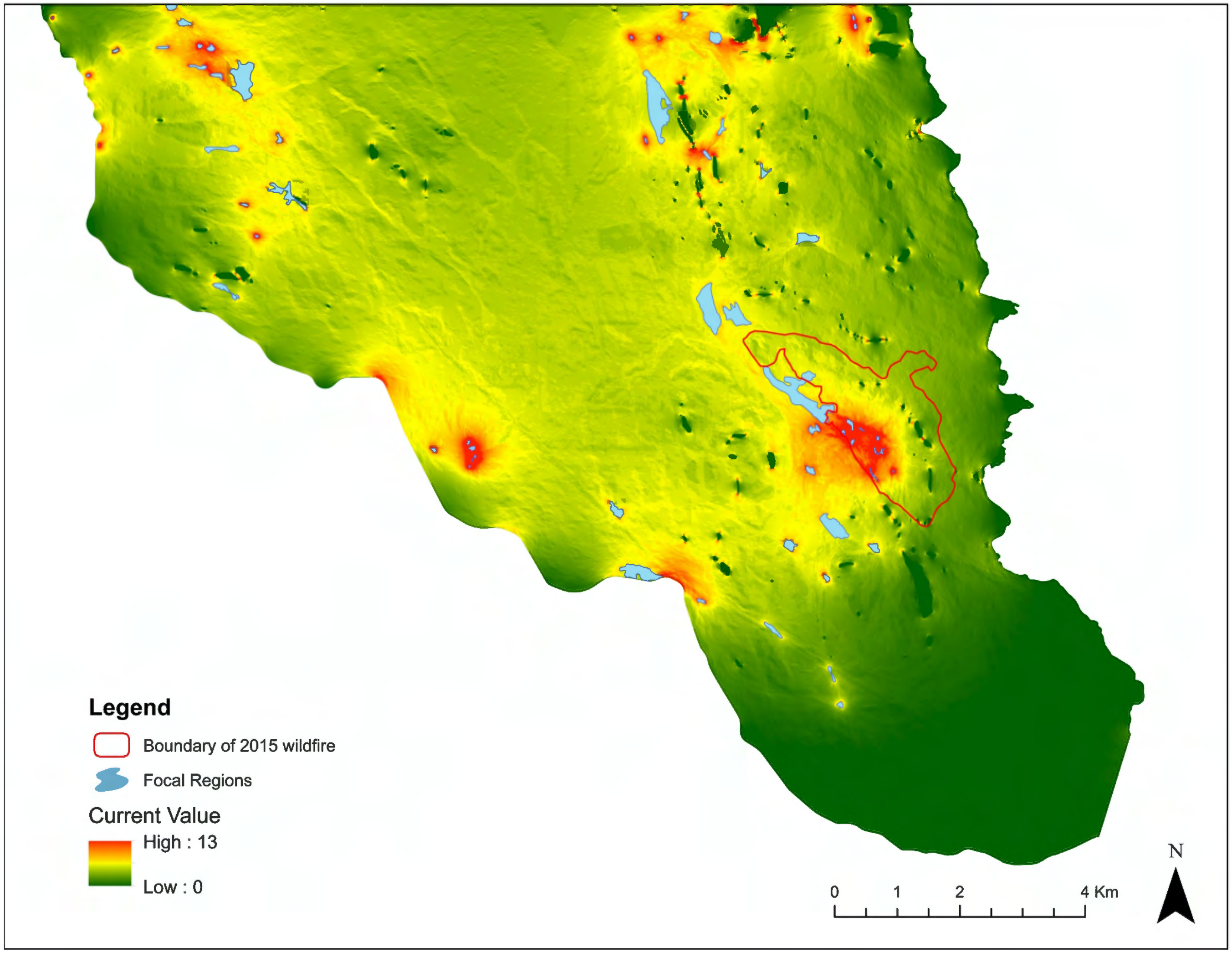


Figure 7. This is the current map produced with Circuitscape for the southern half of the Sechelt Peninsula. The wetlands and lakes are shown as the wetland and lake focal regions and displayed by blue polygons. The fire-burned patch is outlined with a red line. Values range from dark green to red, or 0 to 13 amperes respectively. The dark green represents areas with no current flowing through these cells. Red represents areas of high electrical current, or in other words, high functional connectivity and probability of NRLF moving through the region. Hotspots of high electrical current occur where there are clusters of many small focal regions.

There is a vast area within the landscape in the middle of the study area where no focal regions area present, but there is still a range of low to intermediate values (light green and yellowish green). The presence of focal regions on both the west and eastern sides of this region create some flow of movement in this center area as it moves from one side to the other. Areas of high current (red) are concentrated around locations with focal regions. The size and intensity of these high current areas increase and form “hotspots” where there are many small focal regions as opposed to a single large patch like, say, a lake. Small red areas appear on the sides of some restrictions (i.e.: dark green patches). This occurs where the current is forced to flow through a small area, or in other words, the frogs are forced to move around the movement barriers and direct and concentrates their movement on either side of the restriction.

A map was created displaying a close-up on the priority-restoration area of the four connectivity analyses for better comparison (Figure 8). The first (Figure 8a) is the same as the previous map and shows a cluster of high current in the center where many small focal regions already exist. This area is bordered by barriers to the east due to steep slopes. The addition of the three small focal regions in option 1 (Figure 8b) creates a bright red patch of high electrical current. It also increases the flow of current in the south-eastern region of the existing network of wetlands by creating a region of high current between the focal regions. Option 2 (Figure 8c) shows a small area of high current surrounding the new focal regions as well as slightly increasing the flow of current in the overall surrounding area seen as a yellow ring around the patch. The patches in option 2 do not lead to a greater increase in current than options 1 and 3 despite being substantially larger (3,760 m^2 versus 1,743 and 1,687 m^2 respectively). Option 3 (Figure 8d) shows the single added patch is surrounded by a thin band of high current. Option 3 creates a slightly stronger flow of current between the two large existing focal regions as shown by a larger diffused ring of orange around the patch and an increase from yellowish green to pure yellow linking this patch to the wetland above it.

When comparing the three potential restoration sites, option 1 has the greatest overall increase in current (or probability of movement), and options 2 and 3 have a relatively similar current values flowing directly around the habitat patches. Option 1 is also the most highly connected to the existing network of wetlands, followed by option 3 which does somewhat increase the flow of movement between the two large focal regions in the northeast corner. Option 2 is the most isolated of the potential restoration sites analysed.

