Government of Northwest Territories | Gouvernement des Territoires du Nord-Ouest

NWT Cumulative Impact Monitoring Program (NWT CIMP)
FINAL REPORT TEMPLATE 2023-2024

1. Project Information			
NWT CIMP #	CIMP220		
Project Title	Can caribou coexist with human development in Northern Canada? Forecasting land use changes using resource development potential mapping to improve caribou future forecasts.		
Project Lead and Organization	Eliot McIntire, University of British Columbia		
Date Submitted	26th April 2024	**Project Length:** *years of NWT CIMP funding*	3
Type of Research	☒ Science ☐ Traditional Knowledge		
Valued Component *Check all that apply. If 'other' please specify.*	☒ Caribou ☐ Fish ☐ Water ☐ Other:________		
NWT Area/Region and Closest Community	☒ North/South Slave ☒ Dehcho ☒ Sahtú ☒ Gwich'in ☐ ISR ☒ Wek'èezhii Closest NWT Community(s): ________		
Project Location *(Provide specific coordinates; or if regional, provide 4 coordinates for the bounding box.)*	North: 69.1685893312397 South: 59.9962362747699 East: -111.47293924 West: -136.210252538489 Please use DD.MMMMM format		
Project Keywords *(at least four)*	Anthropogenic disturbance, caribou, forecasting, development potential		
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Two high resolution photos have been provided to NWT CIMP with this report, along with associated captions, and credit name. I have the photographer's consent to use the photo, as well as the permission of any people in the photo.	☒ I confirm		
2. Consent			
I acknowledge and permit the completed report, including photos to be posted for public access on the NWT Discovery Portal.	☒ I agree		
3. Key Messages			
• Anthropogenic disturbances significantly affect boreal caribou habitats and populations.			

- However, at the relatively low levels of anthropogenic disturbance that currently exists (0.2% annual increase), the predicted herd-level population growth rates (lambda) show relatively minor change between now and 2041.
- The SpaDES tool can help building models to forecast landscape changes and their impacts, supporting proactive conservation planning.
- Natural and anthropogenic disturbance effects vary across the Northwest Territories, indicating a need for localized management strategies.
- The study highlights the value of integrated management strategies and iterative forecasting to conserve critical wildlife habitats effectively.

4. Abstract

Anthropogenic disturbances are a primary driver of global ecological changes, impacting everything from Earth's surface elements to the reproductive biology and survival rates of species such as the boreal caribou. This study harnesses the power of Predictive Ecology, using the SpaDES tool, to develop a generic simulation module for forecasting anthropogenic disturbances. Our work focuses on applying this tool to assess boreal caribou population growth. By integrating a series of predictive modules within the SpaDES framework, we forecast the cumulative effects of anthropogenic disturbances on the habitat and population dynamics of boreal caribou over a 30-year period, from 2011 to 2041. In addition to these 2 caribou indicators, we also present results from a 3rd approach: a caribou Integrated Step Selection Analysis (iSSA) for the NWT herds. We evaluate different scenarios of disturbance rates and their direct consequences on caribou populations, demonstrating significant spatial and temporal variations. The ability of our model to integrate various types of disturbances and predict their effects on such an important species offers a substantial advancement in the field of conservation ecology and provides a crucial tool for managing the delicate balance between development and wildlife conservation. This work not only emphasizes the urgency of mitigating anthropogenic impacts but also highlights the effectiveness of modular, predictive approaches in ecological conservation strategies.

5. Introduction

Anthropogenic disturbances are directly responsible for numerous global changes (Vörösmarty and Sahagian, 2000; Lamont et al., 2003; Ager et al., 2010; Friggens and Beier, 2010; Sen and Peucker-Ehrenbrink, 2012; Barlow et al., 2016; Gaynor et al., 2018; Pirotta et al., 2019). In the boreal forest, human disturbances affect soils and tree nutrition and growth (Maynard et al., 2014), wildfire patterns (Campos-Ruiz et a., 2018) and wildlife predator-prey interactions (Neilson and Boutin, 2017). Importantly, human disturbances are the most important driver of woodland boreal caribou (Rangifer tarandus caribou*; hereafter "caribou") populations decline (Superbie et al., 2019; Stewart et al., 2020), by both direct (Sorensen et al., 2008; Found et al., 2022), and indirect impacts (Neilson et al., 2022; Stewart et al., 2023). Boreal caribou are found across Canada's boreal forests, predominantly inhabiting old-growth and mature coniferous areas (Neilson et al., 2022). This species is of social and cultural importance for numerous Indigenous communities (Hummel & Ray, 2014; Borish et al., 2021) and their sharp decline over the past thirty years (Hebblewhite, 2017) highlights the urgent need for their conservation.

Caribou management and conservation, as any other species or natural resources, can greatly benefit from ecological forecasts (Tulloch et al., 2020). Predictive Ecology, the science which deals with ecological forecasts is a subdiscipline of ecology based on quantitative predictions based on models (Peters, 1977, 1982; McGill et al., 2007; Houlahan et al., 2015; Mouquet et al., 2015; Clark et al., 2001; Travers et al., 2019). It can greatly enhance conservation and natural resource management by predicting emerging risks, aiding at-risk species, and developing strategies for multiple stressors (Ednie et al., 2023) due to its PERFICT foundation – make frequent Predictions, Evaluate models, make models Reusable, Freely accessible and Interoperable, built within Continuous workflows that are routinely Tested (McIntire et al., 2022) – for iteratively building and comparing models, and testing hypotheses (Wenger & Olden, 2012; Belete et al., 2017). Nonetheless, even with piling evidence of both the negative impacts of anthropogenic disturbances on the boreal forest ecosystem and the boreal caribou (Maynard et al., 2014; Neilson and Boutin, 2017; Campos-Ruiz et a., 2018; Superbie et al., 2019; Stewart et al., 2020; Sorensen et al., 2008; Johnson et al., 2020; Found et al., 2022; Neilson et al., 2022; Stewart et al., 2023), and the importance of forecasting for effective resources and wildlife management and conservation (Dietz et al., 2018; Travers et al., 2019; McIntire et al., 2022), the availability of tools for anthropogenic disturbance forecasting is limited. There are simulation tools for specific processes such as roads (SimapD; Finke et al., 2008), and forest harvest (WS3; Paradis et al., 2021), and even modular approaches such as the one used by LANDIS-II (Scheller and Miranda, 2015), which provides both a road simulator and a harvest module. The last, which can be combined with a forest growth and mortality, a wildfire, and a pests' module, are a commendable effort in the direction of forecasting complex landscapes. However, there are, to our knowledge, no generic tools which can forecast a larger variety of different types of human disturbances concomitantly, such as mining, wind power stations, oil and gas exploration, and, importantly, seismic lines creation. This is important because of all potential positive and negative interactions between different types of disturbance (Sturtevant and Fortin, 2021). Therefore, using SpaDES (Chubaty and McIntire, 2022), our work aimed at building a generic anthropogenic disturbance simulation tool in the form of a SpaDES-compatible module. We coupled our module with a forest growth and mortality, a wildfire and a caribou collection of modules, and forecasted landscape changes and its cumulative effects on boreal caribou in the Northwest Territories, Canada.

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6. Methods

SpaDES

SpaDES (Chubaty and McIntire, 2022) is a tool for developing and sharing modular code based on the PERFICT principles (McIntire et al., 2022). It supports the creation of SpaDES compatible computer code and orchestrate their interactions. The modular part of SpaDES comes from what we call SpaDES modules, which are SpaDES' central piece. These modules represent stand-alone processes in a workflow, such as "Download and Prepare Data", "Parameterize and Fit the Model", "Make Forecasts", "Prepare Figures", "Validate the Model", "Perform Posthoc Analysis", "Present Results in a Shiny App", among others. Technically, SpaDES is an R metapackage (https://spades.predictiveecology.org/). In addition to facilitating the creation of continuous workflows, this metapackage also facilitates the implementation of various event-based models, especially those that are spatially explicit. It supports raster-based, event-based, and agent-based models. At its core, it utilizes the SpaDES.core simulation components which are based on a discrete event simulation (DES) framework. This framework promotes modularity and allows users to enhance functionality by integrating custom simulation modules (refer to SpaDES.tools and SpaDES.experiment for more information). The package includes a variety of tools for visualizing rasters and maps through quickPlot, and features caching methods for ensuring reproducibility in simulations via the reproducible package. Additional features are available through the SpaDES.addins and SpaDES.shiny packages. Lastly, the SpaDES.project package allows for the setup of projects of any complexity with a few lines of code. SpaDES is neither the sole nor the initial tool designed to assist scientists in constructing and optimizing workflows. Notable alternatives include tidyverse (Wickham et al., 2019) and targets (Landau, 2021). However, while tidyverse and targets require users to actively manage and control the workflow, SpaDES allows the workflow to organically emerge from the modules developed by contributors, which may or may not be the end-users themselves. This architecture implies that users are not required to deeply understand the intricacies of the modules within their workflow. Instead, each module within SpaDES is designed to be self-explanatory, dictating its own operational parameters, data requirements, and output specifications. Consequently, the workflow is shaped by the interdependencies among the data handled by these modules, allowing users to observe the progression of tasks as they integrate the modules.

