

Linking projections from species distribution models and management in Indigenous communities

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Abstract

Species distribution models (SDMs) are widely used to forecast invasions, but translating these predictions into management remains challenging. We address this using the introduced northern red-legged frog (*Rana aurora*) on Haida Gwaii (British Columbia, Canada), where rapid expansion has been reported since its detection in 2002. We combined information from historical and contemporary surveys to: 1) estimate current range and expansion rate, 2) investigate human-mediated dispersal, and 3) predict future distribution under climate change. We then explored how model outputs can inform management in an Indigenous community. Projections suggest that without intervention, NRLFs will occupy most of the northern part of Haida Gwaii (Graham Island) by 2040 and are likely to reach much of the southern part of Moresby Island by 2081, including ecologically and culturally significant areas. Northern red-legged frogs expanded at $\sim 1.9 \text{ km yr}^{-1}$ and occupied $\sim 24\%$ of Graham Island by 2017. Populations appeared across habitat blocked by inaccessible saltwater inlets, suggesting this spread was facilitated by humans. Climate change is expected to further increase habitat suitability in key areas in the near term, while declining suitability in other areas in the long term ($\geq 2081\text{--}2100$). Engagement with the Haida Nation and local community highlighted limitations of eradication and emphasised strategies to limit human-assisted dispersal and prevent spread to uninvaded areas.

Introduction

Non-native species pose a major threat to island ecosystems, where endemic species are often ill-equipped to cope with novel competitors, predators, and pathogens (Blumstein & Daniel, 2005; Kier et al., 2009; Tershy et al., 2015). Frog introductions to island ecosystems, whether accidental or intentional, have emerged as a significant conservation concern (e.g., Beard & Pitt, 2005; Denoël & Dufresnes, 2025; Li et al., 2011; Measey et al., 2012). Once established, invasive frog species can rapidly expand due to the absence of natural predators, broad dietary flexibility, and high reproductive output (Li et al., 2011; Measey et al., 2017). Impacts of invasive frogs are wide-ranging and include competition with native amphibians and fish, food-web impacts and spread of pathogens such as *Batrachochytrium dendrobatidis* (e.g., Denoël & Dufresnes, 2025; Measey et al., 2012). Ongoing research emphasizes the importance of early detection, biosecurity measures, and targeted management strategies to mitigate the ecological consequences of frog invasions (Measey et al., 2017). Quantifying the spread and potential distribution of invasive frogs is therefore a key challenge for conservation and management, particularly in island systems (Bellard et al., 2016; Doherty et al., 2016).

Here we focus on the invasion of the northern red-legged frog (*Rana aurora*; hereafter NRLF) across Haida Gwaii, an archipelago off the north coast of British Columbia, Canada. The Haida Gwaii archipelago is globally significant for biodiversity, having served as a glacial refugium during the last glacial maximum, and invasive species are identified as the top threat to ecosystem integrity in Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site (Archipelago Management Board, 2018).

NRLFs are native to the Pacific Northwest of North America where populations have declined across much of their range due to habitat loss, disease (*Batrachochytrium dendrobatidis*), predation by invasive bullfrogs (*Lithobates catesbeianus*), and possibly climate change (COSEWIC, 2015). Based on these overall declines, it is listed as “Special Concern” under Canada’s Species at Risk Act (COSEWIC, 2015). However, in Haida Gwaii populations have increased. The species was first recorded on Haida Gwaii in 2002 (Ovaska et al., 2002) and is thought to have been introduced from an unknown source in the native range of the NRLF in British Columbia (Pauly et al., 2008). A similar introduction occurred on Chichagof Island, Alaska in 1982, where the species has spread rapidly and is classified as invasive (Hodge, 2004; Lerum & Piehl, 2007; McClory & Gotthardt, 2008).

NRLFs have expanded their range on Haida Gwaii since 2002, but the current extent of their distribution, the rate of spread, and the role of human-mediated dispersal remain poorly understood (Gaston et al., 2008; Ovaska et al., 2002; Pauly et al., 2008). NRLF distributions are expected to continue shifting under climate change. Previous modelling efforts suggested increasing habitat suitability on Haida Gwaii, but were based on relatively few observations and coarse spatial resolution (Pauly et al., 2008).

Haida Gwaii is the ancestral home of the Haida Nation (a group of indigenous people of the Pacific Northwest Coast of North America) and has a single native amphibian species, the Western toad (*Anaxyrus boreas*); Hlk’yáan K̓’ust’áan in X̱aad Kil; Hlk’yan k̓’uust’an in X̱aayda Kil (Haida Language Council, 2022; Skidegate Haida Immersion Program, 2015). There is particular concern that NRLFs may affect native species assemblages on Haida Gwaii, including the Western toad, through antagonistic interactions or by acting as a vector for chytrid fungus (Gamlen-Greene, 2022; Gaston et al., 2008). Recent work has shown that Western toads on Haida Gwaii may be weaker competitors with NRLFs than mainland toad populations, increasing concern about potential impacts as frog populations expand (Gamlen-Greene, 2022).

The Haida Nation has substantial responsibilities and interests in managing biodiversity on Haida Gwaii, and values are a central component of decision-making. Caring for land and ecosystems is considered a responsibility (*‘Laa guu ga ḵanhllns*; X̱aayda Kil), and concepts of interconnectedness (*Gina ‘waadlux̱an gud ad kwaagid*; X̱aayda Kil), balance (*Giid tlljuus*; X̱aayda Kil), stewardship (*TilX̱anda*; X̱aayda Kil), accountability (*Til’yahda*; X̱aayda Kil) and respect (*Yahguudang*; X̱aayda Kil) are fundamental to Haida perspectives on environmental management (Council of Haida Nation & Government of Canada, 2018; Salomon et al., 2023). Frogs also have cultural significance within Haida oral histories and art (Williams-Davidson, 2017), adding a cultural dimension to questions surrounding the presence and management of introduced anuran species.

One way to help use observational data to inform amphibian management is with species distribution models (SDMs). SDMs are widely applied to forecast species distributions and invasion risk under current and future environmental conditions (Elith & Leathwick, 2009; Franklin & Miller, 2009). Although these models are increasingly used to support conservation and invasive species management, it is often unclear how SDM predictions are translated into management decisions that account for local

values, governance structures, and societal constraints (Addison et al., 2013; Villero et al., 2017). A small but growing body of work has begun to explore participatory and Indigenous-informed approaches to species distribution modelling, demonstrating that Indigenous and community knowledge and values can inform model inputs, interpretation, and decision relevance (Evangelista et al., 2018; Skroblin et al., 2021). For example, Campbell et al. (2022) showed how collaboration with Indigenous partners in northern Australia expanded the biocultural benefits of SDMs by aligning modelling outputs with Indigenous priorities and stewardship practices. Similarly, Mucioki et al. (2022) combined SDMs with Indigenous Knowledge to assess conservation needs of culturally significant plant species, grounding model predictions in the lived experience of Tribal members to better inform conservation prioritisation. Despite these advances, such approaches remain uncommon in the SDM literature, particularly in studies focused on non-native species.