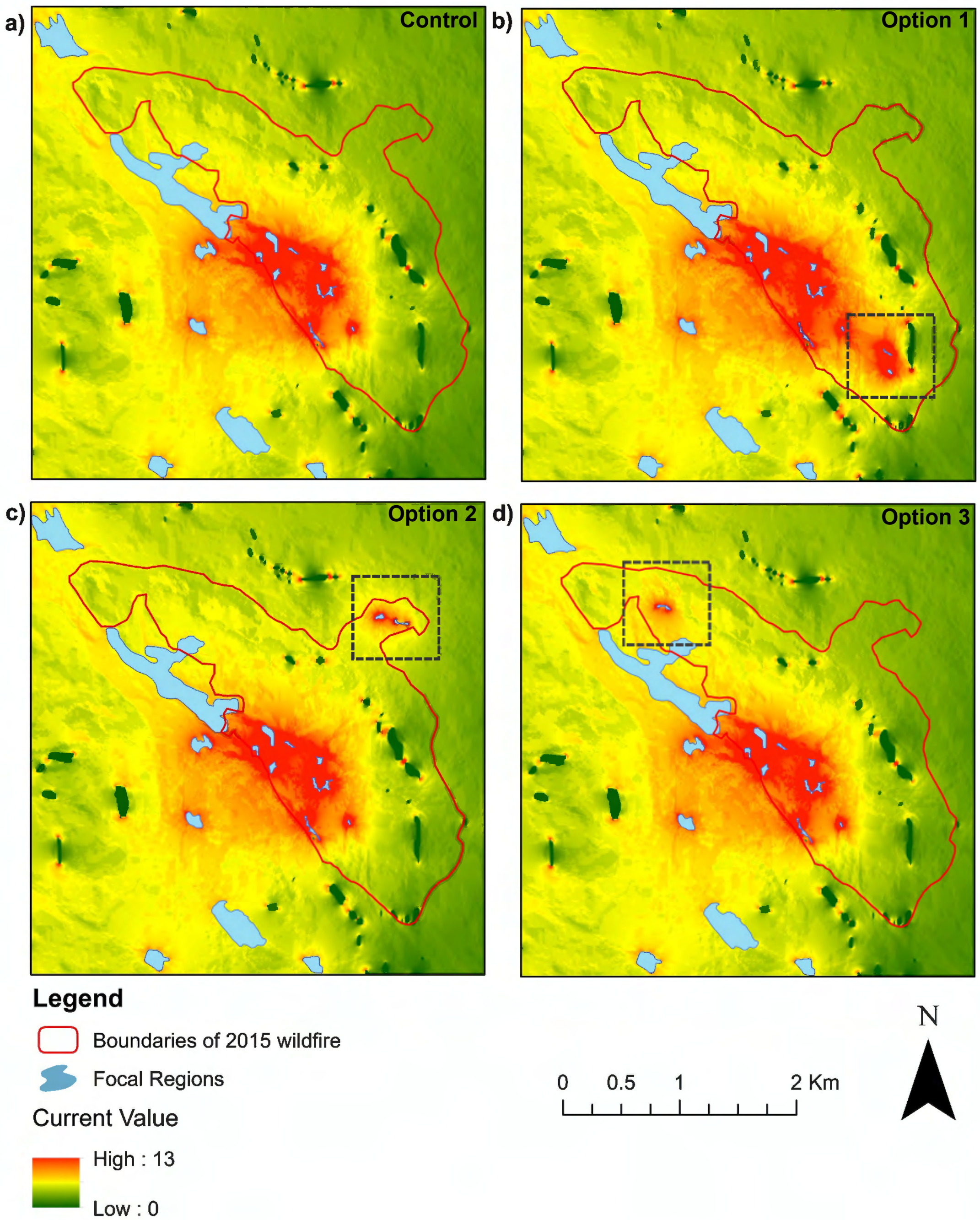


Figure 8. The current maps above show the four different options analysed in Circuitscape. The existing focal regions in a) shows the landscape in its current form and serves as a control from which to compare the other options of potential restoration sites. The box in b) through d) show the area where the focal regions (i.e.: potential restoration sites) have been added. Option 1 (b) shows a new hotspot created by the addition of three small wetlands in the south-east corner. Option 2 (c) shows another situation in which two small patches are added in the north-east of the fire-burned patch. Option 3 (d) shows the last hypothetical situation where a single larger focal region is added to the north-west of the fire-burned patch.

4. Discussion

4.1. Implications for NRLF

From the current maps (Figure 8), we can see that the greatest amount of current is concentrated in an area near the middle of the fire-burned patch. This hotspot is created by multiple interacting factors. Many little wetlands (focal regions) occur in this area, which implies a greater number of individuals and, therefore, a greater probability of current passing through this area. By comparing this area with the same area on the HSI map (Figure 6), we see that this area overlaps with a pocket of lower habitat suitability, surrounded by an area of higher suitability. The greater probability of movement in this area, produced by the greater number of focal regions, interacts with the higher resistance (low suitability index) to funnel that movement (i.e.: current) into the hotspot

Of the three potential restoration options presented (Figure 8 b-d), the sites analyzed in option 1 (Figure 8 b) show the greatest overall increase in movement. We can therefore predict that this will have the most impact on increasing NRLF functional connectivity. These sites are not contributing to the connection of other wetland habitat through the addition of steppingstones as the area is bounded by movement barriers (i.e.: steep slopes) on the east and there are no focal regions on the other side of these barriers. However, the high probability of movement shows that the created wetlands would be highly accessible to NRLF, meaning it is probable they will be colonized. These sites could effectively serve to increase their usable habitat and provide the population with a greater capacity to buffer against disturbances. The fact that these sites will not connect other wetlands to the network of existing NRLF wetland habitat also means we are not opening the current network of wetlands to the possible invasion of undesirable wetland species, such as the invasive American bullfrogs.

From the functional connectivity analysis, I hypothesize that options 2 and 3 (Figures 8 c) and d) respectively) may not provide as much benefit to NRLF populations relative to option 1. While they show strong current directly around the focal regions and are connected to the rest of the network of lakes and wetlands by regions of yellow, or intermediate current values, the overall increase in current does not equate that of option 1. Option 2 is furthest from any existing focal regions and does not serve to connect any other focal regions further in the landscape either. Option 3, on the other hand, does somewhat help strengthen the connection between the two larger focal regions by increasing the probability of individuals moving from both focal regions to this new site.

The research presented predicts that the sites considered for restoration shown in option 1 are in a suitable location to be accessible by NRLF and to effectively increase the total area of their breeding habitat. Adding new breeding habitat to the existing network of wetlands will promote the increase of NRLF population sizes as well as increase the redundancy in their habitat, which will in turn increase their resiliency to disturbances and climate variability. While the increase in electrical current at this patch and its surroundings is not as great as in option 1, option 3 would be the next best choice for wetland restoration as it could help strengthen the connections between the two larger patches (a lake and a wetland).

It should be stressed that this is a predictive exercise that can help identify general areas to focus restoration efforts. It compares the relative effects among different potential restoration sites on landscape connectivity and the overall breeding habitat accessible to NRLF. Specific sites will still need to be evaluated and confirmed in the field. Furthermore, the predictive power of this tool can be refined in time as more data is gathered and added to the model inputs.

4.2. Model Limitations

As with most modelling experiments, there is significant uncertainty in the results and associated interpretation reported here. The uncertainties within different parts of the analysis are explained below.

Uncertainties within the HSM

The connectivity analysis is based on the HSM, meaning that the greatest source of uncertainty lies within the HSM. Any uncertainty and errors from the HSM are carried into the connectivity analysis. There are certain data layers used as criteria for suitability in the HSM, such as the TEM data, that have greater uncertainties associated with them.

The TEM layer has greater uncertainty associated with it than other layer as these are general classifications of the ecosystems. It does not reflect the detailed variation within these polygons or the presence of microhabitat that could be suitable (or not) for NRLF. These surveys were conducted in 2008 and 2009 and may have changed some over the past decade, especially after a severe disturbance such as a wildfire or a clearcut. Furthermore, certain areas within this layer were not surveyed, mainly because they are within protected areas or urban/suburban areas. These were attributed an intermediate suitability rank (2) as an average, but likely contains habitat that ranges in suitability from 1 to 3. While there is a high level of uncertainty associated with these areas, none of these areas occur within the fire-burned area or the surrounding areas presented in Figure 7.

The slope and elevation layers are more reliable as they reflect physical aspects of the landscape that do not change appreciably over human time scales. The literature is also more specific as to which range of values NRLF occur. For the final layer, the NDVI can be derived from very recent satellite imagery and as such, is a good reflection of the current vegetation cover. However, it does not reflect differences in structural stages within the range of values from 0.6 to 1 (reflecting a total vegetation cover). For instance, it does not discriminate between a tree canopy or dense shrublands. This is relevant as NRLF have a higher preference for a closed tree canopy than shrublands which are much more difficult for them to travel through.

Field surveys should be conducted to both to confirm (or refute) the HSM's prediction on habitat suitability and to further our general understanding of NRLF distribution and habitat preferences. A targeted monitoring framework can be especially effective and efficient at gaining the desired information specific to NRLF occurrence (Nichols & Williams 2006). As more data is gathered by the SCWP on specific occurrence of NRLF on the Sunshine Coast, this uncertainty will be reduced.

Interpretations of the Connectivity Analysis

A careful interpretation of the functional connectivity analysis of potential wetland restoration sites is required to gain the desired insight (Circuitscape 2021). The relative current in a specific location does not only reflect the ease of movement, but also the amount of current passing through that location, which speaks to both the assumed population size (or the concentration of focal regions within a region) and the conductivity of cells in the surrounding landscape. Therefore, an area of high current can mean high functional connectivity, a greater population size resulting from the high number of focal sites, surrounding barriers causing the current to concentrate in a specific area, or a combination of these three factors.

Intermediate shades of light green and yellowish green can indicate areas where the matrix is relatively favourable and easy to move through and therefore the current is not concentrated into specific regions, or where no focal regions exist in that specific area but are surrounded by focal regions on either side. Despite the lack of lakes and wetlands in the central reaches of the study area (vast central area in light green in Figure 7), NRLF can be travelling through this area to be accessing different lakes and wetlands on either side.

Conversely, an area with no current (dark green areas in Figures 7 and 8) can either mean there is a total barrier to NRLF movement, or that no focal regions exist past that specific area and there is therefore no reason for NRLF to move through this area, such is the case when entering the municipality of Sechelt. It is important to note that areas with darker shades of green do not necessarily mean that it is impossible for NRLF to occur here, but rather that it is very unlikely to be so. Keeping in mind the goal of the research is to identify the best possible locations to restore wetland sites that are highly accessible to NRLF for colonization, serving to increase the overall breeding habitat and functional connectivity of the landscape. We seek locations with the highest probability of occurrence. It is therefore acceptable to exclude some locations where NRLF may stray to, but with low probability or frequency of occurrence.

Although the different current values indicate specific attributes within the landscape and is carefully interpreted to understand the underlying cause, the nature of interpretation inherently subjective and should be treated as a guide rather than an absolute truth.