Data Collection

The method for compiling and mapping resource potential followed Suzuki and Parker (2016) for six types of resource development. Extensive search for available datasets, even modified/improved copies was conducted to identify all potential datasets which could provide information regarding (A) existing disturbances, and (B) potential for new disturbances to be developed. For that purpose, a table was build detailing any difficulties regarding data downloading or loading. The table of all data can be found at: https://docs.google.com/spreadsheets/d/1Pc1QwEpfw13rYM1PVQzNVO-3xzb5k5E-7u0yYoVzSOs/edit#gid=267195017. Many of these datasets came from the Government of NWT data repositories.

Anthropogenic Disturbances Module

In the present work, we proposed the creation of a generic disturbance simulation tool in the form of a SpaDES module named anthroDisturbance_Generator. The workflow can be reproduced by running the R code available at https://github.com/tati-micheletti/anthroDisturbance_NT/blob/main/RunMe.R. but for testing purposes, the file https://github.com/tati-micheletti/anthroDisturbance_NT/blob/main/runMeExample.R was produced. The module proposes a generic approach to generating disturbances, by classifying these in three categories: enlarging, generating and connecting. Enlarging disturbances (i.e., potentialSettlements, potentialSeismicLines) are a class of disturbance that will be expanded outwards from the existing disturbances, simulating a disturbance which expands in terms of area from existing ones. Generating disturbances (i.e., potentialWindTurbines, potentialOilGas, potentialMineral, potentialForestry) are disturbances which are generated in new places based at rates and sizes provided by the user, or derived by data. Lastly, connecting disturbances (i.e., potentialPipelines, potentialTransmission, potentialRoads) are expected to create connections between disturbances generated and existing networks, for example, connecting generated wind power stations to existing transmission lines, oil and gas facilities to existing pipelines, and all new facilities and harvesting blocks to an existing road network. Figure 1 shows the full project workflow with connection between inputs, outputs, and all modules. Figure 2 demonstrates specifically the modules and processes of anthropogenic disturbances simulation.

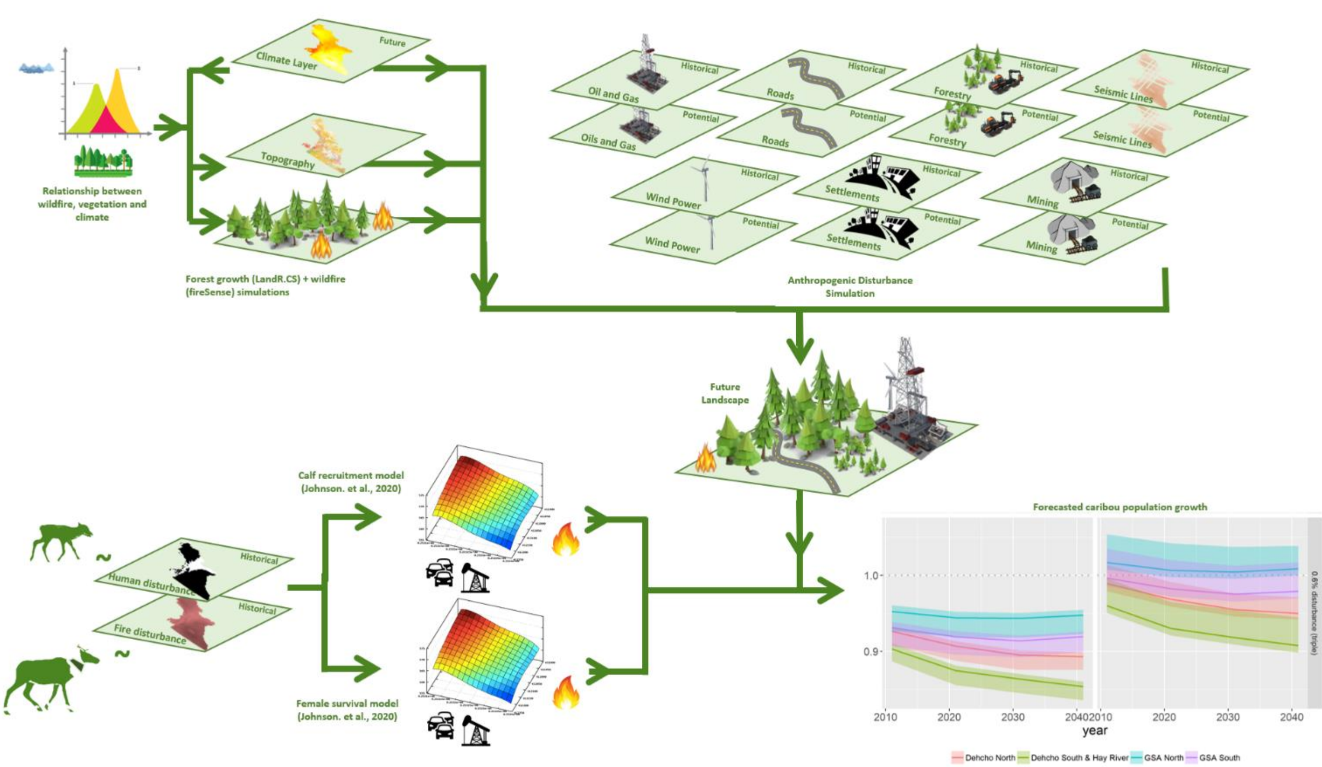

Figure 1. Inputs, outputs and relationship between landscape forecasting models and caribou population growth models and integrated step selection analysis (see text).

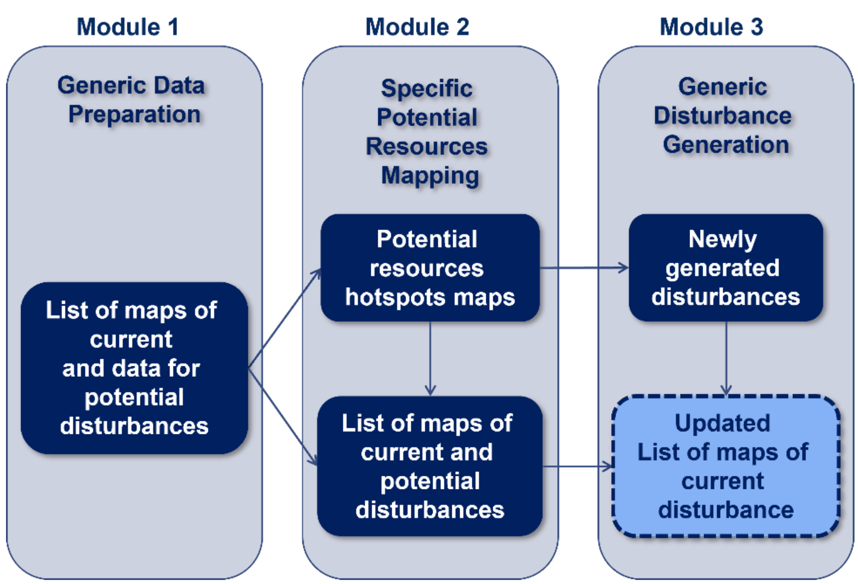

Figure 2. SpaDES modules and data flow of anthropogenic disturbances simulations.