In this study, we asked: (1) how far and how fast NRLFs have expanded their introduced range on Haida Gwaii; (2) whether spatial patterns of occupancy suggest human-mediated dispersal; (3) how climate change is likely to influence future habitat suitability; and (4) how local context—including Haida values and societal constraints—may shape the interpretation and application of SDM outputs for invasion management, incorporating the perspective of a Haida land manager.

Materials & Methods

Breeding occurrence data

Our research was completed with permission from the Solutions Table, Council of the Haida Nation (CHN), BC Parks (Parks Use permit 108846) and wildlife sampling permits from the British Columbia Ministry of Forests (MRNA16-236743).

Breeding occurrences (i.e., presence or absence/non-detection of egg masses or tadpoles) were collected for the native and non-native range of the NRLF in British Columbia (BC) ($n = 609$ locations in total; $n = 117$ Haida Gwaii, $n = 492$ native range; Fig. 1). Breeding occurrences, as opposed to observations at all life stages, were used because the large egg masses have been found to have a high detection probability for NRLFs (0.947, 90% CI) (Rowe et al., 2019). Adult observations have a much lower detection probability (i.e., confidence in the absences), in part due to being quite cryptic. For the native range in BC, 492 NRLF breeding occurrences were used; Vancouver Island ($n = 286$; Fig. 1) and the BC mainland ($n = 206$). These native range observations were sourced from historic surveys from 1998–2012 (COSEWIC, 2015). To describe the Haida Gwaii range (non-native range in BC), 117 NRLF breeding occurrences from Haida Gwaii were used. These consisted of: 1) a breeding survey of Graham Island (*X̱aaydag̱a Gwaay.yaay linagwaay* in *X̱aayda Kil*) in spring 2017 (54 sites; Fig. 1b), the only invaded island in the archipelago; 2) 160 additional sites that were opportunistically sampled between April–May 2017–2019 within Graham Island and Kamdis Island; and 3) eight observations from BC Parks, BC Ministry of Forests and the Council of the Haida Nation from 2015–2016 (Fig. 1). Details on survey data selection and filtering can be found in the Sup. Mat.

609 sites surveyed in the non-native range and in the native range in BC (n = 492). Inset shows Haida Gwaii points (n = 117); legend refers to both native range and Haida Gwaii.

b) Frog habitat on Haida Gwaii.

Environmental variables

Fifteen publicly accessible GIS environmental layers (nine climate and six habitat variables; Sup. Mat.; Table S1) rather than microscale habitat variables (e.g., pond depth) were used in order to model habitat suitability in areas that were not sampled. The variables were selected *a priori*, and were included because they all have been shown previously to influence the suitability of habitat for NRLF breeding (COSEWIC, 2015; Gerick et al., 2014; Hayes et al., 2008; Licht, 1971). All variables in the non-native (Haida Gwaii) range had analogues in the native range to: 1) determine whether a true niche shift was occurring, rather than the filling of a preadapted niche (Fitzpatrick & Hargrove, 2009; Petitpierre et al., 2012), and 2) avoid predicting to environments beyond the training data (Elith & Leathwick, 2009).

Freshwater habitat variables were accessed from the Freshwater Atlas, and forest cover was accessed from the GeoBase Land Cover dataset in December 2020 — both published by the BC Ministry of Forests. A Digital Elevation Model (DEM) was sampled from USGS — their 1 arc-second resolution model (~ 30 meters) (Farr & Kobrick, 2000). Details on how these environmental variables were sampled can be found in Sup. Mat.

Current and future seasonal climate variables were accessed from Climate BC version 7.1 (Mahony et al., 2021; Wang et al., 2012, 2016), which is a program that downscales PRISM gridded monthly climate normal data at 800 x 800 m resolution (Daly et al., 2008) to scale-free point locations. For the current climate, the normal period from 1991–2020 was used. For the future climate models, the CMIP6 climate projections with the SSP2-4.5 scenario for 2021–2040 and 2081–2100 were used. An ensemble of 13 general circulation models (GCM) from these climate projections created by Mahony et al. (2021) was used because an ensemble is likely to be more reliable than any single GCM projection (Pierce et al., 2009). The SSP2-4.5 assumes moderate mitigation of future greenhouse gas emissions that are approximately consistent with current economic trends and emission policies. For spring climate, we included mean and minimum temperatures, climate moisture index, number of frost-free days, degree days > 5°C and mean precipitation (Table S1). For summer climate, we included minimum temperature, climate moisture index and mean precipitation (Table S1).

Documenting the past and current range on Haida Gwaii

Presence observations of the NRLF's initial distribution (in 2002) and their 2017 distribution were used to generate past and current range extents. For the 2002 distribution, we used all ten NRLF observations from (Ovaska et al., 2002) and one unpublished observation from Tom Reimchen in 2002, in a pond near Mayer Lake (T. Reimchen, unpublished data). For the 2017 range, we used all 57 presence observations

from our 2017 random and non-random sampling. To compare the range of the NRLF in 2017 to 2002, the area (km²) of the minimum convex hull (MCH) was calculated for both periods (Licata et al., 2019; Worton, 1987). A minimum convex hull is the smallest polygon that contains all sites with no interval angles exceeding 180 degrees. The MCHs were generated in *QGIS* using the convex hull tool (using presence points) and clipped the hull to the coastline. We then used the *QGIS Field Calculator* tool to calculate the area (km²) of the MCHs. Kamdis Island was included within Graham Island as a whole for calculations.

Calculating the range expansion rate on Haida Gwaii

We calculated how fast the NRLF was expanding its range on Haida Gwaii by calculating an average dispersal rate (R_{ave}) by using the square root of the area occupied in 2002 compared to 2017 (*QGIS* (projection EPSG: 3005)) : R_{ave} (km/year) = ($\sqrt{\text{area km}^2 \text{ 2017}} - \sqrt{\text{area km}^2 \text{ 2002}}$) / (2017 – 2002) (year) (Skellam, 1951; Gilbert & Liebhold, 2010). Two straight-line dispersal rates for NRLFs were calculated to get an estimated minimum and maximum dispersal rate, using the straight-line distance from 1) the most northern NRLF observation in 2002 to the most northern point in 2017 and 2) the most western NRLF observation in 2002 to the most western point in 2017. The straight-line dispersal rate (R_s) was calculated as: R_s (km/year) = distance (km) / (2017 – 2002).

Observations near St’alaa Kun (Collison Point) were excluded from the western dispersal rate calculation because these presences are likely the result of human-mediated dispersal. St’alaa Kun/Collison Point is located across a very fast-flowing and deep saltwater channel that is over 500m wide and is frequently travelled across via boat (area labelled in Fig. 3). Furthermore, all observations from around the western side of Masset Inlet (between the western-most presence and St’alaa Kun/Collison Point) were absences (n > 50).