Sampling efforts

Because the area around the hotspot of existing wetlands (Figure 7 and 8a) has had greater efforts invested in mapping wetlands in prospect of creating new habitat here, I suspect this area has been over-estimated in relation to the surrounding landscape, meaning the ratio of current concentrated in this area relative to the surrounding landscape is higher in the results than they are in reality. However, wetland habitat has already been restored by the SCWP in this same area, contributing to the increased amount of current flowing through this area relative to the surrounding landscape.

Furthermore, all wetland and lake patches were used for the focal regions in the connectivity analysis. Not all of these patches have been surveyed for presence of NRLF egg masses. I made this assumption based on their proximity to known NRLF occurrence. However, surveys should be conducted at sites where NRLF have not previously been confirmed. The focal regions file must then be updated to produce a current map with greater confidence.

4.3. Future Research

The HSM is created in such a way that one can update the input files and re-run the HSM by following the step-by-step guide presented in Appendix C. The new HSI results and/or a new version of the focal regions can be used in Circuitscape to update results of the current map. A detailed guide of every model step, the tools used, ranking scheme and the rational for each are described in Appendices B and C. Therefore, anyone wanting to use or adapt the model in the future will have all the steps required to facilitate this process.

When running the model in the future, it will be important to update some of the layers to represent the evolving landscape. Notably, a recent version of Sentinel 2 satellite imagery should be retrieved to calculate the NDVI as the vegetation cover and cutblocks will surely have changed. Furthermore, once breeding habitat is created, these new habitat patches should be added to the focal region raster file. Similarly, if any habitat patch currently included in the “focal regions” file is found to not have NRLF present, it should be removed from the file. Circuitscape can then be run with the updated files to see how the landscape has evolved (in the perspective of NRLF) and where subsequent restorations efforts should be focused. It would also be interesting to test the effects of different wetland size, shape, number, and configuration. For example, how might multiple small wetlands versus one large one of the same total area affect the overall connectivity of the landscape?

It would be greatly beneficial to continue wetland-mapping efforts to gain a better knowledge and understanding of the landscape. This is of particular importance for smaller wetlands which are important breeding habitat for amphibians but are not legally recognized (Maxcy 2004) and therefore also not included in government-sponsored wetland mapping efforts. This will also help reduce the bias in the Circuitscape analysis around the fire-burned patch where more wetland mapping has already been conducted relative to the surrounding landscape.

Finally, more amphibian surveys should be conducted in new regions to advance our knowledge of NRLF occurrence, and which specific wetlands are colonized and used as breeding habitat. It would be beneficial to conduct surveys of relative abundance and habitat features at specific wetlands where NRLF presence is confirmed to advance our understanding of specific features preferred by NRLF which can then be included and focused on in restoration projects.

4.4. Concluding Thoughts

The final maps serve as a guideline of general areas for the SCWP to focus their efforts on. The HSI shows the relative suitability for NRLF of each 10 x 10 m cell in the landscape, while the current map of functional connectivity predicts areas where NRLF movement is concentrated. The model offers the possibility to test the relative effects of different potential restoration sites to better understand which may have the greatest positive effects on NRLF populations by increasing available breeding habitat and redundancy within the population.

From the results, I predict that the 2021 restoration site represented in option 1 would provide the greatest impact on NRLF populations by providing breeding ponds in an area that would be highly accessible to the current NRLF populations. If the restored wetlands have the right biophysical conditions, it is highly likely that it will be colonized by NRLF. These wetlands are also in a region that is surrounded by steep slopes and no other wetlands, which reduces the possibility of invading species like the bullfrog and the green frog.

Despite the limitations of the model, it provides an enhanced understanding of how the creation and enhancement of new wetland habitat affects the functional connectivity for NRLF. Moving forward, the SWCP can continue to use the model to explore the relative effects of different potential wetland sites being assessed for restoration. They can also track the evolution of the expanse and connectivity within the landscape for NRLF breeding habitat by updating the model as they restore new habitat and gain more information on NRLF occurrence.

References

Abney CR, Blazer SW, Dueckman A, Baylis A, Clements DR (2019) Early Spring and Early Vanishing Wetlands as Harbingers of the Future? The Climate Change Trap for Ephemeral Pond-Breeding Frogs. Northwest Science 93:52

Adams MJ (1999) Correlated Factors in Amphibian Decline: Exotic Species and Habitat Change in Western Washington. The Journal of Wildlife Management 63:1162

Adams MJ (2000) Pond Permanence and the Effects of Exotic Vertebrates on Anurans. Ecological Applications 10:10

Adams MJ, Pearl CA (2007) Problems and opportunities managing invasive Bullfrogs: is there any hope? In: Biological invaders in inland waters: Profiles, distribution, and threats. Gherardi, F, editor. Invading Nature - Springer Series In Invasion Ecology Vol. 2 Springer Netherlands, Dordrecht pp. 679–693

Adams MJ, Pearl CA, Glavan S, McCreary B (2011) Non-native species impacts on pond occupancy by an anuran: Anuran Occupancy Changes. The Journal of Wildlife Management 75:30–35

Adamus PR (2014) Effects of forest roads and tree removal in or near wetlands of the Pacific Northwest: a literature synthesis (Report no. CMER 12-1202). Washington State Forest Practices Adaptive Management Program. Washington Department of Natural Resources, Olympia, WA

Aubry KB (2000) Amphibians in Managed, Second-Growth Douglas-Fir Forests. The Journal of Wildlife Management 64:1041

BC Ministry of Environment, Lands, and Parks - Resource Inventory Branch (BC MoE) (1998a) Species inventory fundamentals. Resources Inventory Committee, Victoria, B.C.

BC Ministry of Environment, Lands, and Parks - Resource Inventory Branch (BC MoE) (1998b) Inventory methods for pond-breeding amphibians and painted turtle. Resources Inventory Committee, Victoria, B.C.

BC Ministry of Environment, Lands, and Parks - Resource Inventory Branch (BC MoE) (1999) British Columbia wildlife habitat rating standards. Resources Inventory Committee, Victoria, B.C.

BC Ministry of Environment - Ecosystems Branch (BC MoE) (2008) Digital data standards for species distribution modeling. Resources Information Standards Committee, Victoria, B.C.

Brown CJ, Saunders MI, Possingham HP, Richardson AJ (2013) Managing for Interactions between Local and Global Stressors of Ecosystems Dupont, S, editor. PLoS ONE 8:e65765

Brown DJ, Street GM, Nairn RW, Forstner RJ (2012) A Place to Call Home: Amphibian Use of Created and Restored Wetlands. International Journal of Ecology 2012:1–11

Bunnell C, Bunnell F, Baylis A, Juteau C (2016) Long-Term Monitoring of Northern Reg-Legged Frog (Rana aurora aurora) in the Little Cambell River Watershed – 2009-2014. A Rocha Conservation Science Series. A Rocha Canada, Surrey, BC, Canada.

Caren Peak (2014) 49°38,31.00"N and 123°53'29.05"W. Google Earth Pro (accessed 26 April 2021)

Center for Forest Conservation Genetics (CFCG) (n.d.) Subzone/variant climate data. The University of British Columbia (Vancouver, BC). https://cfcg.forestry.ubc.ca/resources/cataloguing-in-situ-genetic-resources/subzonevariant-climate-data/#CWH (accessed 24 April 2021)

Chan-McLeod ACA (2003) Factors Affecting the Permeability of Clearcuts to Red-Legged Frogs. The Journal of Wildlife Management 67:663

Chan-Mcleod ACA, Moy A (2007) Evaluating Residual Tree Patches as Stepping Stones and Short-Term Refugia for Red-Legged Frogs. Journal of Wildlife Management 71:1836–1844

Circuitscape (2021) About: Circuitscape. https://circuitscape.org/about/ (accessed 5 April 2021)

Copernicus Sentinel 2 data (2020) USGS Earth Explorer, processed by ESA. https://earthexplorer.usgs.gov/ (accessed 5 April 2021)

COSEWIC (2015) COSEWIC assessment and status report on the northern red-legged frog, Rana aurora, in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa

Decout S, Manel, Miaud C, Luque S (2010) Connectivity loss in human dominated landscape: operational tools for the identification of suitable habitat patches and corridors on amphibian's population. In: Forest Landscapes and Global Change. Bragança, Portugal. pp. 661-666

Digital Elevation Model (DEM) [raster] (2012) BC Data Catalogue. Victoria, BC. https://pub.data.gov.bc.ca/datasets/175624/ (accessed 5 April 2021)

Environment and Climate Change Canada (Env. & C.C. Canada) (2017) Management plan for the northern red-legged frog (Rana aurora) in Canada. Environment and Climate Change Canada, Ottawa

Fisher MC, Garner TWJ (2020) Chytrid fungi and global amphibian declines. Nature Reviews Microbiology 18:332–343