Inputs

The module requires three objects to be provided by the user or by another module: *disturbanceParameters* and *disturbanceList,* and *disturbanceDT*. The first is a table (format .csv) with information about the sector the disturbance belongs to (i.e., Energy, Settlements, Oil & Gas, Mining, Forestry, or Roads), the name of potential disturbances (i.e., potentialSettlements, potentialWindTurbines, potentialCutblocks, potentialMines, etc.), and the disturbance type, which can be classified into Enlarging, Generating and Connecting. It is important to note that it is possible to have two entries for the same disturbance sector but using different types if, for example, both expansion and generation of new disturbances is desired (i.e., settlements) at different rates. The object *disturbanceList* is a list (general category such matching the sector) of lists (specific classes such as settlement, seismicLines, cutblocks, oilGas, etc.) containing special information (rasters or shapefiles) about the most likely locations the disturbances will happen. The higher the value, the more likely a disturbance will happen there. The last, *disturbanceDT*, is a table structured to guide the handling of spatial data by defining critical parameters for each dataset. Each row specifies the dataset's sector classification (dataName), source URL (URL), the specific polygon type to extract (classToSearch), the field containing this polygon type (fieldToSearch), and the overarching data class (dataClass). Additionally, it details the shapefile within a .zip if applicable (fileName), the data type to use (dataType), and it is set up primarily for use in the Northwest Territories unless otherwise specified by the user. Optionally, the user can also provide the study area and a raster to determine the resolution and extent of the analysis, and a *DisturbanceRate* table, which indicates the rate of increase in disturbance (in %) per year in reference to the study area. If not provided, this table will be generated by calculating the disturbance (using Environment and Climate Change data).

Outputs

The module updates the *disturbanceList* once new disturbances have been generated, and creates the *currentDisturbanceLayer*, which is a binary raster object indicating where disturbances have already occurred. Specifically, this module outputs one layer for each of the desired sectors. With default parameters, it outputs a list of layers with simulated new mines, new oil and gas facilities, forestry activities, enlarged settlements, new wind power stations, new transmission lines, new pipelines, enlarged seismic lines, and new roads connecting all new facilities to the existing networks. These outputs allow for the caribou population growth modules to use the simulated disturbances to forecast caribou population growth.

Parameters

It is also possible to change some of the module's parameters to adjust it to specific needs. An extensive list of parameters and their descriptions can be found in the module's documentation (https://github.com/tati-micheletti/anthroDisturbance_Generator).

As the module *anthroDisturbance_Generator* needs specific inputs regarding potential resources and current disturbances, two other modules were created for this purpose. The first, *anthroDisturbance_DataPrep*, is a generic data preparation module, which aims at harmonizing different anthropogenic disturbance datasets. It's primarily intended for the Northwest Territories region, but its structure is universal. It needs metadata information provided by *disturbanceDT*, described above. The second module, *potentialResourcesNT_DataPrep*, is a NWT-specific module to generate potential resources layers for the Northwest Territories. It harmonizes layers and information from different sectors, converting them into potential resources layers, which are used by the *anthroDisturbance_Generator* module to generate the disturbances.

Northwest Territories

For the NWT case study, we specifically proposed to use the SpaDES framework to (1) complete resource development potential mapping within the boreal region within the Northwest Territories, to (2) integrate the resource development potential mapping with a vegetation-wildfire-climate-caribou projection model developed for the boreal region within Northwest Territories, and to (3) simulate through time (2011-2041) the regional cumulative effects of resource development, vegetation, wildfire, and climate on boreal caribou population demographics (population change) forecasts within caribou herds. We examined three resource development scenarios within the boreal region within the Taiga Plains Ecozone in Northwest Territories: (a) Business-as-usual (BAU), a 0.2% increase of disturbances per year, which matches current disturbance increase rate in the region, (b) 0.4% (double), and (c) 0.6% (triple) increase per year. Any specific disturbance proposals (i.e., new road network, or new mines) can be included in the module by specifically adding a georeferenced layer as an input to the module, with the accompanying metadata (please see *disturbanceParameters* , *disturbanceList,* and *disturbanceDT* documentation).

The outputs from the *anthroDisturbance_Generator* module are then used as inputs by the module *caribouPopGrowth_disturbance*, which aims at harmonizing the *disturbanceList* (list of lists containing the forecasted disturbances by class and sector) into *bufferedAnthropogenicDisturbance500m*, a raster layer of disturbances buffered by 500m, which is needed by the module *caribouPopGrowthModel* (Micheletti, Chubaty & McIntire, 2023). This module simulated then boreal caribou population growth (lambda) using models produced by Johnson et al. (2020) for each individual herd within the study area. Please note that it is possible to replace such models with locally developed ones (i.e., to use yearly incoming new caribou data) with minor modifications to the *populationGrowthTable* object, as long as the predictor variables are the same (please see Johnson et al., 2020 Table 1). Alternatively, the module *caribouPopGrowthModel* can be used as template for creating custom-made models (i.e., it will be necessary code the creation of other predictors for forecasting).
While seasonality is likely an important factor for resource selection, we believe it does not play a role in the population growth model, considering these are annual models (i.e., the models consider what happened to the population through the whole year, across all seasons). Forecasts for caribou were bootstrapped 100 times using the standard error to account for the coefficient's confidence interval. The same quantile was used for female survival and recruitment, which means that both demographic variables are highly correlated. In other words, a herd that has good recruitment will also present good female survival rate. Two scenarios were then used to forecast caribou population growth: top and the bottom 10% of the bootstrapped confidence intervals of coefficients determined by Johnson et al. (2020). This was done due to the lack of information on which quantile of the data each of the herds belong to.

Caribou Integrated Step Selection Analysis

In addition to using estimating caribou populations using the national population models, we also developed an Integrated Step Selection Analysis (iSSA) whose aim is to evaluate how environmental changes and disturbances influence the behaviour of boreal caribou and build predictions of these influences to help guide the protection and management of boreal caribou. We do this by fitting an iSSA that takes movement into account. This component of the NWT CIMP effort is also an important contributor to the Western Boreal Initiative (WBI), which is a collaborative effort that was begun jointly by the Canadian Forest Service and the Canadian Wildlife Service. Because of this, this report was able to use data compiled for the WBI project as inputs as well as data from the other components (anthropogenic layers) and other data compiled for this project specifically.

We outline in Tables 1 and 2 the covariates that we used, including the reclassified land cover that was used.

Table 1. Description of data types used in iSSA and sources.

Landscape variable	Data type	Source
Landcover	Yearly high resolution forested landcover	https://opendata.nfis.org/mapserver/nfis-change_eng.html
Timber harvest	Canada forest harvest	https://opendata.nfis.org/mapserver/nfis-change_eng.html
Fires	National Burned Area Composite	https://cwfis.cfs.nrcan.gc.ca/ha/nfdb?type=nbac&year=9999
Roads	Transport Networks in Canada	https://open.canada.ca/data/en/dataset/2dac78ba-8543-48a6-8f07-faeef56f9895

Other linear features (i.e., transmission lines, seismic lines, etc.)	ECCC boreal caribou linear feature disturbance	https://catalogue.ec.gc.ca/geonetwork/srv/search?keyword=disturbance,%20boreal,%20forest,%20caribou,%20habitat,%20mapping,%20landcover,%20landuse (2010)
		https://open.canada.ca/data/en/dataset/a71ab99c-6756-4e56-9d2e-2a63246a5e94 (2015)
Polygonal human footprint	ECCC boreal caribou polygonal feature disturbance	https://catalogue.ec.gc.ca/geonetwork/srv/search?keyword=disturbance,%20boreal,%20forest,%20caribou,%20habitat,%20mapping,%20landcover,%20landuse (2010)
		https://open.canada.ca/data/en/dataset/a71ab99c-6756-4e56-9d2e-2a63246a5e94 (2015)

Table 2. Land classifications from the yearly landcover product (Hermosilla et al., 2018, 2022) and proportion available within 750m of the cleaned dataset. We reclassified the data into simpler categories so that all jurisdictions had at least 1% availability of each variable. Reclassification names represent those used when recoding the variable.