To explore the future range of the NRLF based on dispersal ability alone, we generated a map showing areas of Haida Gwaii that the NRLF could and could not access in 2040 and 2081, assuming the constant annual range expansion rate calculated in section 1.4 (e.g., no landscape resistance or other factors). Average range expansion rate (R_{ave} = 1.9km/year) was used for northern Haida Gwaii and was multiplied by the number of years since the 2017 survey (2040 = 23 years; 2081 = 64 years) to get the distance (d) they could disperse ($d = R_{ave} * (\text{future year} - 2017)$). This distance was used in *QGIS* to create buffers around the 2017 minimum convex hull to generate the area the NRLF could disperse to (and hence map future range expansion). We assumed no major human-assisted dispersal events, as well as creating an alternative map that assumed the NRLF would reach Moresby Island (*Gwaii Haanas* in *X̱aad Kíl*) in the next few years.

We estimated the minimum time the species had been present on Haida Gwaii by dividing the maximum distance between any two observation points recorded in 2002 (17.6 km), measured using the *QGIS*

Measure Tool, by our estimates of minimum, and maximum straight line dispersal rates (1.1, and 2.5 km yr⁻¹, respectively), which we then subtracted from the year 2002 to get the date.

Predicting habitat suitability on Haida Gwaii using a Random Forest model

We used a Random Forest algorithm to model the current and future habitat suitability for the NRLF on Haida Gwaii using the *randomForest* R package (Liaw & Wiener, 2002). Random Forest models have been used widely in invasion and conservation studies and SDMs (Burns et al., 2020; Hill et al., 2017; Sung et al., 2018; Zhang et al., 2020), in part because they can handle large numbers of collinear variables, and are resistant to overfitting, making them very useful for prediction (Breiman, 2001; Prasad et al., 2006; Sarquis et al., 2018; Segal, 2004). The Random Forest model used the covariates in Table S1 and presences/absences from both native and non-native ranges (n = 609), because pooling data across both non-native and native ranges has been found to improve invasive predictions (Broennimann & Guisan, 2008; Fitzpatrick et al., 2008; Pili et al., 2020; Sales et al., 2021). Random Forest settings can be found in the Sup. Mat.

We assessed the accuracy of the Random Forest model (model calibration) by: 1) dividing the occurrence data into 70% training data (consisting of 70% of the Haida Gwaii data combined with all the native range data) and 30% testing data (the rest of the Haida Gwaii data); and 2) calculating the area under the receiver operating characteristic curve (AUC), Kappa coefficient and root mean square error (RMSE) (Allouche et al., 2006; Boyce et al., 2002; Fawcett, 2006). The model predicting habitat suitability on Haida Gwaii performed reasonably (AUC = 0.76, Kappa = 0.52, RMSE = 0.45). As mentioned earlier, the training and testing data from Haida Gwaii did not include absences that could be due to distribution disequilibrium.

We used this model to predict habitat suitability across Haida Gwaii at a 250 m² resolution using R, and mapped these predictions in QGIS. Following recommendations by Pili et al. (2020) and (Sales et al. (2021), the model used for generating maps was trained on 100% of data from both ranges. To assess whether climate change would alter habitat suitability for the NRLF on Haida Gwaii in the future, we compared the mean current and future values of habitat suitability across all grid cells on Haida Gwaii (Wright et al., 2016). Details on map projections are in Sup. Mat.

Quantification of suitability change and threshold sensitivity analyses were conducted in R. Predicted habitat suitability values for the current climate and two future periods (2021–2040 and 2081–2100) were extracted at the grid-cell level and combined into a single dataset using a unique grid identifier. For each grid cell, changes in suitability were quantified by calculating the difference between future and current predicted values. Cells were classified as exhibiting increased, decreased, or unchanged suitability based on whether this difference was positive, negative, or equal to zero. The total number and proportion of grid cells in each category were then calculated separately for each future period.

To evaluate changes in suitable habitat extent and assess sensitivity to threshold choice, continuous suitability values were converted to binary suitable/unsuitable classifications using three thresholds (≥ 0.4 , ≥ 0.5 , and ≥ 0.6). For each threshold and time period, the number of grid cells meeting or exceeding the threshold was summed and compared to the current-climate baseline to calculate absolute and proportional changes in suitable habitat extent.

Community engagement

R Gamlen-Greene conducted community outreach and engagement with different communities on Haida Gwaii over a six-year period, from 2017 to 2022. These efforts focused on science communication and education around amphibian identification, including four school field trips, four outdoor community events covering amphibian identification and monitoring at ponds (Fig. 2), visiting over 13 primary and secondary classes, employing a local field assistant, three public talks and helping start a community amphibian monitoring program. To support decision-making by local land managers, we consulted with the Council of the Haida Nation, BC Ministry of Forests, and BC Parks staff on Haida Gwaii during the study design phase. Based on this engagement, habitat suitability outputs were produced at a 250 m resolution, as coarser products (e.g., 1 km resolution) were considered insufficiently detailed for management applications at relevant spatial scales. We note that while outputs were mapped at 250 m resolution, their effective precision is constrained by the resolution of underlying environmental datasets. These engagement activities were designed to support relationship-building, study design, knowledge exchange, and management relevance, rather than to systematically sample perspectives across all Haida Citizens or land management agencies.

Results

Range expansion on Haida Gwaii

The range of the NRLF on Haida Gwaii increased over 15-fold within 15 years from 2002 (97 to 1509 km², 2002–2017, respectively). The area occupied by NRLFs on Haida Gwaii in 2017 represents 24% of Graham Island. Their mean range expansion rate was 1.9 km/year. The range expansion rate did not appear consistent across Graham Island, with the rate being faster in the northeast than the southwest. The largest straight-line distance between an observation in 2017 and the closest observation from 2002 was 38 km (Fig. 3a). This occurred in the northeast, transecting forested wetland of low topographic complexity, and represents a range expansion rate of 2.5km/year. By contrast, in the mountainous areas on the west side of Graham Island, the range expansion rate was much lower, approximately 1.1 km/year (straight-line distance of 16.6km). Additionally, there is a small, occupied area in the northwest (Collinson Point area), which is surrounded by unoccupied areas (Fig. 3a).

The estimated minimum time NRLF had been present on Haida Gwaii when first recorded in 2002 is between 7 and 16 years. Assuming a single introduction event and constant population growth, this

indicates that NRLF must have been present by at least 1986–1995, although introduction may have occurred earlier.

Potential expansion and human-mediated dispersal

Our estimates indicate that continued range expansion of NRLFs on Haida Gwaii is primarily constrained by saltwater barriers rather than terrestrial habitat. Despite low reported tolerance of NRLFs to saltwater immersion, the species appears to have crossed Masset Inlet on Graham Island to St’alaa Kun/Collision Point, a ~ 500 m saltwater channel (Fig. 3a). Given the frequency of boat traffic in this area, this pattern is consistent with human-mediated dispersal rather than natural movement across saltwater.