Forest Range and Practices Act: Forest Planning and Practices Regulation (2004) BC Reg 14/2004. https://canlii.ca/t/551gd (accessed 25 April 2021)

Garner TWJ, Perkins MW, Govindarajulu P, Seglie D, Walker S, Cunningham AA, Fischer MC (2006) The emerging amphibian pathogen *Batrachochytrium dendrobatidis* globally infects introduced populations of the North American bullfrog, *Rana catesbeiana*. Biology Letters 2:455–459

GBIF.org (2021) GBIF Occurrence Download 29 March 2021. https://doi.org/10.15468/dl.pnqvqu (accessed 3 April 2021)

Gerick AA, Munshaw RG, Palen WJ, Combes SA, O'Regan SM (2014) Thermal physiology and species distribution models reveal climate vulnerability of temperate amphibians Ladle, R, editor. Journal of Biogeography 41:713–723

GIS Geography (2021) Sentinel 2 Bands Combinations: GIS Geography. https://gisgeography.com/sentinel-2-bands-combinations/ (accessed 4 April 2021)

Govindarajulu P, Nelson C, LeBlanc J, Hintz W, Schwantje H (2013) Batrachochytrium dendrobatidis surveillance in British Columbia, Canada. BC Ministry of Environment

Grand LA, Hayes MP, Vogt KA, Vogt DJ, Yarnold PR, Ritcher KO, Anderson CD, Ostergaard EC, Wilhelm JO (2017) Identification of habitat controls on northern red-legged frog populations: implications for habitat conservation on an urbanizing landscape in the Pacific Northwest. Ecological Processes 6:44

Green RN, Klinka K (1994) A Field Guide to Site Identification and Interpretation for the Vancouver Forest Region. British Columbia Ministry of Forests, Victoria, BC

Haggard JAG (2000) A Radio Telemetric Study of the Movement Patterns of Adult Northern Red-Legged Grogs (*Rana aurora aurora*) at Freshwater Lagoon, Humboldt County, California. Master's Thesis, Humboldt State University, Arcata, California

Hamilton PT, Richardson JML, Govindarajulu P, Anholt BR (2012) Higher temperature variability increases the impact of *Batrachochytrium dendrobatidis* and shifts interspecific interactions in tadpole mesocosms. Ecology and Evolution 2:2450–2459

Hayes MP, Quinn T, Klaus O, Schuette-Hames JP, Serra Shean S (2008) Maintaining Lentic- breeding Amphibians in Urbanizing Landscapes: The Case Study of the Northern Red-legged Frog (*Rana aurora*). Pages 133-149 in: Mitchell JC, Jung Brown RE, Bartholomew B (eds) Urban Herpetology. Herpetological Conservation, Number 3. Society for the Study of Amphibians and Reptiles Urban Herpetology, Salt Lake City, Utah (USA)

Kiesecker JM, Blaustein AR (1998) Effects of Introduced Bullfrogs and Smallmouth Bass on Microhabitat Use, Growth, and Survival of Native Red-Legged Frogs (Rana aurora). Conservation Biology 12:12

Kiesecker JM, Blaustein AR (1997) Population Differences in Responses of Red-Legged Frogs (*Rana aurora*) to Introduced Bullfrogs. 78:9

Licht LE (1971) Breeding Habits and Embryonic Thermal Requirements of the Frogs, Rana Aurora Aurora and Rana Pretiosa Pretiosa, in the Pacific Northwest. Ecology 52:116–124

Licht LE (1969) Comparative breeding behavior of the red-legged frog (*Rana aurora aurora*) and the western spotted frog (*Rana pretiosa pretiosa*) in southwestern British Columbia. Canadian Journal of Zoology 47:1287–1299

Licht LE (1974) Survival of embryos, tadpoles, and adults of the frogs *Rana aurora aurora* and *Rana pretiosa pretiosa* sympatric in southwestern British Columbia. Canadian Journal of Zoology 52:613–627

Marsh DM, Trenham PC (2001) Metapopulation Dynamics and Amphibian Conservation. Conservation Biology 15:10

Maxcy KA (2004) Red-legged frog (*Rana aurora aurora*). Pages 1-12 in: Accounts and Measures for Managing Identified Wildlife – Accounts V. B.C. Ministry of Water, Land and Air Protection, Victoria, B.C.

McInnis V (2021a) VegSurveyData.xlsx. figshare. Dataset. https://doi.org/10.6084/m9.figshare.14336966.v1 (accessed 5 April 2021)

McInnis V (2021b) Photos associated with vegetation data. figshare. Media. https://doi.org/10.6084/m9.figshare.14336978.v1 (accessed 5 April 2021)

McRae BH (2006) Isolation by Resistance. Evolution 60:1551–1561

McRae BH, Dickson BG, Keitt TH, Shah VB (2008) Using Circuit Theory to Model Connectivity in Ecology, Evolution, and Conservation. Ecology 89:2712–2724

McRae BH, Shah VB (2011) Circuitscape User Guide: Circuitscape. https://docs.circuitscape.org/Circuitscape.jl/latest/usage/ (accessed 4 April 2021)

Meidinger DV, Pojar J, eds. (1991) Ecosystems of British Columbia. BC Ministry of Forests, Research Branch, Victoria, B.C

Mote PW, Salathé EP (2010) Future climate in the Pacific Northwest. Climatic Change 102:29–50

Nichols J, Williams B (2006) Monitoring for conservation. Trends in Ecology & Evolution 21:668–673

O'Regan SM, Palen WJ, Anderson SC (2014) Climate warming mediates negative impacts of rapid pond drying for three amphibian species. Ecology 95:845–855

Pearl CA, Adams MJ, Leuthold N, RB Bury. (2005) Amphibian occurrence and aquatic invaders in a changing landscape: Implications for wetland mitigation in the willamette valley, Oregon, USA. Wetlands 25:76–88

Richardson JML, Govindarajulu P, Anholt BR (2014) Distribution of the disease pathogen *Batrachochytrium dendrobatidis* in non-epidemic amphibian communities of western Canada. Ecography 37:883–893

Riparian Areas for Protection Act: Riparian Area Protection Regulation (2019) BC Reg 178/2019. https://canlii.ca/t/54bnb (accessed 25 April 2021)

SC Museum & Archives (n.d.) Sechelt: Sunshine Coast Museum & Archives. https://www.sunshinecoastmuseum.ca/sechelt.html (accessed 5 April 2021)

Schuett-Hames JP (2004) Northern red-legged frog (Rana aurora aurora) terrestrial habitat use in the Puget Lowlands of Washington. Master's Thesis, The Evergreen State College, Olympia, Washington

SCWP (n.d.) Our Goals. Sunshine Coast Wildlife Project: Sunshine Coast Wildlife Project. www.coastwildlife.ca/our-goals (accessed 25 April 2021)

Semlitsch RD, Bodie JR (1998) Are Small, Isolated Wetlands Expendable? Conservation Biology 12:1129–1133

Storm RM (1960) Notes on the Breeding Biology of the Red-Legged Frog (Rana aurora aurora). Herpetologica 16:251–259

Stuart SN, Chanson JS, Cox NA, Young BE, Rodrigues ASL, Fischman DL, Waller RW (2004) Status and Trends of Amphibian Declines and Extinctions Worldwide. Science 306:1783–1786

Sunshine Coast Conservation Area (SCCA) (2012) Map of BEC Subzones of the Sunshine Coast Forest District. https://www.thescca.ca/index.php?option=com_content&view=article&id=298&Itemid=242# (accessed 25 April 2021)

Taylor PD, Fahrig L, Henein K, Merriam G (1993) Connectivity Is a Vital Element of Landscape Structure. Oikos 68:571

Taylor PD, Fahrig L, With KA (2006) Landscape connectivity: a return to the basics. In: Connectivity Conservation. Crooks, KR & Sanjayan, M, editors. Cambridge University Press, Cambridge pp. 29–43.

