Moose (*Alces alces*) Habitat Suitability Modelling in Northern Ontario

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Abstract

The impacts of forestry practices on moose (*Alces alces*) habitat suitability in Northern Ontario are increasingly becoming of concern to Indigenous communities who rely on moose for subsistence, culture, and traditional practices. In light of declining moose populations across Ontario, increasing forestry pressure, land use change, and concerns raised by local Indigenous communities regarding the impact of clear-cuts and glyphosate application on moose habitat, we have created a moose Habitat Suitability Index (HSI) model for the roughly 1.63×10^6 ha Missinaibi Forest Management Unit (FMU), located east of Wawa, ON. Our model used 6 suitability criteria we identified as being relevant through a thorough review of the Ontario Ministry of Natural Resources (OMNR) forestry biodiversity conservation guidelines, and available scientific literature and Indigenous Traditional Ecological Knowledge (TEK), including snow depth, snow interception, food source preferences, roads, open water bodies, and scheduled forestry harvests. While our findings are preliminary, our results demonstrate the potential significance of including recently harvested forest data in HSI models. For our model we found that highly suitable areas of moose habitat are mainly distributed along the edges of the Missinaibi FMU, with these areas being fragmented and often quite small in comparison to an adult moose's typical home range. Further, 17.74% of the Missinaibi FMU was found to have suitable habitat at a level greater than 50%. We recommend that our model is further expanded to better understand the impacts of forestry on moose habitat suitability in Northern Ontario across a larger extent (i.e., across multiple FMUs) to get a better idea of moose population-level dynamics.

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Introduction

National declines in moose (*Alces alces*) populations pose a threat to the food security, culture, and traditional practices of Indigenous communities in Canada (F. Moola, lecture notes, GEOG*3210, 2022; Priadka et al., 2022). Like caribou, moose have served and continue to serve as an important part of many Indigenous People's diets as both a subsistence and traditional food, as a single animal can yield as much as 300 kg of meat, an excellent source of protein, iron, and other vitamins, alongside hair and hide, which can be used to make durable clothing and other commodities (Health and Social Services [HSS], 2017; Kuhnlein & Humphries, n.d.; F. Moola, lecture notes, GEOG*3210, 2022; Priadka et al., 2022). Upheld by the R. v. Powley (2003) ruling, which recognized Métis rights to hunt, under Section 35 of the 1982 Constitution, Indigenous Peoples have the right to harvest moose and other wildlife to meet their food needs, without provincial nor federal hunting regulations (Priadka et al., 2022; Salomons & Hanson, n.d.). While not without outside opposition, community-level Indigenous governance has allowed for the continued harvest of moose and other wildlife in a sustainable manner (Priadka et al., 2022). However, with recent local and regional declines in moose populations across North America (Bell, 2022; Suzuki, 2022; Timmermann & Rodgers, 2017), Indigenous governance over hunting limits and Indigenous food security are being threatened (Allen, 2022; Natural Resources and Northern Development [NRND], 2022; White, 2017), which is of great concern to Indigenous communities across Canada.

While not as publicized as the national decline in woodland caribou (*Rangifer tarandus caribou*) (Environment Canada, 2018), moose population declines have been widely reported by governmental, non-governmental, and Indigenous authorities alike for the past couple of decades (Ministry of Natural Resources and Forestry [MNRF], 2022; Priadka et al., 2022; Suzuki, 2022; Timmermann & Rodgers, 2017). From MNRF (2022) aerial moose counts, the moose population in Ontario has decreased to an estimated 91,200 individuals, from the est. 115,000 peak in the early 2000s (Arangio & MacDonald, 2023). This decline has been proposed to be attributed to a multitude of factors including: habitat loss, fragmentation and degradation (Fischer & Lindenmayer, 2007), climate change (Hoy et al., 2018; MNRF, 2022; Weiskopf et al., 2019), disease outbreaks (Ranta & Lankester, 2017), increased moose-vehicular collisions (Cunningham et al., 2022), and predator interactions (e.g., decreased canopy cover, increased snow depth, predator facilitation) (Keech et al., 2011). Of particular interest for this project and of rising acknowledgement and concern is the impact of forestry operations on moose populations in Ontario (Connor & McMillan, 1990; Crête 1988; Koetke et al., 2023; Milner et al., 2013; Ontario Ministry of Natural Resources [OMNR], 2010; Schreiber, 2016).