Using observed rates of spread on Graham Island together with habitat suitability projections, we estimated the potential timing of occupation of adjacent areas under scenarios where saltwater barriers are breached. These estimates suggest that, if dispersal continues through contiguous suitable habitat, NRLFs could occupy much of Graham Island by approximately 2040, with much of the archipelago potentially becoming occupied by 2081, including areas within Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site (Fig. 3b). These timeframes reflect modelled spread using expansion rate alone, under favourable conditions, with human-mediated dispersal across Skidegate Channel to Moresby Island.

Arrows represent the furthest and shortest distances to the range limits from the 2002 points. All features overlayed on a 1-arc digital elevation model (Farr & Kobrick, 2000). MCH = minimum convex hull.

b) Map showing potential range of the northern red-legged frog on Haida Gwaii based on a range expansion rate of 1.9km/year with human dispersal at different times (current range 2017, 2021–2040, 2081–2100).

Habitat suitability on Haida Gwaii with climate change

Areas of high habitat suitability for NRLFs given current climatic conditions on Haida Gwaii include the already occupied lowlands of northeastern Graham Island (Fig. 4a, 3a), and much as yet unoccupied habitat near Sandspit and Naden Harbour (Fig. 3).

Mean habitat suitability for the NRLF on Haida Gwaii using climate ensembles for 2021–2040 (Fig. 4b) and for 2081–2100 (Fig. 4c) was predicted to increase by 7.6 and 29.4%, respectively, as compared to current conditions (Sup. Mat.; Fig. S3). Habitat suitability increased with climate change relative to the current climate in the majority of Haida Gwaii (Fig. 5). Under the 2021–2040 scenario, 65.5% of cells (105,237 cells) showed increased suitability, while 34.5% (55,454 cells) decreased and < 0.1% (90 cells) showed no change. By 2081–2100, the proportion of cells exhibiting increased suitability rose to 75.4% (121,246 cells), with 24.6% (39,524 cells) decreasing and < 0.01% (11 cells) remaining unchanged. In both 2021–2040 and 2081–2100 projections, northwestern Graham Island, western Graham Island and

Moresby Island became more suitable, whereas central eastern Graham Island (the core of the current range) became less suitable.

Figure 5. Projected changes in habitat suitability for NRLF relative to current climate (normal period 1991–2020) for Haida Gwaii. Current climate versus 2021–2040 climate (ensemble model with SSP2-4.5 scenario) and current climate versus 2081–2100 climate (ensemble model with SSP2-4.5 scenario).

The summer climate moisture index was the most important variable in the Random Forest model predicting habitat suitability on Haida Gwaii, followed by seven similarly performing variables that were a mix of climate and habitat variables (Sup. Mat.; Fig. S4). Although causality is not inferred with a Random Forest (Pearl, 2009), habitat suitability was predicted to increase with increased climate moisture index, precipitation, minimum spring temperature and degree days above 5°C (Sup. Mat.; Fig. S5). Conversely, habitat suitability decreased with increasing distance to nearest wetland, stream density and elevational range (Sup. Mat.; Fig. S5). Climate change on Haida Gwaii is predicted to increase spring climate moisture index, precipitation, minimum temperature and degree days above 5°C (Sup. Mat.; Fig. S6a-d). Climate change is also predicted to decrease summer climate moisture index on Haida Gwaii (Sup. Mat.; Fig. S6e). Given the rapid rates of spread observed in more and less homogenous terrain, and overall increase in habitat suitability under climate change predicted here, salt water barriers to dispersal appear to be the only barrier to further invasion.

Estimates of suitable habitat extent derived from binary thresholds varied markedly with threshold choice (Fig. S7). Using a lower suitability threshold (≥ 0.4), the total area classified as suitable increased by 8.4% of the landscape (13,547 cells) in 2021–2040 and by 33.6% (53,952 cells) in 2081–2100. At an intermediate threshold (≥ 0.5), suitable habitat declined slightly in 2021–2040 (– 1.4%, – 2,196 cells) but increased by 8.7% (13,951 cells) by 2081–2100. In contrast, when suitability was restricted to high-quality habitat (≥ 0.6), the extent of suitable habitat declined under both future periods, decreasing by 5.8% (9,311 cells) in 2021–2040 and by 5.1% (8,209 cells) in 2081–2100. Together, these results indicate that projected increases in suitability were concentrated primarily within low-to-moderate (0.4–0.5) suitability classes, while areas of highest suitability (≥ 0.6) exhibited net contraction through time.

Discussion

Northern red-legged frogs (NRLFs) have expanded rapidly across Haida Gwaii since being detected in 2002, driven by natural dispersal and implied human transport. By 2017, NRLFs had occupied 24% of Graham Island, and without intervention they appear to be capable of occupying all suitable habitat in Haida Gwaii within decades. Because climate change is likely to increase habitat suitability in future on much of Haida Gwaii, our findings imply that NRLFs represent a potential threat to ecologically and culturally significant sites including Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site. We discuss the implications of these predictions below and how

they may be applied in decision-making contexts informed by values, responsibilities, and management priorities identified through engagement with Haida Citizens, stakeholders and the local community.

Northern red-legged frogs have spread far and fast

The NRLF has increased its range 15-fold from 2002–2017, now occupying ~ 24% of Graham Island. NRLFs have spread at an average rate of 1.9km/yr across Graham Island since 2017, which is comparable to estimates for native and non-native anurans elsewhere. For example, Pacific Chorus Frogs expansion their ranged at 2 km/yr on Haida Gwaii (Reimchen, 1991), similar to estimates for range expansions by other non-native amphibians (1.2–2 km/yr) (Bingham et al., 2021; Pagano et al., 2024). Our straight line estimates (1.1–2.5 km/yr) are also below the seasonal straight-line dispersal rate of the NRLF in its native range (3.5–4.8 km/yr; Hayes et al., 2007).

Our results suggest that NRLFs could disperse to much of Graham Island by 2040; including the eastern side of Graham Island and most of the central north of Graham Island. Additionally, our estimated minimum time NRLFs have been present on Haida Gwaii is between 7 and 16 years. This indicates that NRLF must have been present by at least 1986–1995, although the introduction may have occurred earlier. Population growth, spatial spread, and detection processes could result in a longer interval between introduction and observed distribution in 2002.

Humans have mediated the dispersal of the NRLF

Humans have likely facilitated the spread of the NRLF on Haida Gwaii, via transporting them across saltwater barriers, and perhaps additional introductions (e.g., children moving them around). Humans have a huge role to play in whether the NRLF spreads across Skidegate Channel to Moresby Island. As of 2026, there have been no official reports of NRLFs on Moresby Island. Should Skidegate Channel be breached— most plausibly through human transport—our combination of observed spread rates and habitat suitability modelling suggests that large portions of adjacent habitats on Moresby Island could be occupied within decades, including ecologically and culturally significant areas such as Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site (Fig. 3b). From a conservation planning perspective, these findings highlight that preventing human-assisted transport across existing saltwater barriers is likely the most effective lever for limiting further NRLF expansion, and that public awareness and engagement will be critical components of any such strategy.