Classification	Reclassification
wetland-treed	mix forest
Broadleaf	mix forest
Mixedwood	mix forest
Coniferous	needleleaf
Bryoids	veg
Shrubs	veg
Herbs	veg
Wetland	wets
Water	open
snow_ice	open
rock_rubble	open
exposed_barren_land	open

The model

The following are the fixed effects that were fit to collar data used a mixed model approach (random effects are not shown here):

log(sl_+1)*cos(ta_) + prop_needleleaf_start:log(sl_+1) + prop_mixforest_start:log(sl_+1) + prop_veg_start:log(sl_+1) + prop_wets_start:log(sl_+1) + prop_needleleaf_end + prop_mixforest_end + prop_veg_end + prop_wets_end + log(ts_fires_end+1) + log(sl_+1):log(ts_fires_start+1) + log(ts_harv_end+1) + log(sl_+1):log(ts_harv_start+1) + log(distlf_end+1) + log(sl_+1):log(distlf_start+1) + log(distlf_other_end+1) + log(sl_+1):log(distlf_other_start+1) + disturbance_end

where "sl_" is *step length*, "ta_" is *turning angle*, "start" is the value in the pixel at the start of the step, "end" is the value at the end of the step, "prop" is *proportion*, "ts" is *time since*, "distlf" is *distance to paved/rail linear features*, distlf_other is *distance to unpaved linear features* (e.g., roads), "harv" is *harvest*, "needleleaf", "mixforest", "veg", "wets" are all land cover classes. We visualize the results of this equation fitting by mapping predictions from the model on a standardized scale of "Intensity of Selection" (from 0 to 10). We included a random slope that corresponded to each fixed effect and interaction in the model as well as a random intercept for each cluster of used/available points per step, as described by Muff et al. (2019).

As this work was incorporated as part of a larger Western Boreal Initiative effort including data from other jurisdictions, we aimed to find a collar fix rate interval that maximized data from all jurisdictions. Thus, we used all data with a 13-hour fix rate. Like other habitat selection analyses, the response variable of the model was used/available. We extracted habitat variables for each used and available point from 30m x 30m resolution rasters. The proportions of landcover types were calculated within a 750m radius, the median step length of caribou over a 13-hour interval, of the focal raster cell. Distance to values were calculated as the distance between the used/available point and the nearest linear feature. We chose this resolution to capture the variation in habitat and environmental features available to caribou as they move through the landscape.

In comparison to the DeMars (2020) resource selection function model, several differences can be observed. First, there is a difference is in how availability is defined in the model. With iSSAs the available points are defined as random points that the caribou could theoretically reach in the next step in their movement trajectory whereas the RSF defines availability randomly within the herd or home range, depending which scale is being examined. Furthermore, the iSSA incorporates movement parameters (step length and turn angle) in the model both on their own and interacting with different habitat types. Defining availability by where a caribou can theoretically move and incorporating movement parameters within the model frequently reduces biases in habitat selection estimates. Furthermore, this iSSA is based on yearly data whereas the RSF can examine data both seasonally and yearly. Lastly, we use slightly different habitat variables from different sources (Table 1) compared to the NWT RSF, as was necessary because the iSSA had to be able to be run on data outside of NWT as well. Notably, we also examined time since fire and harvest as a continuous variable, not categorical time chunks. Overall, the RSF and iSSA examine different time and spatial scales.

It is important to highlight that, at this time, the iSSA model is not directly linked to the population growth rate model; that is a future goal. The population growth rates are forecasted from Johnson et al. (2020) are aspatial and dependent only on the amount of disturbance within the herd, not the movement information provided by the iSSA.

7. Results

We have generated predictions of anthropogenic disturbance for decadal time steps, from 2021 to 2041 for three scenarios of annual disturbance rate increase: 0.2, 0.4 and 0.6% (buffered to 500 meters) of the total area. We chose 0.2% as it represents the current average annual increase that we calculated from the overall average from the datasets we had access to. 0.4% and 0.6% represent, therefore a doubling or tripling of the rate. Because we did not have current lambda estimates for each of the herds we were forecasting, we instead used an approach that makes this uncertainty explicit. Specifically, for each herd, we present results for the “top” and “bottom” (i.e., if the actual population lambda for, say Dehcho North is at the 10% quantile of what the population model predicts and also if it at the 90% quantile of the possible lambda). This allows for the projections to be used by managers who can substitute the known lambda into these plots.

Anthropogenic disturbance generation and landscape simulations

Regarding anthropogenic disturbances generated inside the caribou herds, we observed percentage increases between 64% for forestry, and 94% for seismic lines in the 30 years the analysis was performed for. Both mining and wind power plants were not generated inside the area, as both disturbances present currently low generation potential in the area (Table 1).

Table 1. *Percent simulated area disturbed by sector and type in 2011 and 2041, the rate between 2011 and 2041, the mean yearly change and percent increase in disturbance in 30 years across all caribou herds in Northwest Territories, Canada.*

Disturbance Sector	Specific Disturbance	Percent of Area 2011	Percent of Area 2041	Rate 2011-2041	Mean Yearly Change (%)	Percent Increase Disturbance
Settlements	Settlements	0.11	0.13	0.02	0.07%	84.62%
Oil and Gas	Seismic Lines	26.29	27.94	1.65	5.50%	94.09%
Forestry	Cutblocks	0.14	0.22	0.08	0.27%	63.64%
Oil and Gas	Oil and Gas Facilities	0.19	0.25	0.06	0.20%	76.00%
Energy	Wind Power	0	0	0	0.0%	0.00%
Mining	Mines	0	0	0	0.0%	0.00%

Moreover, herds differed in terms of total fire and anthropogenic disturbances simulated in 30 years. While northern herds presented a reduction in fire incidence, the southern herds presented an increase (Table 2). Differences in increase in total anthropogenic disturbance was also observed for herds (Table 2).

Table 2. *Total natural and anthropogenic disturbances from data (2011) and simulations (2041) for each caribou herd, for each disturbance increase rate scenario.*

Herd	Area (ha)	Scenario	Year	Disturbed by Fire	Anthropogenic disturbances
GSA South	2 508 394	0.2%	2011	32.32%	15.64%
			2041	12.26%	19.99%
		0.4%	2011	32.32%	15.64%
			2041	11.62%	23.78%
		0.6%	2011	32.32%	15.64%
			2041	10.95%	27.84%
GSA North	920 525	0.2%	2011	20.13%	11.63%
			2041	2.98%	14.40%
		0.4%	2011	20.13%	11.63%
			2041	2.93%	16.88%
		0.6%	2011	20.13%	11.63%
			2041	2.82%	19.80%
Dehcho North	1 718 906	0.2%	2011	28.48%	18.09%
			2041	39.21%	22.80%
		0.4%	2011	28.48%	18.09%
			2041	36.42%	27.09%
		0.6%	2011	28.48%	18.09%
			2041	33.41%	31.69%
Dehcho South + Hay River	4 608 425	0.2%	2011	12.99%	33.94%
			2041	45.29%	41.67%
		0.4%	2011	12.99%	33.94%
			2041	40.00%	47.88%
		0.6%	2011	12.99%	33.94%
			2041	34.61%	54.31%

The simulations also provided layers of each individual type of disturbance (Figure 3), which have been uploaded to an open dataset repository (https://zenodo.org/records/11061759). These layers can be freely used when planning for caribou management.