Tschaplinski PJ, Pike RG (2010) Riparian Management and Effects on Function. Pages 479–525 in: Compendium of Forest Hydrology and Geomorphology in British Columbia. Land Management Handbook 66 Vol. 1 B.C. Ministry of Forests and Range, Victoria, BC

USGS (n.d.) NDVI, the Foundation for Remote Sensing Phenology: USGS. https://www.usgs.gov/core-science-systems/eros/phenology/science/ndvi-foundation-remote-sensing-phenology?qt-science_center_objects=0#qt-science_center_objects (accessed 5 April 2021)

VRI - Forest Vegetation Composite Layers (All Layers) [database] (2020) BC Data Catalogue. Ministry of Forests, Lands, Natural Resource Operations and Rural Development, Victoria, BC. https://catalogue.data.gov.bc.ca/dataset/vri-2020-forest-vegetation-composite-layers-all-layers- (accessed 4 April 2021)

Wind E (2000) Effects of Habitat Fragmentation on Amphibians. Conference on the Biology and Management of Species and Habitats at Risk, Kamloops, 15-19 February 1999.B.C. Ministry of Environment, Lands and Parks, and University College of the Cariboo, Kamloops, BC

Wind E, Dunsworth G (2007) Using amphibians to monitor the effectiveness of variable retention harvesting systems on Vancouver Island. Conference on Monitoring the Effectiveness of Biological Conservation, Richmond, 2-4 November 2004, Richmond, BC

Appendix A. Species Account - *literature review*

A.1 Names

Scientific: *Rana aurora*
Common: Northern red legged frog
Species code: A-RAAU

A.2 Status

SARA: Schedule 1 – Special Concern

BC Wildlife Act: Schedule A; blue-listed; ranked S3S4

BC's Conservation Framework:

Priority 1 for Goal 2: Prevent species and ecosystems from becoming at risk
Priority 2 for Goal 3: Maintain the diversity of native species and ecosystems
Priority 3 for Goal 1: Contribute to global efforts for species and ecosystem conservation (Env. & C.C. Canada 2017)

Priorities raised by BC's NRLF recovery plan, contained with the Canadian government's management plan (Env. & C.C. Canada 2017) include:

- Addressing knowledge gaps about species distribution, relative abundance, and population ecology.
- *Protect key habitat including aquatic (breeding), terrestrial (foraging), and inter-connections (migration and dispersal).*
- Prevent the spread of introduced species to breeding wetlands.
- Reduce levels of urban, agricultural, and forestry pollutants in terrestrial and aquatic habitats.
- Prevent disease transfer by people and implement baseline monitoring.
- Reduce knowledge gaps about species vulnerability to emerging epidemic disease and the effects of climate change, and how these effects may be synergistically magnified in altered habitats.
- Increase public education and awareness to promote threat mitigation and population recovery efforts in human-altered areas where NRLF persist.

**Italicized point underline priority that is directly linked to my project.*

A.3 Distribution

Provincial Range

In BC, NRLFs are found on Vancouver Island, the Gulf Islands, and on the mainland, west of the Coast Mountains. On the mainland, they are found throughout the Frazer River Valley until Hope, up the Sea-to-Sky corridor until Whistler, along the Sunshine and Central Coasts up to Smith Sound. Introduced populations also exists on Haida Gwaii and Chigagof Islands. Over 50% of their known range in Canada is concentrated on Vancouver Island. The exact northeastern extent of their range is unknown as it is very remote and no systematic amphibian surveys have yet been conducted. The NRLF lives within the Coastal Western Hemlock (CWH; -dm, -ds, -mm, -vh, -vm, -xm) and Coastal Douglas-fir (CDF; -mm) biogeoclimatic units (Env. & C.C. Canada 2017).

Elevational Range

Their elevational range depends on the latitudinal position. NRLF can thrive at higher elevations in southern parts of its range (i.e.: Oregon and California). In BC, the highest location at which NRLF was recorded was at 1020 m. NRLF are, however, more common (i.e.: have higher rates of wetland occupancy) and occur in greater densities at elevations below 500 m asl (Env. & C.C. Canada 2017).

Global Context

The NRLF is distributed along the Pacific Coast, west of the Coast and Cascade Mountains, from southwestern BC to northwestern California. The Canadian portion of their population only accounts for one third of the global population. The NRLF populations occurring in the study area on the Sechelt Peninsula are nearing the northern extent of their range. They are also limited by the Coast Mountains to the east (Env. & C.C. Canada 2017).

A.4 Project Area

Sechelt Peninsula, Sunshine Coast, BC

Table A1. Hierarchical classification system of ecosystem zones of the study area in the Sunshine Coast, BC.

Ecoprovince:	Georgian Depression (GED)
Ecoregions:	Lower Mainland (LOM)
Ecosections:	Georgia Lowland (GEL)
Biogeoclimatic Zones:	Coastal Douglas Fir (CDF), moist maritime (mm) Coastal Western Hemlock (CWH), variants xm1 and dm Mountain Hemlock (MH), moist maritime (mm)

A.5 Overview of Life Cycles

As with most amphibian species, NRLF depend highly on both terrestrial and aquatic habitats. Amphibians generally require three habitats: an aquatic habitat for breeding, a foraging ground that is usually found in terrestrial habitats, and a place to hibernate which can be in either terrestrial or aquatic habitats (Licht 1969).

Emergence from hibernation occurs once daily temperatures remain over 5°C for multiple days consecutively (Licht 1969). On the Sunshine Coast, this usually occurs in late March or early April (M. Evelyn, SCWP, pers. comm.). Shortly after emergence, they begin migrating to breeding ponds. They are mainly a nocturnal species, reserving large movements and breeding during the night and twilight hours. Their travels seem to be stimulated by cloud cover and precipitation, when temperatures are warmer (Licht 1969). Males arrive at breeding ponds approximately a week before females, although females were seen in the upland forests surrounding breeding ponds. Breeding occurs once water temperatures are maintained over 7°C. Most females lay their eggs quickly, varying from two to four weeks (Licht 1969). Tadpoles emerge in late July or early August (Env. & C.C. Canada 2017).

In the fall, the frogs migrate to their overwintering habitat where they will hibernate for three to four months until temperatures rise above 5°C again. Even less is known of their overwintering habitat. They do not have the ability to freeze, and therefore most likely seek refuge from freezing temperatures at the bottom of ponds and lakes, or under a thick layer of leaf litter (Licht 1969; Schuett-Hames 2004).

A.6 Habitat Use and Life Requisites

Specific Habitat

Breeding

Breeding occurs in a variety of different types of freshwater habitats. They require standing water to breed and are mainly found in wetlands with at least 50% emergent vegetation (Licht 1969). Occupancy of ponds is negatively associated with amount of open water. Pond with <25% open water are more likely to be occupied by NRLF than those with >50% open water (Pearl et al. 2005). Extirpation rates within ponds is greatly associated with habitat features. Rates were lowest when wetlands had >60% emergent vegetation and their perimeter had >35% trees (Adams et al. 2011). Structurally complex wetlands with ample microhabitats available are consequently ideal breeding habitats (Licht 1969). Sites with greater sun exposure are correlated with higher productivity (Abney et al. 2019). However, productivity is also positively correlated with cooler water temperatures, indicating the important of cool temperatures in early spring (Abney et al. 2019).

Males emit their mating call when under a minimum water depth of 7 inches [17.78 cm] (Licht 1969). Females attach the egg masses in areas with sun exposure at a depth ranging from 30 cm to 1.5 m and attached to stalks of sturdy vegetation like sedges (*Carex spp.*), cattail (*Typha latifolia*), water lilies (Nymphaeaceae), or submerged sticks and willow (*Salix spp.*) branches (Licht 1969). Survival of embryo to emerge as tadpoles is approximately 90% (Licht 1974). The eggs hatch approximately five or six weeks later, depending on water temperatures (Storm 1960).

The critical thermal range of NRLF embryos and larvae is 4-21° Celsius. Both the upper and lower lethal temperatures are the lowest of any frog species in North America and ranges from (Licht 1971). The tadpoles develop throughout the summer, require four to five months to develop and emerge in late summer to early fall (Maxcy 2004). Tadpoles feed on algae and detritus (Licht 1974). Survival of NRLF tadpoles is low, averaging 5% survival rates from the number of eggs counted to the number of metamorphs that successfully emerge as juveniles. The main cause of mortality of tadpoles seems to be from predation, which is offset by the large number of offspring produced by females in a single egg mass (Licht 1974).

While NRLF are found in larger permanent ponds, ephemeral ponds are important breeding habitat for NRLF as they lack the presence of predatory fish and other competing species that are associated with permanent ponds (Adams 1999). Ephemeral ponds must, however, retain sufficient water until metamorphosis can be completed at the end of the summer, in late July or early August (Env. & C.C. Canada 2017). They can also utilize the riparian borders of lakes and slow-moving streams as breeding habitat (Maxcy 2004). Beaver dams are also correlated with high NRLF productivity as they create beneficial conditions for breeding and tadpole development. They raise water depth, increase the length of the hydroperiod, and change wetland vegetative communities (Env. & C.C. Canada 2017)

Foraging (Adults and Juveniles)

Less is known about NRLF adults. They are highly terrestrial and may spend up to 90% of their time for growth and feeding occurs in terrestrial habitats (Haggard 2000). However, they are a discrete and mainly nocturnal species (Licht 1969) making them difficult to observe. They forage in damp, shaded areas and are more active on warm rainy night nights (Storm 1960). Forests spanning from 450 m to at least 5 km is important to adults for cover, foraging, and migratory corridors (Grand et al. 2017). They are negatively correlated with high elevation, slope, and recently cut/open forests (Adams 1999, Maxcy 2004, Wind & Dunsworth 2007). Conversely, they are positively correlated with flatter sites that have standing water, at lower elevations, with southernly aspects, abundant riparian vegetation, a closed canopy, and abundant coarse wood (Adams 1999; Schuett-Hames 2004). Due to their mucilaginous skin, they remain heavily dependent on sources of moisture. This moisture can be obtained from microhabitats occurring in the forest. Decaying wood is an important source of moisture and thermal refugia during dry summer spells. However, even adult frogs can depend on wetland habitat during summer droughts when the forests dry out and can no longer provide sufficient moisture for frogs (Schuett-Hames 2004).