Northern red-legged frogs will continue to spread with climate change

Using updated data and modelling approaches, we found that climate change is likely to increase the spatial extent of environments that are climatically permissive for establishment across Haida Gwaii, while simultaneously reducing the availability of high-quality habitat, rather than producing a uniform increase in suitability as reported by Pauly et al., (2008). The west coast of Haida Gwaii, northeast Moresby Island, and parts of Gwaii Haanas National Park Reserve, National Marine Conservation Area

Reserve, and Haida Heritage Site are predicted to become more suitable and could likely support the NRLF in the future should they reach those areas.

Although mean suitability increased in both time periods, and 65.5% of Haida Gwaii showed increased suitability by 2021–2040 and 75.4% by 2081–2100, this signal was driven largely by gains within low-to-moderate suitability classes rather than expansion of core habitat. This pattern was strongly dependent on suitability threshold choice: lower thresholds indicated substantial habitat expansion, whereas higher thresholds revealed net contraction, demonstrating that contrasting conclusions can arise from the same suitability surface. Projected losses of high-suitability habitat, therefore, raise questions about longer-term persistence on Haida Gwaii (2081 and beyond).

While it remains uncertain whether reduced availability of high-quality habitat will limit population persistence, evidence from the species' native range in British Columbia suggests that such constraints are already operating and are likely to intensify under continued climate change (Gerick et al., 2014). Similar decoupling between overall suitability gains and losses of core habitat has been documented across taxonomic groups and systems (Bhuyan et al., 2025; Carrell et al., 2023; Hodapp et al., 2023; Syphard et al., 2026), highlighting that increases in suitability may not necessarily translate into improved conditions for long-term population persistence.

How model outputs can inform management in an Indigenous community

The rapid expansion of invasive species often results in eradication efforts without consulting communities to assess and support local values. Through engagement with the Haida Nation and other stakeholders, it became evident that several features of the local social and historical context are particularly relevant to NRLF management on Haida Gwaii. Many of these factors work against eradication as a management strategy, including: (1) confusion around amphibian identification and unfamiliarity of current culture with historic conditions (shifting baseline); (2) the cultural value of amphibians and a strong ethic of respect for living beings; and (3) limited management capacity and competing priorities.

One factor influencing reluctance among some Haida citizens to treat NRLFs as invasive is amphibian misidentification, coupled with unfamiliarity of current culture with historic conditions. Successive generations have grown up alongside species that were absent from the landscape only decades earlier, and many people are unaware that the NRLF is an introduced species. The NRLF is commonly mistaken for the native Western toad or the introduced Pacific Chorus Frog (Fig. 5). This pattern was evident during community engagement associated with amphibian research on Haida Gwaii, where requests for native Western toad observations frequently resulted in photographs of NRLFs (Gamlen-Greene, 2022).

Many Haida community members also hold positive childhood memories associated with frogs, often from a time when Western toads had already declined or disappeared from some locations. As a result, only a small number of elders retain lived experience of Haida Gwaii before the introduction of frogs, and

perceptions of which amphibians “belong” on the islands have shifted over time. Given the deep respect afforded to elders and their knowledge within Haida culture, elders are often sought for wise counsel (Gina k’aadang.nga gii uu tll k’anguudang; *X̱aayda Kil*) (Council of Haida Nation & Government of Canada, 2018; Salomon et al., 2023), positive historical experiences with frogs may further influence attitudes toward frog management today.

Further adding to the reluctance of some Haida to kill NRLFs, amphibians are highly valued in Haida culture. The frog crest, a prominent and important part of Haida culture, belongs to the Eagle Moiety of the Haida Nation. “Frogs” are present in many Haida oral histories and *X̱uuya Ḵaagang.ngas* narratives, though these accounts are generally thought to refer to the Western toad rather than frogs as understood in a Western taxonomic sense (Williams-Davidson, 2017). This linguistic choice by early translators may contribute to contemporary confusion around which amphibians are native to Haida Gwaii. Another important Haida value concerns the desire not to waste living things. For frogs, culling would involve killing adults and removing egg masses from wetlands (Vimercati et al., 2021), and at present there is no pathway to use these animals for food or other purposes. Invasive species management tends to align more closely with Haida values when waste can be put to beneficial use, as demonstrated by invasive white-tailed deer culls in Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site where meat was distributed to schools and community members (de Ryk & Trumpener, 2017). Given the cultural significance attributed to frogs and other amphibians, there may be ambivalence or reluctance toward controlling NRLFs for some Haida citizens. Consequently, eradication of a frog species may require particularly compelling justification and consideration of Haida values and responsibilities, including balance and respect (Council of Haida Nation & Government of Canada, 2018; Salomon et al., 2023).

Another constraint on NRLF eradication is the magnitude of resources required relative to other management priorities. Removing all life stages of NRLFs from the thousands of aquatic habitats across their current range on Graham Island—estimated at 1,509 km² in 2017 and likely expanded since—would entail substantial and ongoing commitments of time, labour, and funding (Vimercati et al., 2021). For the Haida Nation, such investments would compete directly with other pressing socio-economic and environmental obligations, including responses to old-growth logging, housing shortages, unemployment, and the pursuit of Haida title law cases. In this context, large-scale eradication is not only technically challenging but also difficult to justify in relation to broader governance responsibilities and resource constraints.

Engagement with representatives of the Haida Nation and local participants in this research emphasised the importance of education, relationships, and responsibilities across generations as key components of approaches to managing NRLFs on Haida Gwaii, alongside consideration of technical control options. In Haida governance and stewardship contexts, participants highlighted that knowledge is commonly understood as something passed between generations, and that care for land and non-human beings is shaped by responsibilities to both ancestors and future Haida. Educational approaches that situate introduced species within their cultural, historical, and ecological contexts—particularly when introduced

early in life—were identified as important for supporting this sense of responsibility and for fostering longer-term awareness of the impacts and pathways associated with non-native species.

Many non-native or invasive species programmes have developed within governance structures shaped by Anglo-colonial histories, in which Indigenous authority and practical knowledge have often been marginalised, constraining trust and opportunities for sustained collaboration (Graham et al., 2026; Maclean et al., 2022; Ohlsson & Przybylinski, 2023). In contrast, a growing body of Indigenous-led and Indigenous-informed initiatives demonstrates that non-native species management can be more enduring and context-appropriate when grounded in Indigenous custodianship, relational accountability, and locally defined priorities, including education, prevention, and place-based decision-making (Graham et al., 2026; Reo & Ogden, 2018; Seebens et al., 2024). In the context of Haida Gwaii, these insights suggest that applying SDM outputs to NRLF management may be most effective when they support culturally meaningful strategies—such as education, prevention of human-assisted dispersal, and protection of uninvaded areas—rather than defaulting to externally imposed, eradication-focused models. Community-based education and engagement can support broader participation in identifying and reporting NRLF observations (e.g., through platforms such as iNaturalist) and help reduce human-assisted dispersal via measures such as signage at key transport corridors, including the Skidegate Channel; these approaches facilitate non-lethal management and align with cultural respect for frogs.