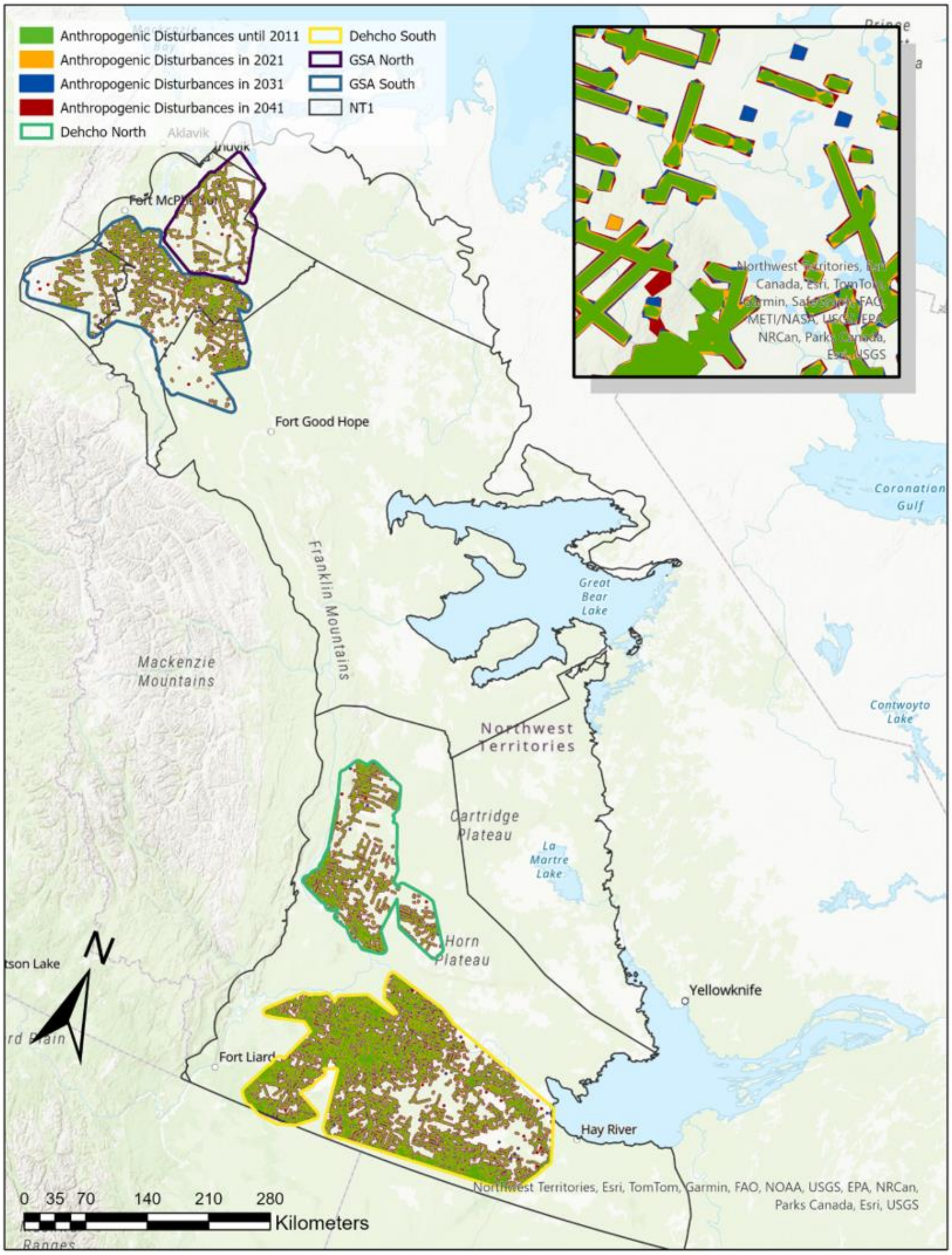

Figure 3. Disturbances generated within caribou herds in the Northwest Territories, Canada, per year.

Caribou population growth dynamics

Caribou population growth is presented in Figure 4. Assuming all herds belong to the bottom 10% quantile (i.e., in comparison to all caribou herds across Canada which were considered by Johnson et al., 2020), resulted in consistent population decline, as lambda did not rise above 1. Still, it is worth mentioning that for both BAU (i.e., disturbances increasing at 0.2% per year) and 0.4% (i.e., double the current increase rate) scenarios lambda was higher by 2041 than in 2011 for both GSA populations. In contrast, both Dehcho populations presented consistent decline of lambda for all scenarios and population quantiles. The only population that presented uncertainty above 1 (i.e., positive population growth) was GSA North for the BAU scenario, for top 10% quantile.

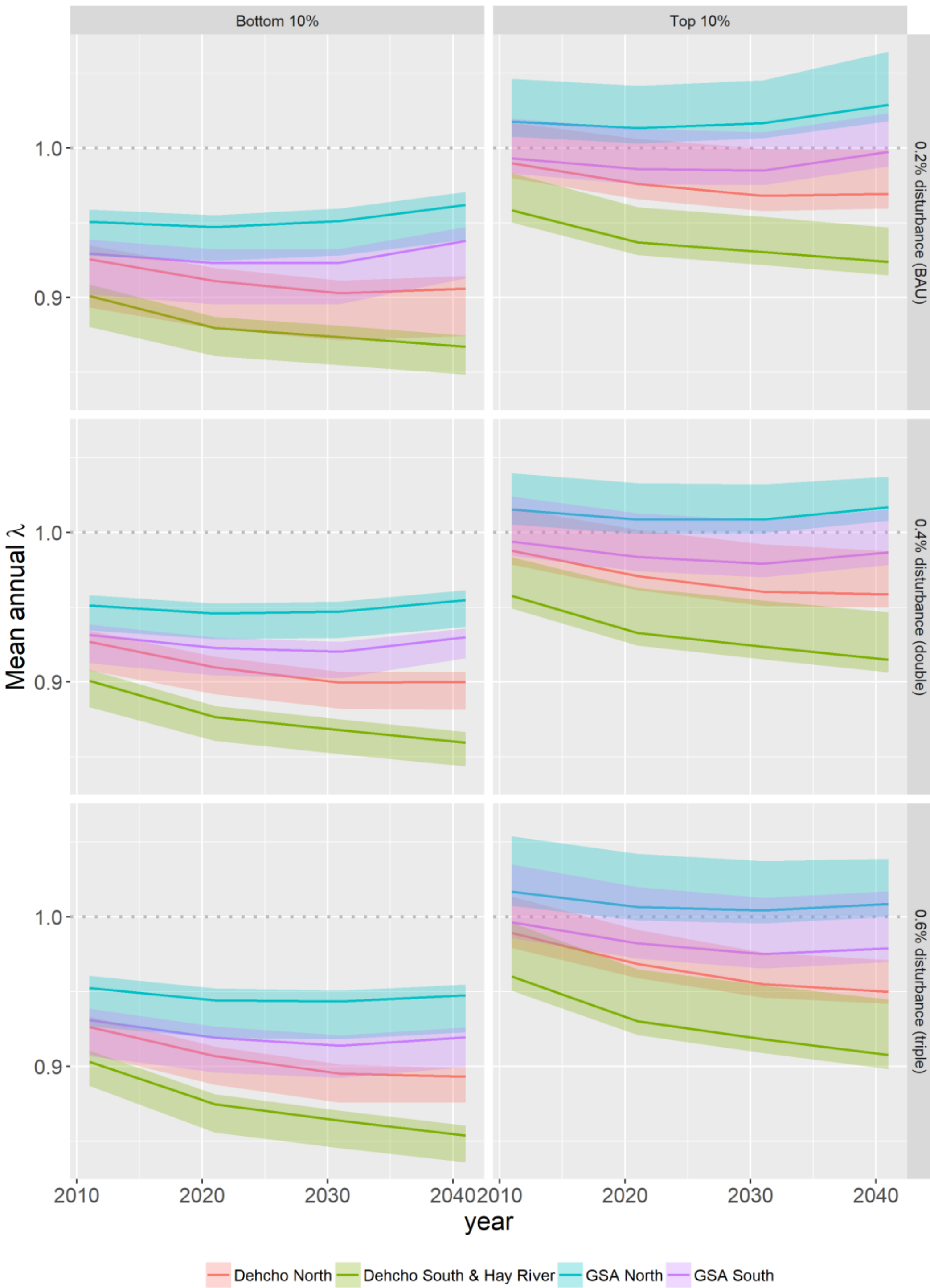

Figure 4. Caribou population growth (lambda) forecasts for NT1 herds for three disturbance scenarios assuming herds belong to both bottom and top 10% quantiles of all Canadian herds.

It is important to highlight, that at the time the project was developed the caribou population growth rate for NWT herds was not available to us. The next iteration of simulations will, however, will take into consideration the data available (data sharing agreement has already been signed) and the results will be updated based on the available data.

Caribou Integrated Step Selection

NWT-specific model

We show results for the NWT herds based on data from 2015-2020 (Figure 3). This figure shows, in general, how habitat selection, when movement is accounted for, varies through space. There is no obvious spatial pattern at the scale of NWT in the results.