Migration

While their home range is small (approx. 78 m, ranging from 5 to 221 m), they commonly travel 1 km between their breeding and overwintering sites and have been found up to 4.8 km from their breeding ponds. Their long-distance travelling occurs in three discrete events: breeding in early spring, post-breeding in early summer, and pre-overwintering in the fall (Schuett-Hames 2004; Env. & C.C. Canada 2017).

Hibernation

Little is known or their overwintering habitats. They have been found on the forest floor, hidden under a layer of leaf litter or decaying wood, in slow-moving streams, and likely at the bottom of ponds (Licht 1969, Schuett-Hames 2004). They are not freeze tolerant and must seek refuge from freezing temperatures (Env. & C.C. Canada 2017). Overwintering habitats are not be considered; I am assuming that adequate wetland and upland habitat also provides quality overwintering habitat.

Living Habitat

Feeding

Tadpoles are herbivorous. They forage filamentous algae in the water column, scrape algae and biofilms off substrate, and eat decaying vegetation in the wetlands. Food is generally abundant and not a limiting factor in their development (Licht 1974).

Juveniles and adults are opportunistic foragers. Juveniles continue to depend highly on aquatic habitat for food. They are often found hiding in the vegetation around the shoreline waiting to ambush its prey, either in the water, air, or on the shore.Adults mainly forage in the upland forest habitats, eating insects, spiders, and slugs, limited only by the size of their gape (Maxcy 2004).

Security

Tadpoles require microhabitats provided by emergent vegetation or woody debris on the pond floor to hide from predators. Juveniles use the riparian vegetation and shoreline wetland plants to hide themselves. Adults often hide in leaf litter or in decaying wood. When near wetlands, they will often jump in when something/someone approaches (Schuett-Hames 2004).

Thermal

Tadpoles generally cluster in the warmest water available. This is usually in shallow water with frequent sun exposure. If the water temperatures drop, they may seek refuge at the pond bottom or under insulating debris (BC MoE 1998b). Adults require microhabitats in the upland forests that can retain moisture during the summer (i.e.: abundant sword ferns (*Polystichum munitum*) and/or skunk cabbage (*Lysichiton americanus*) and coarse wood), and other microhabitats that will remain above freezing temperatures during the winter (i.e.: under leaf litter or at the bottom of ponds and rivers).

Seasons of Use

NRLF life cycles follow a 4-season scheme: winter, spring, summer, and fall.

Table A2. Breakdown of NRLF life requisites per season and month.

Month	Season	Life Requisites
January	Winter	Hibernation
February	Winter	Hibernation /Migration/Breeding
March	Winter	Migration/Breeding/Spawning
April	Spring	Breeding/Spawning
May	Spring	Tadpole development
June	Summer	Tadpole development
July	Summer	Tadpole development/Emergence
August	Summer	Tadpole development/Emergence
September	Fall	Emergence
October	Fall	Emergence/Migration
November	Winter	Migration/Hibernation
December	Winter	Hibernation

A.7 Habitat Use and Ecosystem Attributes

Table A3. Description of ecosystem attributes required for each life requisite.

Life Requisite	Ecosystem Attributes
Feeding	Wetlands with standing water (i.e.: little to no slope), sun exposure (increases algae and biofilms) Surrounding forest cover (adults and juveniles) Riparian/shoreline vegetation (juveniles especially)
Security	Emergent vegetation (aquatic habitats), coarse woody debris, and leaf litter (both) to hide from predators
Thermal	Southern aspect for wetlands with sun exposure during extended periods of the day for tadpoles in ponds Sword ferns, decaying wood, leaf litter, and a closed canopy for protection from desiccation in terrestrial habitats
Breeding	Min. water depth of 30 cm >50% emergent vegetation (sedges, rushes & grasses)
Migrating	Network of connected wetland and forested habitats with little/no barriers to dispersal (roads, cliffs, steep slopes, urban development, etc.) of at least 1 km from the wetland

Appendix B. Habitat Suitability Model: Parameters & Flow Diagram

B.1 Rating Scheme

Table B1. Rating scheme used to classify habitat suitability for NRLF.

% of Provincial Best	Rating	Rank
100-76%	High	3
75-26%	Moderate	2
25-1%	Low	1
0%	Nil	0

As per RISC's minimum requirements, I will use the 4-class rating scheme described in the table on the right (BC Env. 1999). A 4-class rating scheme is used for intermediate knowledge of species' habitat requirements or for large map areas, the latter being the limiting factor of my analysis. The large size of the area to be surveyed will be at the cost of some precision. A measure of the reliability of the information used to build the ratings table will be included for each rating used. This will provide and overall reliability of the map produced. As information is collected and the ratings table is updated, the reliability index will also improve.

There is currently no provincial benchmark defined. Therefore, the reference conditions to which we want to strive for, and that guide the habitat ratings, will be taken from BC's NRLF Management Plan (Env. & C.C. Canada 2017) and other literature sources.

B.2 Ratings Assumptions

Table B2. Rank assigned for each elevation (m asl) class.

Minimum	Maximum	Rank
0	500	3
500	850	2
850	1100	1
1100	5000	0

In BC, NRLF are found in greatest densities at elevations between 0 and 500 m asl (Env. & C.C. Canada 2017). Most NRLF occur below 850 m asl (Maxcy 2004). The highest elevation an NRLF was ever recorded in BC was at 1,020 m asl (Env. &

C.C. Canada 2017). An extra 80 m were left as a buffer given that NRLF may occur at higher elevations but were never recorded.

Table B3 Rank assigned for each slope (degrees) class.

Minimum	Maximum	Rank
0	3	3
3	15	2
15	32	1
32	90	0

Standing and slow-flowing water required by NRLF for breeding occur at low slope gradients. Based on occurrence data on the Sunshine Coast, no NRLF were recorded in locations with greater than 30°. Another 2° were left as a buffer. The values between 3° and 32° were divided with a slightly smaller interval for a rank of 2 than 3, with the assumption that it gets increasingly difficult for NRLF to travel in high-slope areas.

Normalized Difference Vegetation Index (NDVI)

Minimum	Maximum	Rank
-1	0	3
0	0.4	1
0.4	0.6	2
0.6	1	3

NDVI values ranges from -1 to 1. Negative values generally indicate bodies of water, while values ranging between 0.6 and 1 indicate dense vegetation cover. Values around 0 to 0.2 indicate barren or urban lands, and values ranging from 0.2 to 0.4 indicate sparse or unhealthy vegetation (USGS, n.d.). These two categories were lumped together, and both given a rank of 1. No rank of 0 was given seeing as NRLF can travel through barren lands for short distances when required to (Chan-McLeod 2003). Values were also confirmed by cross-referencing the NDVI value with known sites.

Table B5. Rank assigned for each TEM class.

Site Series Name*	Code	Rank
HwBa – Blueberry	AB	2
BaCw - Foamflower	AF	2
Cattail marsh	CT	3
FdPl - Arbutus	DA	1
FdPl - Cladina	DC	1
Fd - Sword fern	DF	1
FdBg - Oregon grape	DG	2
Fd - Salal	DS	1
golf course	GC	2
gravel pit	GP	0
HwCw/Ba - Deer fern	HD	3
Hardhack – Sweet gale wetland	HG	3
HwFd - Kindbergia	HK	2
Hardhack - Labrador tea	HL	3
Hw – Flat moss	HM	2
HwCw - Salal	HS	1
lake	LA	3
HwPl - Cladina	LC	1
Pl - Sphagnum	LS	3
HmBa – Blueberry	MB	2
open water	OW	3
pond	PD	3
CwSs - Skunk cabbage	RC	3
Cw - Foamflower	RF	3
Cw - Sword fern	RS	2
road surface	RZ	0
Spirea - Sedge wetland	SS	3
urban	UR	0
CwYc - Goldthread	YG	3
n/a	ELSE	2

*Plant codes:

Ba: *Abies amabilis* (amabilis fir)

Bg: *Abies grandis* (grand fir)

Cw: *Thuja plicata* (western redcedar)

Fd: *Pseudotsuga menziesii* (Douglas-fir)

Hw: *Tsuga heterophylla* (western hemlock)

Pl: *Pinus contorta* (lodgepole pine)

Ss: *Picea sitchensis* (Sitka spruce)

Yc: *Chamaecyparis nootkatensis* (yellow cedar)

Site series were used to classify the ecosystem based on indicator species, and the site's soil moisture regime. NRLF prefer more humid that offer protection from desiccation. These sites tend to occur in topographical depressions where wetlands are also more likely to occur. Therefore, ponds, lakes, open water and other wetland sites were given a rank of 3. Dry sites with a dominance of salal (*Gaultheria* shallon) were given a rank of 1 as these sites often occur on topographic crests and dense stands of salal are difficult for NRLF to travel through. Intermediate sites were assigned a rank of 2. Restrictions were only set in highly modified landscapes (i.e.: gravel pit, road surface, and urban areas). Codes used to describe the TEM site series are found in the Terrestrial Ecosystem Mapping Map Legend (Timberline Natural Resource Group Ltd. 2008) and descriptions of the site series are found in the Field Guide for Site Identification and Interpretation for the Vancouver Forest Region (Green & Klinka 1994).