Targeted education and training for land managers may further support early detection and rapid response in currently uninvaded areas such as Moresby Island. Preventing spread to Moresby is of particular importance because this island includes Gwaii Haanas National Park Reserve and Haida Heritage Site, an area of high cultural, ecological, and economic significance. At present (2026), NRLFs are confined to Graham Island and Kamdis Island, which is separated from Moresby Island by the Skidegate Channel. Although this channel represents a potential dispersal barrier, it is comparable to Masset Inlet, which appears to have been crossed with the aid of human-mediated dispersal. Management resources could therefore be directed toward preventing human-assisted introductions and removing any frog life stages detected on Moresby Island. Incursions of invasive species often fail to establish or require multiple introductions to do so (Dlugosch & Parker, 2008; Sakai et al., 2001), and early intervention has been shown to be cost-effective for amphibians if implemented promptly (Vimercati et al., 2021). From a broader conservation perspective, eradication also warrants careful consideration given that NRLFs are declining across substantial portions of their native range, and the Haida Gwaii population could potentially serve as a source population.

Limitations and future research

Our estimates of NRLF range expansion may overestimate rates of spread in some areas. Much of the invasion to date has occurred through lowland habitats, whereas a considerable portion of currently unoccupied habitat on Haida Gwaii is mountainous. Topographic barriers are known to slow amphibian dispersal and may reduce realised spread relative to modelled averages (Everts et al., 2025; Peterson et al., 2013). At the same time, human-mediated dispersal could enable rapid establishment in isolated

locations, meaning that expansion rates are likely to vary spatially. As such, the projected rates presented here should be interpreted as broad indicators rather than precise forecasts.

Model performance may also be influenced by temporal mismatches between environmental data and biological observations. Habitat variables were derived from datasets representing conditions in the early 2000s, whereas most NRLF records were collected after 2010, a period during which land cover has changed substantially on Haida Gwaii, particularly through forest harvesting. Updated land-cover data may improve model precision and provide insight into how forest management influences habitat suitability or connectivity for NRLFs. Finally, while this study focuses on distributional dynamics, further research is needed to quantify ecological impacts, including potential interactions with native amphibians and disease transmission (Gamlen-Greene, 2022). Such studies are particularly important while NRLFs have not yet colonised the entirety of Haida Gwaii and management options remain open.

We also note that this study did not include a systematic survey of perspectives across Haida Citizens or land management agencies. Interpretations related to values, priorities, and management considerations are therefore informed by the perspective of the Haida co-author and by insights shared during research engagement with Haida Citizens and land managers, rather than representing a complete assessment of views across these groups.

Conclusion

The NRLF range expanded at an average rate of 1.9 km/yr after 2002 and included ~ 24% of Graham Island by 2017. Humans have dispersed NRLF and could potentially do more without management interventions. Ongoing climate change may also enhance habitat suitability for NRLFs in parts of Haida Gwaii, including ecologically and culturally valued habitats. Though the species is expanding rapidly, eradication is in conflict with values and realities in the Haida Nation and wider community. This suggests value in education and stopping the introduction to Moresby Island. Our findings illustrate how SDM outputs can support—rather than dictate—invasive species management when interpreted alongside local values and governance contexts. This reinforces prior arguments that SDMs are most effective when used as decision-support tools rather than prescriptive forecasts (Sofaer et al., 2019; Villero et al., 2017). Our results are consistent with a growing body of work demonstrating that engagement with Indigenous land managers and local communities can help situate SDM outputs within local priorities and lived experience, thereby clarifying their relevance and applicability to management (Campbell et al., 2022; Evangelista et al., 2018; Mucioki et al., 2022; Skroblin et al., 2021).

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

RGG conceived the idea; RGG designed the sampling with help from PA; RGG conducted the fieldwork on Haida Gwaii; RGG led and funded the community engagement on Haida Gwaii; JP supported fieldwork on Haida Gwaii and contributed his perspective on Haida history, culture and management of frogs; RGG conducted the analysis with help from WG and PA; RGG led the writing of the manuscript with assistance from WG and PA. All authors contributed critically to the drafts and gave final approval for publication.

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Data Availability Statement

Data from Haida Gwaii are available upon reasonable request. The other datasets are managed by the individual biologists responsible for collecting them.