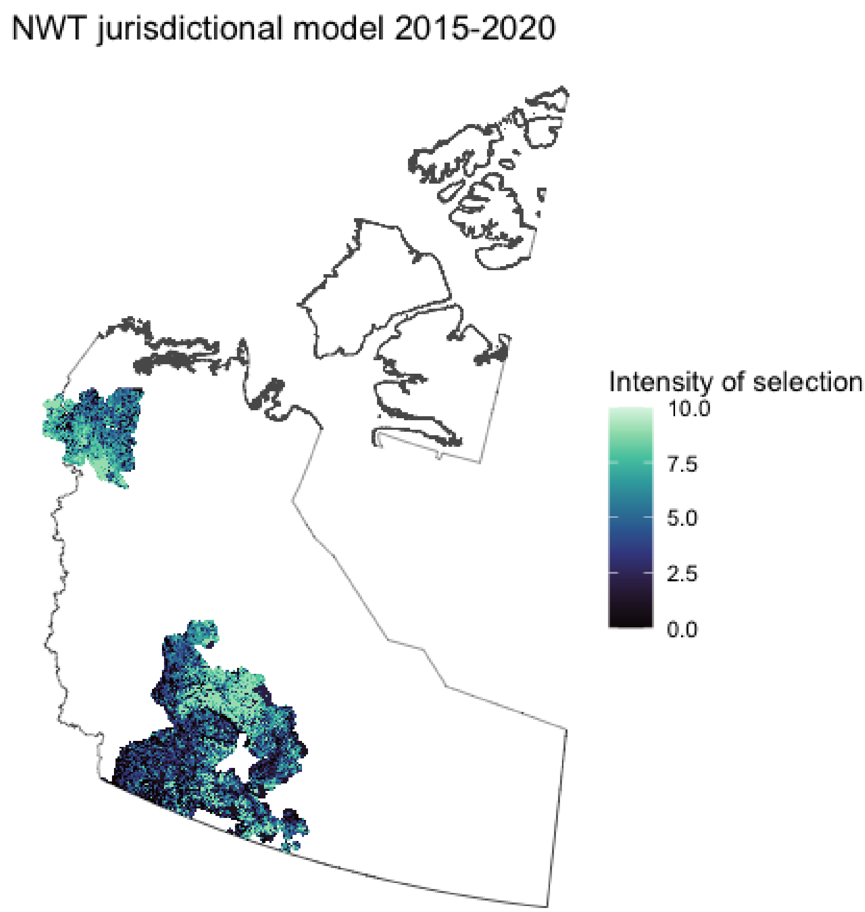

Figure 3. Intensity of use for the years based on CIMP forecasted disturbance for caribou in NWT from collar data between 2015-2020. *Intensity of selection* is an index rescaled from 0 to 10, that demonstrates how strongly different places are selected ("relative selection"), given what is available and what is accessible (this is what distinguishes these from a more traditional Resource Selection Function).

Forecasts

We produced forecasts for 2041 combining the iSSA model and the anthropogenic forecasts presented here. The difference map suggests a tendency towards worsening conditions in the north and improving in the south. These results include climate sensitivity of the vegetation and changes coming from wildfires; however, they do not include land changes (e.g., permafrost collapse, tundra encroachment) due to climate.

Figure 4. iSSA forecasts for NWT.

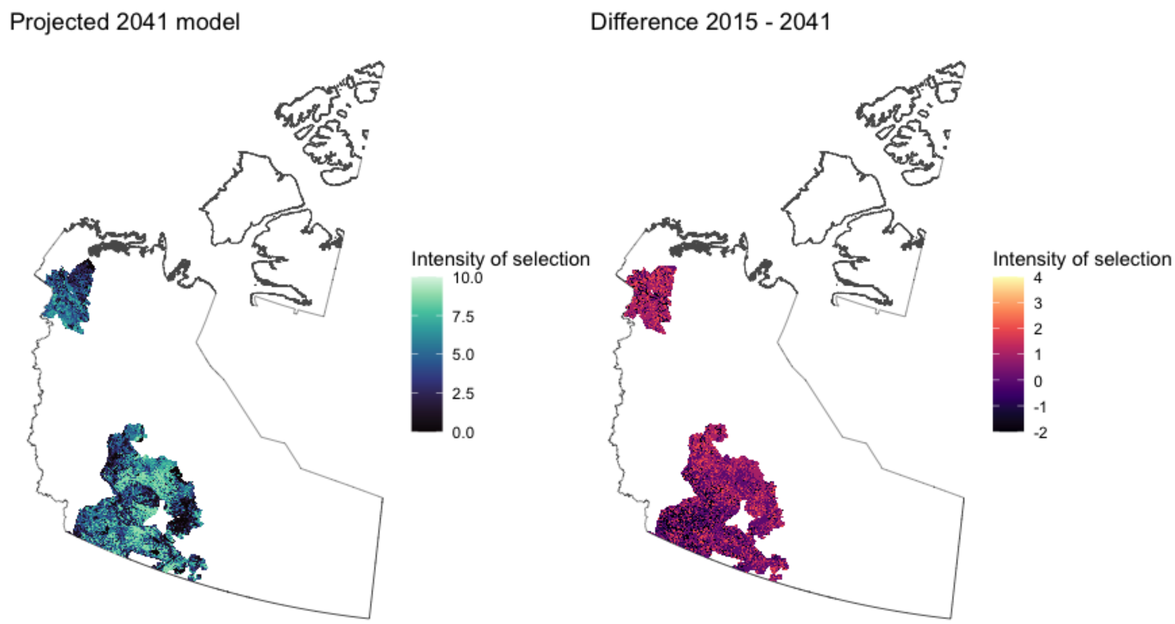

Figure 4. iSSA forecasts for NWT.

Larger context – Western Boreal

We also include the iSSA at the larger Western Boreal Initiative context, as it provides helpful information to interpret the NWT-specific results (Figure 5). For example, in the selection intensity in southern NWT (subplots A and B) is dramatically higher (suggesting dramatically better habitat) than immediately across the BC border. Yet, it also suggests that the declines in the southern NWT are in the same range as declines elsewhere (i.e., purple that is also in BC), but may be stronger than places such as SK.

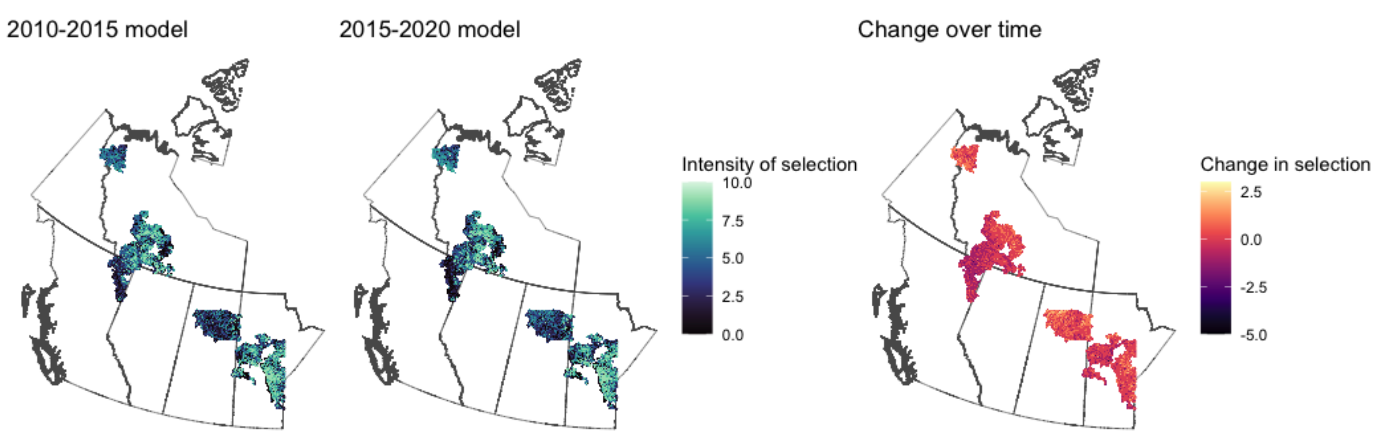

Figure 5. iSSA results for larger Western Boreal Initiative context.