Of particular concern to Indigenous communities, regarding the impacts of the forestry industry on moose populations, is the direct and indirect impacts of herbicides, specifically glyphosate, on their food sources (Kayahara & Armstrong, 2015; LeBlanc et al., 2011; Schreiber, 2016; Traditional Ecological Knowledge [TEK] Elders Group, n.d.). While observations by hunters connecting the herbicide to direct health impacts on moose, e.g., tumours and other abnormalities (TEK Elders Group, n.d.), have yet to be backed by non-governmental nor governmental Western (non-Indigenous) science (Health Canada, 2020; Rolando et al., 2017), multiple studies have documented the negative indirect impacts of glyphosate on moose food sources, including immediate loss of food sources (Connor & McMIllan, 1990), long-term reduced vegetation (Guiseppe et al., 2006), multi-year persistence of glyphosate residues in vegetation (Edge et al., 2021), and increased disease outbreak (van Bruggen et al., 2021). Despite these findings, and the knowledge of Indigenous Peoples' reliance on moose, other wildlife, and medicinal plants (Kayahara & Armstrong, 2015; Priadka et al., 2022), glyphosate application is still permitted in Ontario, and is only mentioned in regard to moose habitat, under "best management practices", i.e., a suggestion, not a strict guideline (OMNR, 2010), further raising concern.

In addition to the impacts of herbicides on moose populations, forestry contributes significantly to moose habitat loss, fragmentation and degradation (Koetke et al., 2023), changes in predator and other inter-species interactions (e.g., increased disease transmission between caribou and moose) (Faust et al., 2018; Gilch, et al., 2011; Keech et al., 2011), and increased moose-vehicular collisions (Cunningham et al., 2022; Fraser & Thomas, 1982). Thus, this raises the question of how much of the moose habitat in northern Ontario is indeed suitable for self-sustaining moose populations.

The distribution of a species' suitable habitat in any region is an inherently spatial problem, and through the use of a Habitat Suitability Index (HSI) model, using a Multi-Criteria Evaluation (MCE), suitable habitat can be identified (Verner & Morrison, 1986). Previous studies have evaluated moose habitat suitability in regions of Ontario and Québec (Dussault et al., 2006; Naylor & Christilaw, 1992; Tendeng et al., 2016), and elsewhere in the world (China (Zhi et al., 2022), Finland (Kurttila et al., 2002), Sweden (Dettki et al., 2003)), using HSI models and varying combinations of the suitability factors previously mentioned. For our project, we specifically focused on moose habitat suitability for moose populations in the Missinaibi Forest Area in the northeast Superior Region of Ontario, situated on Treaty 9 land, which to our knowledge, has yet to be evaluated at the local scale.

This project was prompted by concerns raised by local First Nations communities (Chapleau Cree First Nation (FN), Missanabie Cree FN, and Brunswick House FN), regarding moose population declines in their region, in relation to increasing forest harvest and herbicide use (McCulloch, E., personal communication, February 6, 2023). Our model's purpose is to support ongoing research by MSc candidate Elena McCulloch, School of Environmental Sciences at the University of Guelph, that aims to produce a moose HSI model for the Missinaibi Forest Area which employs Traditional Ecological Knowledge (TEK), i.e., ecological knowledge gathered by Indigenous People from long-term involvement in local ecosystems (Menzies, 2006), governmental and non-governmental data and observations, and the recent scientific literature, by providing a preliminary model incorporating Ministry guidelines (Ministry of Natural Resources [MNR], 2010) for "winter moose emphasis areas" and "moose aquatic feeding areas and mineral licks", relevant scientific literature, local forestry operations (GreenFirst Forest Products [GreenFirst], 2022), and local concerns regarding glyphosate use (McCulloch, E., personal communication, February 6, 2023). Thus, our research objectives were as follows:

Research Objectives

1. Determine the relevant criteria for moose habitat suitability based on information available from the Ontario Ministry of Natural Resources and current literature (Western and Indigenous (TEK) science).

2. Collect data based on criteria relevant to moose habitat suitability, as identified in Objective 1. Use layers attained from the data to build a habitat suitability MCE model for moose.

3. Use resulting MCE model to determine areas of suitable moose habitat (i.e., evaluate the impacts of several environmental, ecological, and anthropogenic factors on the Missinaibi Forest region).

4. Determine areas of improvement in data availability while evaluating the strengths and weaknesses of the model relative to existing habitat suitability models or general knowledge and observations.