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Figures

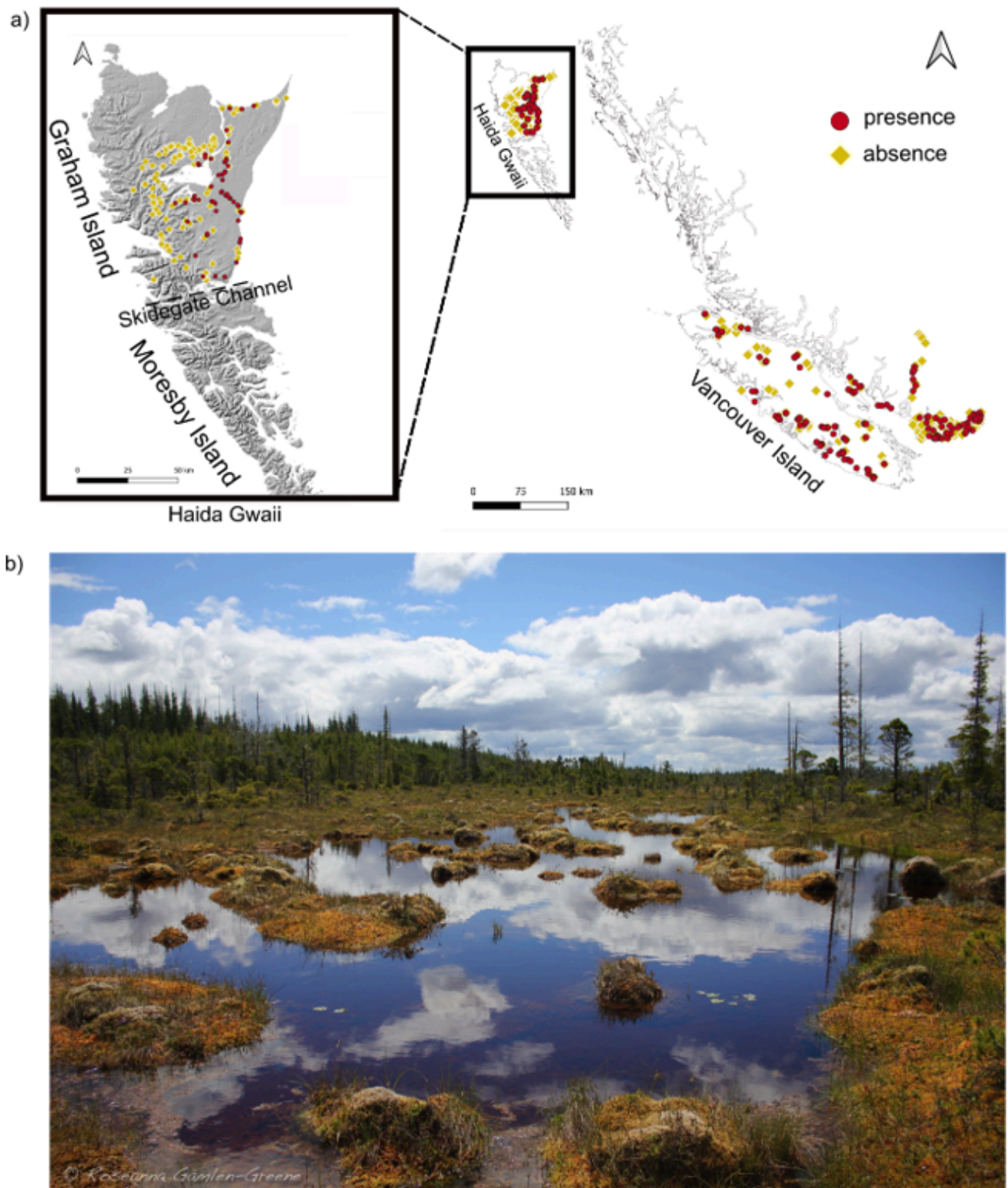


Figure 1

a) Breeding occurrences (presence/absence) of the Northern Red-legged Frog on Haida Gwaii (non-native) and southwest BC (native).

609 sites surveyed in the non-native range and in the native range in BC ($n = 492$). Inset shows Haida Gwaii points ($n = 117$); legend refers to both native range and Haida Gwaii.

b) Frog habitat on Haida Gwaii.



Figure 2

Children from Haida Gwaii conducting amphibian surveys as part of this research. Right — pictured with a juvenile northern red-legged frog.

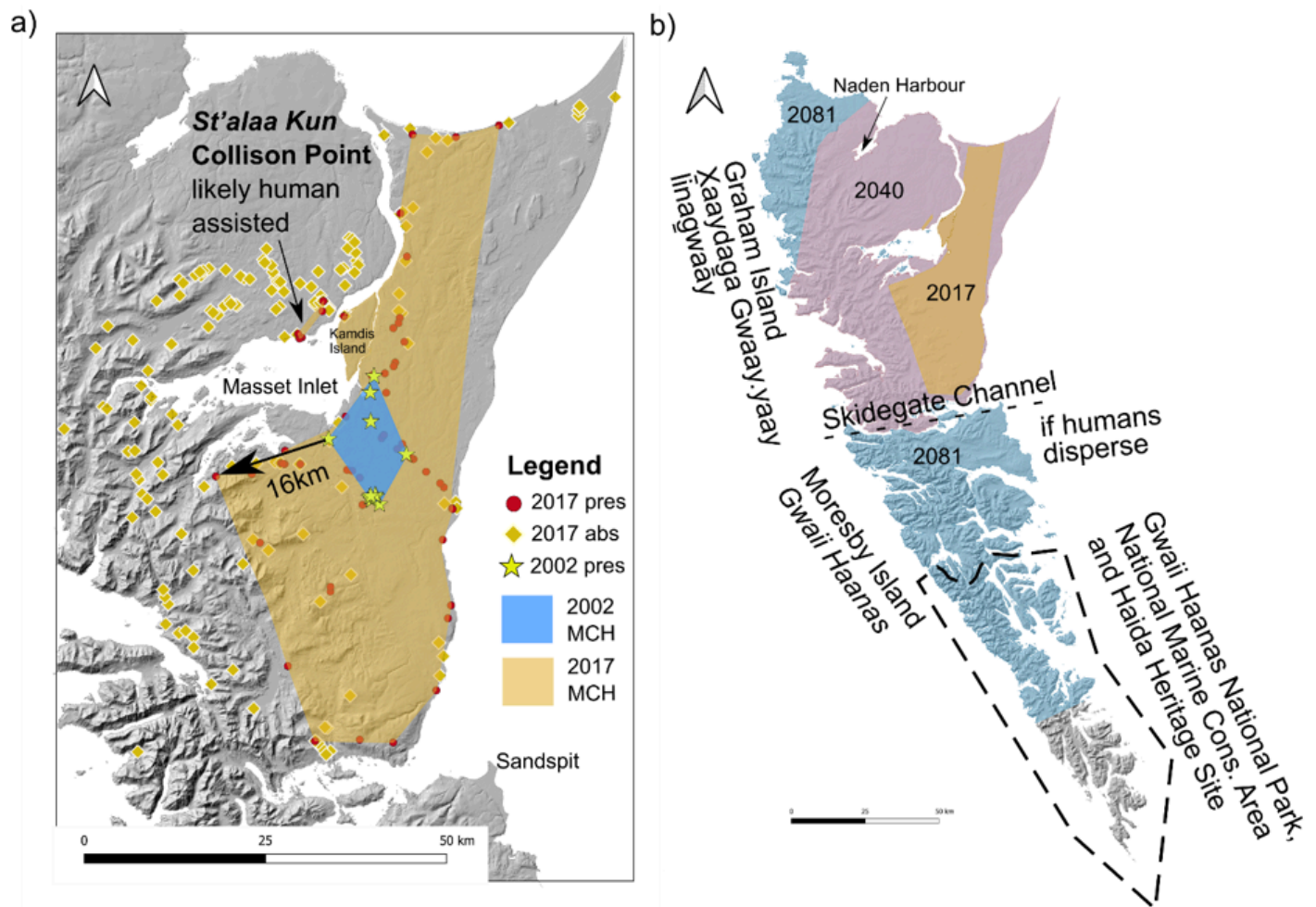


Figure 3

a) Breeding occurrences and current range of Northern Red-legged Frogs on Haida Gwaii in 2002 and 2017.

Arrows represent the furthest and shortest distances to the range limits from the 2002 points. All features overlaid on a 1-arc digital elevation model (Farr & Kobrick, 2000). MCH = minimum convex hull.

b) Map showing potential range of the northern red-legged frog on Haida Gwaii based on a range expansion rate of 1.9km/year with human dispersal at different times (current range 2017, 2021-2040, 2081-2100).