Certain areas within this layer were not surveyed (named as n/a), mainly because they are within protected areas or human settlements. These were attributed an intermediate suitability rank (2) as an average, but likely contains habitat that ranges in suitability from 1 to 3. Data confirms NRLF occurrence in some of these areas, especially near lakes and known wetlands

B.3 Weighting

HSI = ((Elevation * **0.1**) + (Slope * **0.3**) + (NDVI * **0.3**) + (TEM * **0.3**)) * Restrictions

The expression above indicates the overall weighting scheme used to attribute an HSI to each map cell based on the criteria listed above. The elevation was only given a weight of 0.1 (or 10%) because most of the study area (i.e.: the Sechelt Peninsula) is within the NRLF elevational range with only small patches reaching higher than 1,100 m asl. Furthermore, while previous research shows NRLF occur in greater frequency at lower elevations, unpublished data from the SCWP also shows a large population in the Caren Ranges, which is within the higher elevational class. The other three criteria were given equal weights (30% each).

B.4 Habitat Suitability Model Workflow

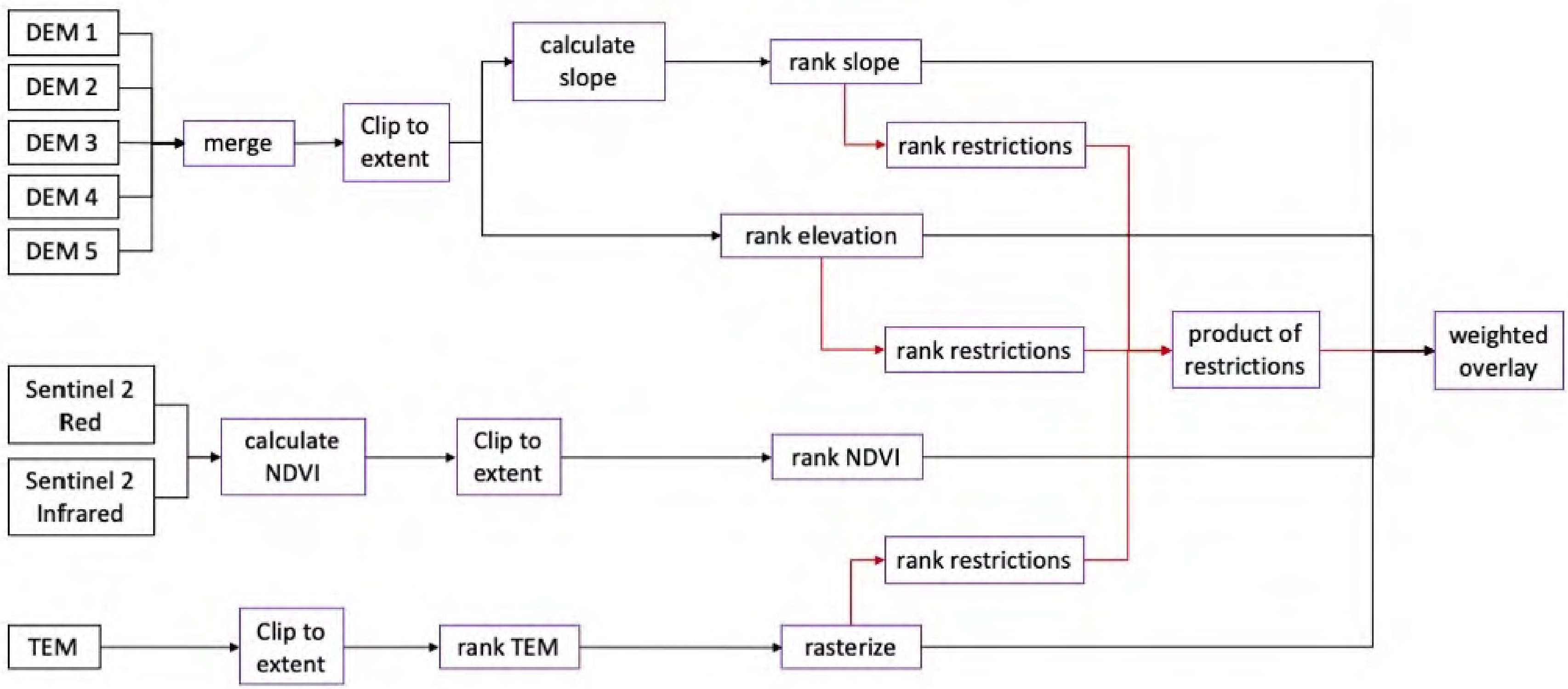


Figure B1. The flow diagram shows the overall steps required in the HSM to produce the HSI, including modifying some of layer in order to rank them (i.e.: slope) and converting them to the right file format (i.e.: TEM). It does not however show every intermediary step that went into producing the HSM, which are described in Appendix C.

Appendix C. Step-by-step User Guide

Below is a guide to using the HSM sub-models to reproduce the HSI that I have used for this research. The ranking schemes can be modified by opening the tables within the sub-model "*HSM_NRLF_2rankRasters"* and changing the values, or by changing the values of the TEM rank in the field calculation expression. Further is also a second guide with detailed information on every step conducted without the sub models and the rationale behind them, as well as some of the issues I encountered and how I worked around them.

D.1 Running the HSM in QGIS 3.10.13 (with sub-models)

- First, import all DEM files
- *Run HSM_NRLF_1DEMs*
  - Save both files in a new folder
  - Name files: SlopeMerged and DEMmerged

  [*This sub-model merges all the DEM files and calculates the slope from the merged DEMs.*]
- Warp(reproject) using GDAL's tool
  - Set target CRS to EPSG3157
  - Save file in same folder
  - Name file: SlopeReproj
- Set project CRS from one of these layers
- Import HSM_extent_EASTonly and NDVI_allLSC
- Set CRS of both layers to EPSG3157
- *Run HSM_NRLF_2rankRasters*

  [*This sub-model clips all the raster files with the extent of the study area then reclassifies each with their respective ranking tables.*]
- Import TEM20k_utm_NEMNSSonly
- Set layer CRS to EPSG3157

  **make sure all layers are in the same projections.
- Clip with HSM_extent using QGIS 'Clip' tool
- Assign rank in Field Calculator
  - Create New field named: STSRrank
  - Copy-paste the following expression

```
CASE
WHEN "STSRSMPCDL" is  'AB' then 2
WHEN "STSRSMPCDL" is  'AF' then 2
WHEN "STSRSMPCDL" is  'CT' then 3
WHEN "STSRSMPCDL" is  'DA' then 1
WHEN "STSRSMPCDL" is  'DC' then 1
WHEN "STSRSMPCDL" is  'DF' then 1
WHEN "STSRSMPCDL" is  'DG' then 2
WHEN "STSRSMPCDL" is  'DS' then 1
```

```
WHEN "STSRSMPCDL" is  'GC' then 2
WHEN "STSRSMPCDL" is  'GP' then 0
WHEN "STSRSMPCDL" is  'HD' then 3
WHEN "STSRSMPCDL" is  'HG' then 3
WHEN "STSRSMPCDL" is  'HK' then 2
WHEN "STSRSMPCDL" is  'HL' then 3
WHEN "STSRSMPCDL" is  'HM' then 2
WHEN "STSRSMPCDL" is  'HS' then 1
WHEN "STSRSMPCDL" is  'LA' then 3
WHEN "STSRSMPCDL" is  'LC' then 1
WHEN "STSRSMPCDL" is  'LS' then 3
WHEN "STSRSMPCDL" is  'MB' then 2
WHEN "STSRSMPCDL" is  'OW' then 3
WHEN "STSRSMPCDL" is  'PD' then 3
WHEN "STSRSMPCDL" is  'RC' then 3
WHEN "STSRSMPCDL" is  'RF' then 3
WHEN "STSRSMPCDL" is  'RS' then 2
WHEN "STSRSMPCDL" is  'RZ' then 0
WHEN "STSRSMPCDL" is  'SS' then 3
WHEN "STSRSMPCDL" is  'UR' then 0
WHEN "STSRSMPCDL" is  'YG' then 3
ELSE 2
END
```