Study Area

This study took place in the Ontario Shield boreal forest of northern Ontario, specifically in the Lake Abitibi ecoregion, which is dominated by mixed and coniferous forests (MNRF, 2022). For our project, we focused on the Missinaibi Forest Management Unit (FMU) (previously the Martel-Magpie FMU) (see Figure 1), due to concerns raised by local First Nations communities regarding links between declining moose populations and increased forestry activity in this region.

The Missinaibi FMU encompasses a total area of 1,631,921 hectares (ha), of which 90% is forested (Rayonier Advanced Materials [RYAM], 2021). Of the total forested area, 1,200,466 ha is considered to be productive forest (non-productive forest being treed muskeg, open muskeg, brush, alder and rock) (RYAM, 2021). For the 2022-2023 period, GreenFirst (2021) have scheduled to harvest 37 910 ha of this productive forest area. The dominant merchantable tree species are poplar, white birch, spruce, pine, fir, cedar, and other conifer species (Tamarack and Hemlock) (Forest Edge, 2022). The preferred silviculture treatment across the FMU is a clearcut, with a conventional harvest method, where ≥ 25 stems (trees) are left per hectare (a minimum of 5 of which are large stem trees) (RYAM, 2021). Further, GreenFirst (2021) employs the use of aerial herbicide (glyphosate) application to remove competing vegetation post-planting of conifer seedlings, which targets aspen, balsam, poplar, alder, willows, and grasses.

While it is necessary that future research looks at moose habitat suitability over a wider area, i.e., multiple FMUs, due to the importance of habitat connectivity and wildlife corridors for moose population-level dynamics (Courbin et al., 2014), given the time constraints, this was too ambitious for our study. To expand on this, each Forest Management Unit is held by a different license holder (OMNR, 2010). For the Missinaibi FMU, GreenFirst Forest Products (previously RYAM Forest Management), is individually responsible for adhering to Ministry standards and guidelines, and making use of suggested best management practices, to preserve moose habitat in accordance with the OMNR (2010) "Forest Management Guide for Conserving Biodiversity at the Stand and Site Scales" (GreenFirst, 2021). Further, to garner an accurate idea of the current status of the forest, we had to look at reported harvested/planned harvest areas and forestry practices (i.e., silviculture practices (planting/forest regeneration, use of herbicides, etc.)), which are reported at a FMU level (see Figure 1), Natural Resources Information Portal, 2021).