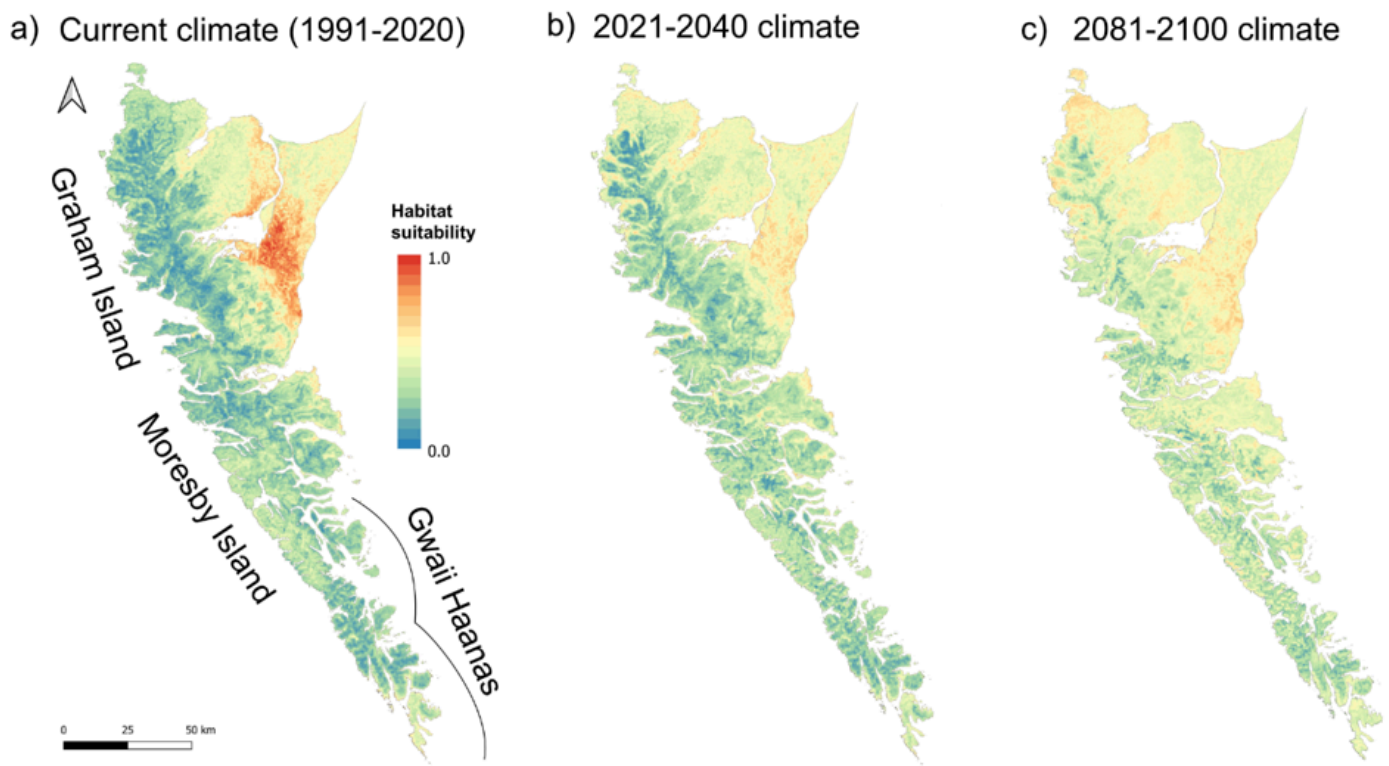


Figure 4

Habitat suitability for the northern red-legged frog on Haida Gwaii. a) Habitat suitability under current conditions (normal period 1991-2020); b) Habitat suitability in 2021-2040 (ensemble model with SSP2-4.5 scenario); c) Habitat suitability in 2081-2100 (ensemble model with SSP2-4.5 scenario).

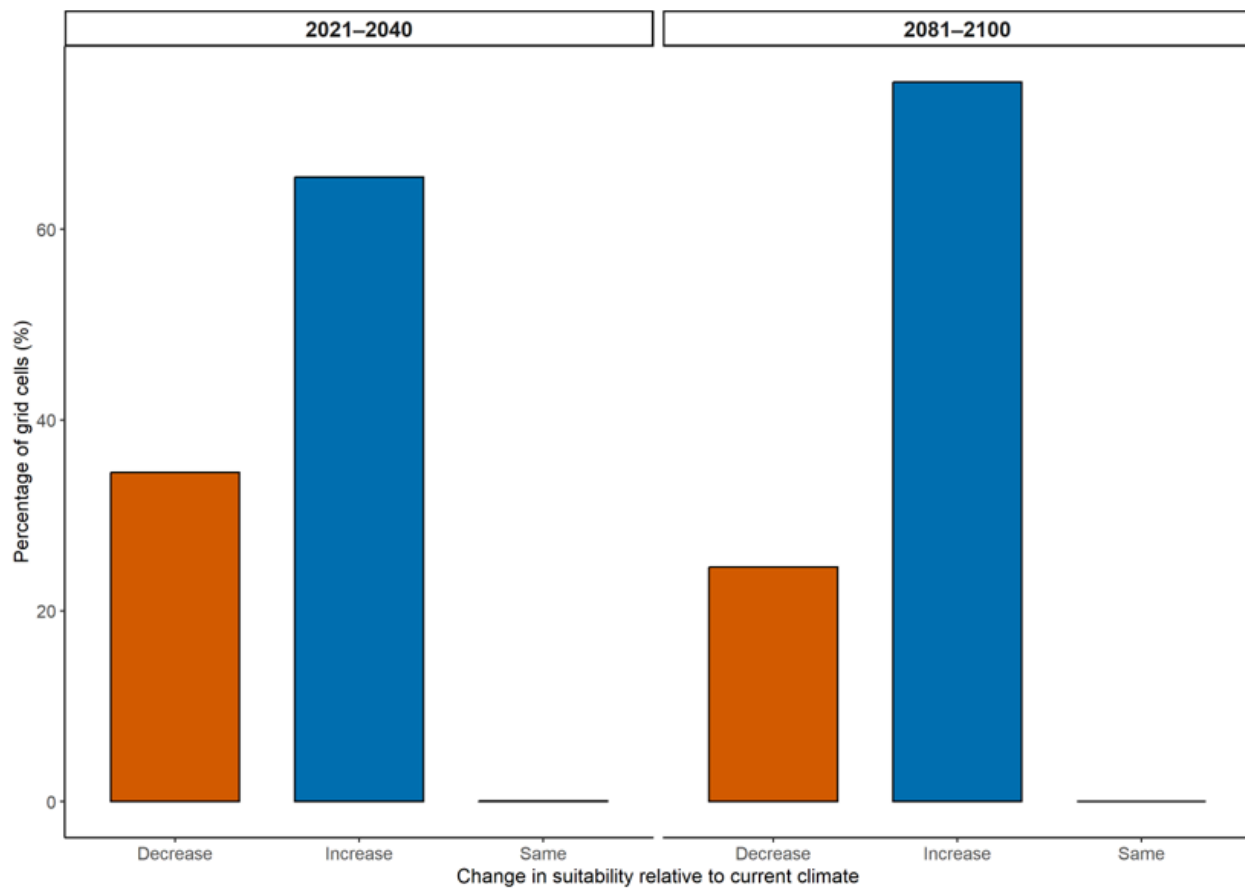


Figure 5

Projected changes in habitat suitability for NRLF relative to current climate (normal period 1991-2020) for Haida Gwaii. Current climate versus 2021-2040 climate (ensemble model with SSP2-4.5 scenario) and current climate versus 2081-2100 climate (ensemble model with SSP2-4.5 scenario).



Figure 6

Fig. 5. Amphibians of Haida Gwaii. a) a pacific chorus frog; b) a northern red-legged frog; c) a western toad; and d) A frog depicted on a Haida totem pole at the mouth of the Hiellen River, Tow Hill, Haida Gwaii; master carver Kilthguulans Christian White.

Supplementary Files

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- [GamlenGreeneetalredleggedfrogHGSupmat140926.docx](#)