8. Discussion

Using SpaDES (Chubaty and McIntire, 2022) we have developed a generic anthropogenic disturbance simulation tool as a SpaDES-compatible module, implemented using the PERFICT principles for predictive ecology (McIntire et al., 2022). This module was integrated with additional modules for forest growth and mortality, wildfire, and caribou population growth and allowed us to forecast landscape changes and their effects on boreal caribou in the Northwest Territories, Canada. Such a framework has been used under an iterative forecasting effort (i.e., taking the next steps after Stewart et al., 2023). Iterative forecasting is essential in ecological studies as it allows for the continuous refinement of predictions and management strategies based on the latest data, models, and techniques. By repeatedly updating forecasts, we can address uncertainties and adjust predictions to better reflect real-world conditions. This process is useful for this study, where environmental dynamics are complex and influenced by multiple interacting factors, presenting cumulative effects. Ultimately, such an approach enhances the accuracy and reliability of conservation efforts, ensuring they remain effective in the face of ongoing ecological shifts.

Anthropogenic disturbance generation and landscape simulations

We showed that it is possible to generate anthropogenic disturbances using the approach of generic classification of disturbances in three categories: enlarging, generating, and connecting. Despite the availability of disturbance simulation models for specific processes (i.e., road building, harvesting, etc.), there is a persistent incompatibility among different ones due to different languages and frameworks underlying the modules (i.e., ws3 written in python, SimapD written in Java, LANDIS-II written in C++). Here we demonstrated the power of genericizing processes using R, a largely known language to researchers (Lai et al., 2019). Our framework allows for any disturbances to be forecasted anywhere in the globe, provided information on potential resources are compiled by the user or, in the case of the Northwest Territories, the additional modules created by the current work (*anthroDisturbance_DataPrep* and *potentialResourcesNT_DataPrep*) are deployed in the workflow.

Herds presented different amounts of wildfire and different amounts of anthropogenic disturbances, with Northern herds having a reduction area burned through time, and less susceptible to increase in anthropogenic disturbance. This reflects the current development level in the region, as well as the landscape characteristics. Marked spatial differences in forest growth, mortality and species dynamics, and wildfire has been previously shown for this region (Stewart at al., 2023), corroborating the current findings and what has been demonstrated for wildfire in Canada (Marchal et al., 2019). Such factors can be important to consider when planning caribou conservation and recovery in the Territory, as conservation efforts can be directed to more stable herds, while recovery efforts can be directed toward more susceptible ones.

Due to the iterative and stochastic nature of forecasting anthropogenic disturbances, the total final disturbances varied from the originally requested scenarios (0.2%, 0.4% and 0.6% increase per year). The greatest variation was observed for the most extreme scenario (0.53% instead of 0.6%), while the BAU scenario presented the exact requested increase. Such difference between requested and realized disturbance rates can be fine tuned in this case by reducing parameters (i.e., *growthStepEnlargingPolys* and *growthStepEnlargingLines*) in the module. This changes, however, has a strong *tradeoff* with runtime. The current modules can be run for the study area tested in approximately 24 hours, but reducing the "step-size" for generating disturbances can lead to significant increases in runtime.

Future modelling directions

Currently, seismic lines changes are being forecasted by increasing the width of current lines up to the expected percentage of the area disturbed. Although this reduced the potential of the module to be used for integrated step (Avgar et al., 2016) and resource selection (Jones and Tonn, 2004; Saher and Schmiegelow, 2005) analysis, it does not influence population growth models (Johnson et al., 2020), as proposed by the current work. Yet, reformulating how seismic lines can be generated could allow for the use of this module to generate disturbances to forecast caribou movement in addition to population growth. Moreover, roads in *anthroDisturbance_Generator* are created using the shortest path between the disturbance and the respective network, which ignores costs of construction. Although at a landscape level this might represent a very small fraction of the total disturbance, it is planned to be improved in future versions by the adoption of the R package roads (Endicott et al., 2023). Lastly, by recovering information from lambda for each herd could significantly improve the results, as herds can be placed in the exact quantile they present currently, reducing the uncertainty in relation to herds' growth rates even more.

Caribou Habitat Selection using Integrated Step Selection Analysis

We present the first effort at forecasting caribou habitat selection using forecasts of anthropogenic disturbance. The overarching patterns at the broad scale demonstrate a shifting in habitat quality towards the northeast (for the Dehcho, Hay River herds), with no clear directional change in the GSA herds. It will be important to evaluate these forecasts again with updates to data and models that will occur over time. It will be interesting to compare these results with current Resource Selection Function approaches that have more and finer resolution of covariates, but no "movement" biology included. We anticipate a peer reviewed publication presenting these results soon.

Caribou population growth and management considerations

Caribou population growth has been forecasted for Northwest Territories herds using the same models and module (i.e., caribouPopGrowthModel) this study used (Stewart et al., 2023). While Stewart et al. (2023) concluded that population growth showed little change during the simulated period, our present work shows more nuanced changes in lambda and an important reduction in uncertainty. The current work responded to previous calls for critical thought when incorporating sources of uncertainty (Stewart et al., 2023) by producing forecasts based on quantile assumptions. Due to the incorporation of explicit anthropogenic disturbance forecasts and these improvement in uncertainty, the present results will be more informative to managers. Importantly, our conclusions are in accordance with several previous boreal caribou studies (Sorensen et al., 2008; Maynard et al., 2014; Neilson and Boutin, 2017; Campos-Ruiz et a., 2018; Superbie et al., 2019; Johnson et al., 2020; Stewart et al., 2020; Found et al., 2022; Neilson et al., 2022; Stewart et al., 2023): management and restoration of critical habitat for boreal caribou should receive increased focus due to, not only the significant impacts of climate-driven vegetation changes and wildfires, but the potential cumulative effects with anthropogenic disturbance.

9. Community Engagement, Communication, and Capacity-building

We have been actively involved in community engagement and communication of project results. As an example, results from our simulations have been translated into native languages (Figure 5) and we are in the process of producing an infographic to showcase our findings for this specific project (that will also be translated), which demonstrates how we are aiming at communicating the results from this work to Indigenous Peoples in the Northwest Territories. Results from this study will be shared widely by our many collaborators at upcoming community meetings across NWT, scientific conferences, and in peer reviewed journals. Moreover, our group has been participating in boreal caribou range planning and survival project meetings since February 2020. There is a trip planned to Yellowknife on 18-20th June to present the results from the current project as well as discuss plans for moving forward with this research.

We admit that COVID happened during the 3 years of this project. This severely hampered and modified our plans for engagement. As described in the previous paragraph, we are attempting to address this in the coming months.