- Convert TEM to raster format by using GRASS' v.to.rast tool
    - Select input type to area
    - Select name of column for 'attr' to STSRrank
    - Set region cellsize to 10
    - Save to file named: TEMranked
- *Run HSM_NRLF_3Restrictions*
    - Save files to the same name as in model

  [*This sub-model will re-rank the restrictions as a separate Boolean file for each criterion, except the NVDI which do not have restrictions.*]
- Open Raster calculator and input the following expression:

  ("ElevRestri@1"*"SlopeRestri@1" * "TEMrestri@1")

  Or the product of the 3 restriction files
- *Run HSM_NRLF_4weighedOverlay*
    - Save file as HSI_ (version running)

  [*This sub-model conducts the weighted overlay of all ranked criteria and restrictions.*]

D.2 Detailed guide to running the HSM in QGIS 3.10.13 (without sub-models)

Create map extent

1) The watershed file is used as the map extent. If a different study area is desired, download a new version of this file with the desired extent.
    - Dataset can be found at: https://catalogue.data.gov.bc.ca/dataset/3ee497c4-57d7-47f8-b030-2e0c03f8462a
    - Alternatively, any other shapefile can be used for desired extent.
2) Remove all areas south/west of the highway (these are mostly urban/private property and have large areas missing of the TEM files). I will provide you with the file, but here are the instructions if it needs to be redone.
    - Import shapefile of highway (which I created from selected feature from the SCRD roads shapefile).
    - Split polygon with line.
    - Select the undesired half and delete it.

Input files

3) Due to difficulties with the DEMs being in a different coordinate system, I first had to import and reproject the DEMs before bringing in any other files.
4) Input DEM files
    - Raster files can be downloaded from: https://pub.data.gov.bc.ca/datasets/175624/
5) Merge files using GDAL's "merge" tool
6) Calculate the slope using GRASS' r.slope.aspect tool
7) Reproject both files (DEM and slope) to the desired CRS using GDAL's warp tool.
    - I set the CRS to EPSG 3157 - NAD83(CSRS) / UTM zone 10N
8) Set the project CRS from this layer
9) Input the map extent, TEM, and Sentinel 2 red and infrared bands (bands 04 and 08) for the whole project extent

NDVI

10) Merge both Sentinel2 tiles together for each respective band (bands 04 and 08) using GDAL's "merge" tool

11) Clip both merged files with map extent

12) Calculate NDVI in the "raster calculator" using the following equation…

$$NDVI = \frac{(\, NIR - Red)}{(\, NIR + Red)}$$

- In the raster calculator, expression should resemble (may change slightly if the file names are different):

("Sentinel2_B08_merged@1" - "Sentinel2_B04_merged@1") /
("Sentinel2_B08_merged@1" + "Sentinel2_B04_merged@1")

13) Rank the calculated NDVI using the reclassify by table tool with the following ranking scheme:

Minimum	Maximum	Rank
-1	0	3
0	0.4	1
0.4	0.6	2
0.6	1	3

- In advanced parameters, set to min >= x > max

*Note: If re-running the model, a recent remote sensing imagery should be downloaded and used as it will reflect the landscape in its most current state as opposed to how it was when I downloaded the data.

- NDVI data was downloaded from USGS Earth Explorer at: https://earthexplorer.usgs.gov/
- Select extent in decimal degrees with 0-1% cloud cover.

Elevation

14) Reclassify elevation by using "reclassify by table" and enter the following ranking scheme:

Minimum	Maximum	Rank
0	500	3
500	850	2
850	1100	1
1100	5000	0

- In advanced parameters, set to min >= x > max

Slope

15) Derive slope from DEM using GRASS' "r.slope.aspect" tool
16) Reclassify slope by using "reclassify by table" and enter the following ranking scheme:

Minimum	Maximum	Rank
0	3	3
3	15	2
15	32	1
32	90	0

- In advanced parameters, set to min >= x > max

TEM 20K

17) Reclassify the site series by using the following expression if the field calculator.
18) Create a new field called STSR_rank
    - Copy-paste the following expression:

CASE

```
WHEN  "STSRSMPCDL" is 'AB' THEN 2
WHEN  "STSRSMPCDL" is 'AF' THEN 2
WHEN  "STSRSMPCDL" is 'CT' THEN 3
WHEN  "STSRSMPCDL" is 'DA' THEN 1
WHEN  "STSRSMPCDL" is 'DC' THEN 3
WHEN  "STSRSMPCDL" is 'DF' THEN 3
WHEN  "STSRSMPCDL" is 'DG' THEN 1
WHEN  "STSRSMPCDL" is 'DS' THEN 2
WHEN  "STSRSMPCDL" is 'ES' THEN 1
WHEN  "STSRSMPCDL" is 'GC' THEN 1
WHEN  "STSRSMPCDL" is 'GP' THEN 1
WHEN  "STSRSMPCDL" is 'HD' THEN 2
WHEN  "STSRSMPCDL" is 'HG' THEN 3
WHEN  "STSRSMPCDL" is 'HK' THEN 2
WHEN  "STSRSMPCDL" is 'HL' THEN 3
WHEN  "STSRSMPCDL" is 'HM' THEN 2
WHEN  "STSRSMPCDL" is 'HS' THEN 2
WHEN  "STSRSMPCDL" is 'LA' THEN 3
WHEN  "STSRSMPCDL" is 'LC' THEN 1
WHEN  "STSRSMPCDL" is 'LS' THEN 2
WHEN  "STSRSMPCDL" is 'MB' THEN 0
WHEN  "STSRSMPCDL" is 'OW' THEN 3
WHEN  "STSRSMPCDL" is 'PD' THEN 3
WHEN  "STSRSMPCDL" is 'RC' THEN 1
WHEN  "STSRSMPCDL" is 'RF' THEN 3
WHEN  "STSRSMPCDL" is 'RK' THEN 3
```

```
WHEN  "STSRSMPCDL" is 'RO' THEN 0
WHEN  "STSRSMPCDL" is 'RP' THEN 2
WHEN  "STSRSMPCDL" is 'RS' THEN 3
WHEN  "STSRSMPCDL" is 'RW' THEN 3
WHEN  "STSRSMPCDL" is 'RZ' THEN 1
WHEN  "STSRSMPCDL" is 'SC' THEN 3
WHEN  "STSRSMPCDL" is 'SS' THEN 2
WHEN  "STSRSMPCDL" is 'UR' THEN 0
WHEN  "STSRSMPCDL" is 'YG' THEN 3
END
```

*Note: if using a different extent, there may be other site series not listed below which will have to be researched and it's ranked determined

19) Rasterize the ranked attribute field using GRASS' v.to.rast tool
    - Set cell size to 10

Restrictions

20) Reclassify all final outputs of previous steps into Boolean rasters by using reclassify by table and enter the following table:

Minimum	Maximum	Rank
0	0	0
1	3	1

    - Make sure it is set to min <= value <= max

21) Then, combine them into a single raster by doing the product of all layers in the raster calculator.

Weighted Overlay

22) In "raster calculator" expression follows as such:

```
(("ElevRanked@1" * 0.1) + ("SlopeRanked@1" * 0.3)
+ ("NDVIranked@1" * 0.3) + ("TEMranked@1" * 0.3))
* "Restrictions@1"
```

D.3 Preparing files for Circuitscape

Focal regions

1) Union all desired vector layers
   - I used all mapped lakes and wetlands.

     ** Note: NRLF presence has been confirmed in many of these habitat patches, but not all have been survey. I included all lakes and wetlands for this analysis, but surveys should be conducted to confirm their presence in the remaining patches.*
2) Remove all overlapping polygons
   - In the field calculator, I created a new field and assigned the row number to each feature and called it "number".
   - I then manually selected overlapping wetlands and changed their values in the attribute table to have matching numbers.
   - Finally, I used the dissolve tool for the "number" attribute
3) Clip the vector layer to the map extent layer
4) Convert vector to raster using the GRASS tool "v.to.rast"

   *Note: don't use SAGA tool; it creates a .sdat file which is huge and not useful!
   - In advanced parameters, set cell size = 10
5) Then export as ASCII file by using raster -> conversions -> translate (convert format)

Conductance Map

1) Convert HSI produced from the HSM into an ASCII file using the "translate (convert format)" tool
   - Set grid size to 10m

Circuitscape tool in ArcMap

Due to problems with matching raster headers, I had to download and use the Circuitscape tool in ArcMap. This package has a tool to convert vector files (i.e.: the focal region files) to rasters using a template (i.e.: the desired HSI map). Then one can use the Circuitscape for ArcMap tool and it will automatically match the raster headers and run. Expect long wait times; it took me on average 17 hours to run the software.