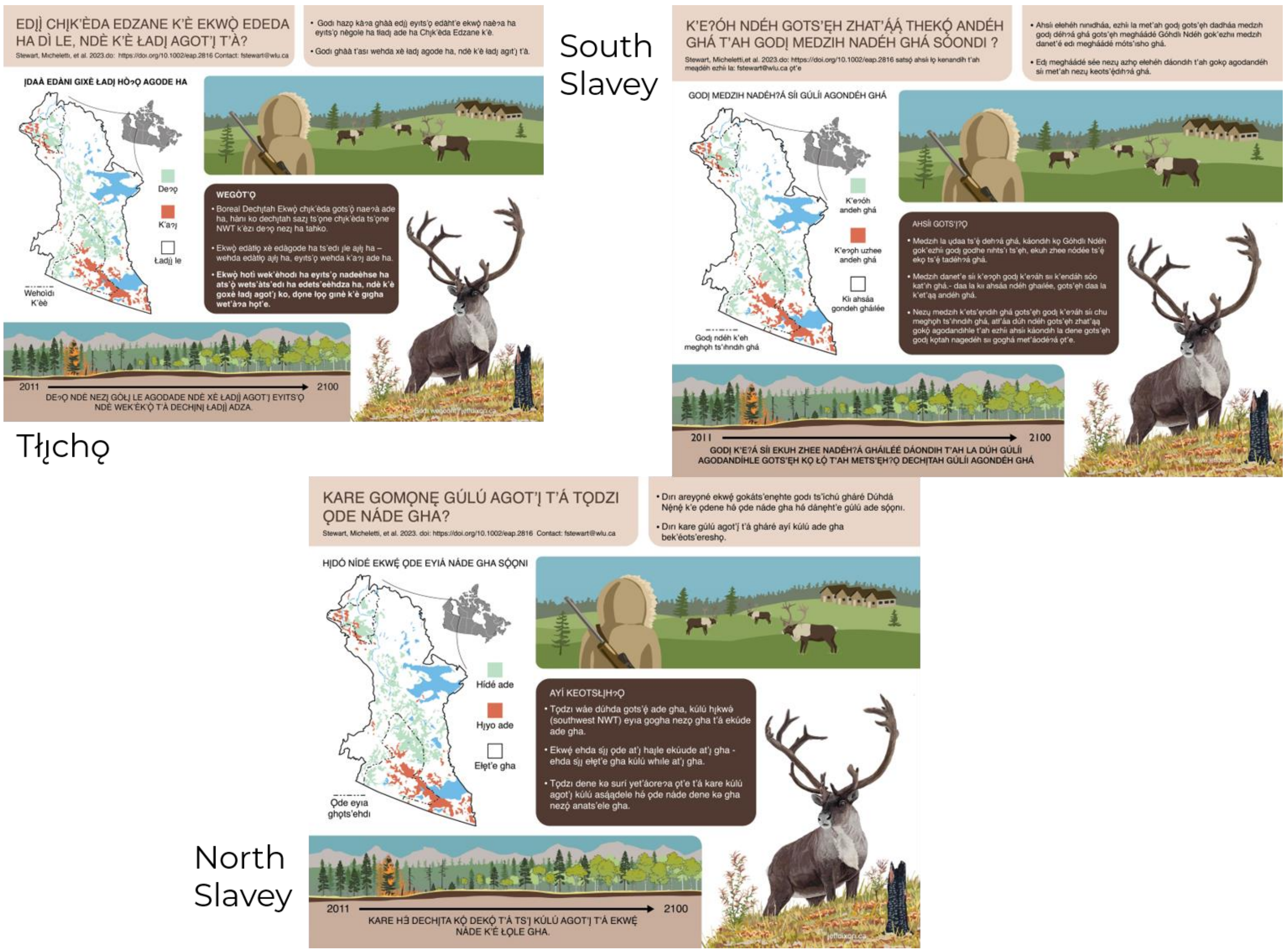

Figure 5. Caribou research project translated into Northwest Territories Indigenous languages.

10. Key Information Needed by NWT CIMP

Check all boxes that apply for the project and provide a brief explanation.

This project …		Briefly explain/describe
Directly impacted a current decision-making process	☒	The working group at the Wek'eezhii boreal caribou range planning unanimously voted on April 28, 2022 to integrate these results into the range plan, marking a significant step forward in species at risk planning in Canada. Results from our study are part of the public registry of Norman Wells 2024 public listening session (SRRB).
Could contribute to a future decision-making process	☒	As our work includes the area of Northwest Territories as a whole, all results from the work can be used for future decision-making process, especially with regards to caribou range planning. Highlights levels of anthropogenic disturbance, in which herds, show more likely negative population growth rates (lambdas) over the next 30 years.

Responded to a community concern	☒	In response to community concerns, the project team presented the NWT caribou results at the Wek'eezhii boreal caribou range planning meeting on April 28, 2022. There was robust engagement and high interest in the uncertainty and forecasts provided by our work. We are in the proceed of getting feedback from the community on the results of this study and looking forward to addressing any questions or concerns that may emerge.
Led to new or enhanced knowledge of cumulative impacts	☒	The work developed has generated future projections of anthropogenic disturbance differentiated by type.
Developed or used of a standardized monitoring protocol(s)	☐	N/A
New or enhanced community capacity	☐	N/A
Led to new or enhanced analytical tools, modeling capacity, or other	☒	The work developed has generated a new tool for forecasting anthropogenic disturbances, which can be used in iterative forecasting cycles. This modelling approach is well suited to braid different knowledge systems (i.e., Traditional Knowledge and Western Science).
Presented to a community audience	☒	• Edehzhie Management Board Staff. Presentations/emails exchanges to help inform management and monitoring plans. • Wek'eezhii boreal caribou range planning meeting (Online): April 28, 2022 • CIMP meeting in Fort Smith: 12 Jan, 2024 • Boreal caribou survival project participants (planned meeting): June 20, 2024 • North Slave Métis Alliance, Wildlife Speaker Series, Apr 17, 2023 • Nę K'ə Dene Ts'ı̨lı̨ Forum Meeting, Feb 03, 2023
Other:	☐	

11. Deliverables

Deliverables identified in proposal	Fiscal Year	Who was it provided to?	Sent to NWT CIMP? Yes/No (*if no, state reason*)	I acknowledge and permit posting for public access on the NWT Discovery Portal
Objective 1A. Develop standardized methods to compile and map resource potential for 5 types of resource development following methods in Suzuki and Parker (2016): (1) forestry, (2) conventional oil and gas extraction and development, (3) mineral	2021	**File:** disturbanceDT.csv **Open Access at:** https://docs.google.com/spreadsheets/d/1Pc1QwEpfw13rYM1PVQzNVO-3xzb5k5E-7u0yYoVzSOs/edit#gid=267195017	Yes	☒ I agree

mining, (4) wind power, (5) linear features and road development.				
Objective 1B. Compile/assemble GIS layers and map resource potential for these 5 types of resource development.	2021	**File:** disturbanceDT.csv **Open Access at:** https://zenodo.org/records/11061759/files/INPUTS.zip	Yes	☒ I agree
Objective 2A. Develop the resource development potential (RDP) module to simulate resource development within historic caribou range for the 5 types of resource development (see Component 1).	2022	**File:** anthroDisturbance_Generator.R **Open Access at:** https://github.com/tati-micheletti/anthroDisturbance_Generator	Yes	☒ I agree
Objective 2B. Apply the LandR forest vegetation module to simulate forest vegetation dynamics and forest harvest as a measure of range condition within caribou range.	2022	**Files:** cohortData_YYYY_yearYYYY.qs pixelGroupMap_YYYY_yearYYYY.tif **Open Access at:** https://zenodo.org/records/11061759/files/RESULTS%20-%20Forest%20Growth%20and%20Mortality.zip	Yes	☒ I agree
Objective 2C. Apply the fireSense module to simulate wildfire dynamics within caribou range.	2022	**File:** rstCurrentBurnList_run1.tif rstCurrentBurn_YYYY_yearYYYY.tif **Open Access at:** https://zenodo.org/records/11061759/files/RESULTS%20-%20Wildfire.zip	Yes	☒ I agree
Objective 2D. Apply boreal caribou modules to simulate caribou resource selection and population demographics (reproduction/ recruitment, mortality, survival).	2023	**File:** populationGrowth.csv **Open Access at:** https://zenodo.org/records/11061759/files/RESULTS%20-%20Boreal%20Caribou.zip	Yes	☒ I agree
Objective 3A. Run a simulation assuming no further resource development (BAU scenario, 0.2%).	2024	**File:** disturbances_SECTOR_TYPE_YYYY_NT_CanESM5_SSP370_0.2_herds_run01.tif **Open Access at:** https://zenodo.org/records/11061759/files/RESULTS%20-%20Anthropogenic%20Disturbances%20Scenario%200.2.zip	Yes	☒ I agree
Objective 3B. Run a simulation assuming a 0.4% increase per year.	2024	**File:** disturbances_SECTOR_TYPE_Y	Yes	☒ I agree

		YYY_NT_CanESM5_SSP370_0.4_herds_run01.tif **Open Access at:** https://zenodo.org/records/11061759/files/RESULTS%20-%20Anthropogenic%20Disturbances%20Scenario%200.4.zip		
Objective 3C. Run a simulation assuming a 0.6% increase per year.	2024	**File:** disturbances_SECTOR_TYPE_YYYY_NT_CanESM5_SSP370_0.6_herds_run01.tif **Open Access at:** https://zenodo.org/records/11061759/files/RESULTS%20-%20Anthropogenic%20Disturbances%20Scenario%200.6.zip	Yes	☒ I agree
End of year additional funds from Fiscal Year 2022-23. Integrated Step Selection Function model results.	2023	**Files:** https://drive.google.com/drive/folders/1URX1kVezld2MPxv8laZ-RaYvv6DOegcp?usp=sharing	Yes	☒ I agree
Additional Deliverables	**Fiscal Year**	**Who was it provided to?**	**Sent to NWT CIMP?** Yes/No (*if no, state reason*)	**I acknowledge and permit posting for public access on the NWT Discovery Portal**
Presentation of the Project (Jan 2024)	2024	Open Access at: https://zenodo.org/records/11061759/files/PRESENTATION.zip	Yes	☒ I agree

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Thank you for your submission!