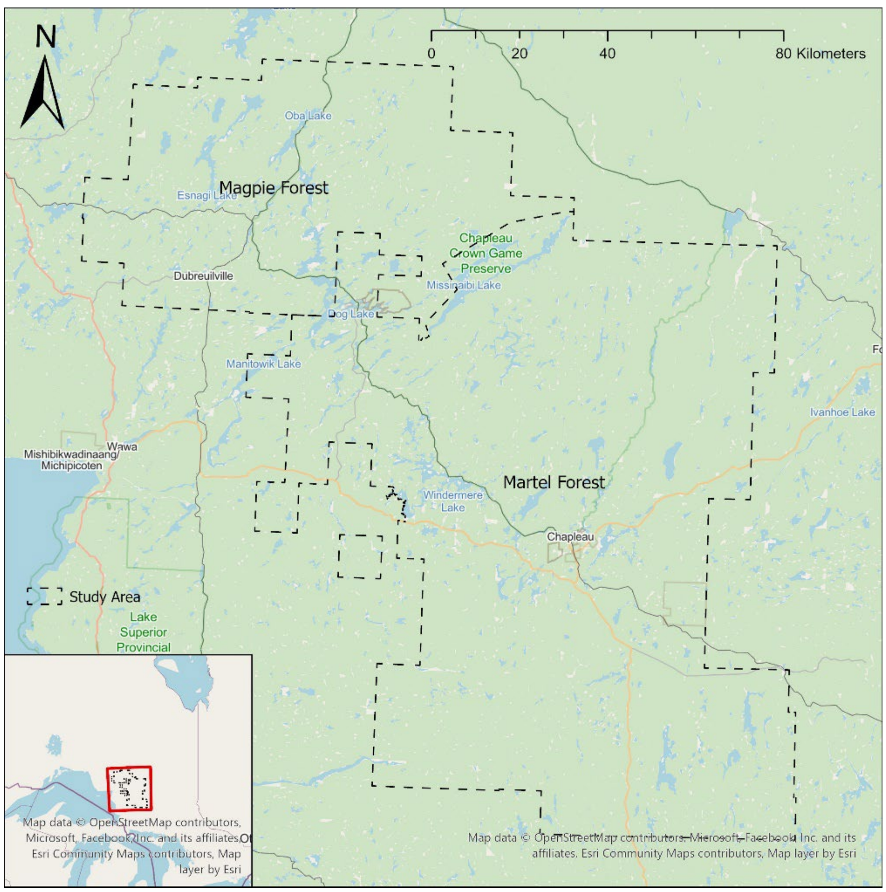

Figure 1 Map of the Missinaibi (previously Martel-Magpie) Forest Management Unit (FMU) boundary. The merging of the Martel and Magpie FMUs was initiated in 2020, which resulted in the dissolution of the administrative boundary between the two original forests (Environmental Registry of Ontario, 2020). Data from the Ontario GeoHub (Land Information Ontario, 2021).

Data & Methods

Suitability Criteria Selection and Accompanying Datasets

Through our review of the available scientific (non-governmental), governmental, and Indigenous teachings (TEK)-based literature, we identified six suitability criteria to include in our model: snow depth, snow interception (capacity) – tree species, food source – tree species, roads, distance from nearest open water body, and scheduled forestry (clear-cut, herbicide application). See Table 1 for the inclusion of these suitability criteria in previous scientific and governmental moose habitat suitability models and literature.

*Table 1. Suitability criteria for moose identified in a sampling of papers reviewed in preparation for the construction of our HSI model. x denotes the identification of the criteria in the paper, which was subsequently used in the researchers' HSI model. * indicates the identification of the criteria in the paper, which was then cited as a recommendation for future studies or as a limitation of the study (highlighting importance of the criteria).*

Criteria	Naylor & Christilaw (1992)	Puttock et al. (1995)	Rempel et al. (1997)	Koitzsch (2002)	Dussault et al. (2006)	OMNR (2010)	Tendeng et al. (2016)	Zhi et al. (2022)
Snow Depth		x	x					x
Snow Interception – Tree Species	x	x	x	x	x	x	x	x
Food Source – Tree Species	x	x	x		x	x	x	x
Roads			x	*	x	x		x
Open Water Bodies	x	x		x		x		*
Scheduled Forestry	x			x		x	x	*

The constraints identified for our HSI model included roads and human settlements, and water bodies, as we reason that these areas would be a) too highly frequented by humans, and b) deforested & developed, leaving them unable to support moose habitat. These cells are represented without a suitability value & as an overlay.

A variety of spatial datasets were used to quantify and represent the various suitability criteria and constraints that we determined were relevant to moose habitat suitability. The source datasets for the criteria and constraints used in our model can be found in Table 2.

Table 2. List of environmental variables and associated datasets used to predict moose habitat suitability.

Variable	Data Name	Metric	Data Extent	Data Type	Source
Criteria					
Snow Depth	Past Weather and Climate Historical Data	Nearby weather station snowfall data.	Ontario	Vector	Environment Canada (2021-2022)
Snow Interception – Tree Species	Forest Resources of Ontario	Area and volume of forest types, common tree species distribution.	Ontario	Vector	MNRF (2021)
Food Source – Tree Species					
Roads	Road Network File (RNF), 2016 Census	Digital representation of Canada's national road network.	Canada	Vector	Statistics Canada, Scholars GeoPortal (2017)
Open Water Bodies	Waterbodies Region - 2020	Polygon features representing bodies of water (including lakes, ponds, and rivers).	Ontario	Vector	DMTI Spatial Inc., Scholars GeoPortal (2020)
Scheduled Forestry	Missinaibi Annual Work Schedule (2022)	Scheduled 2022 harvest areas, wood storage yards, etc.	Missinaibi FMU	Vector	GreenFirst Forest Products (2021)
Constraints					
Human settlement	Built Up Areas Region	Polygons of zones with close buildings.	Ontario	Vector	DMTI Spatial Inc., Scholars GeoPortal (2020)

Map Specifications

The spatial reference used for all layers was EPSG:26917 – UTM 17N, which most closely represented the study area at a scale relevant to the purpose of the model. The UTM projection minimizes horizontal and vertical distortions at large scales in areas close to the specified zone but has significant distortions at small scales or further from the zone. Zone 17N represents most of the area of southern Ontario, including Guelph. This projection also allowed us to measure distances and cell size in planar units (kilometres, metres). A 30m x 30m cell size was chosen for the final HSI raster output. Since all input data was represented in vector form, cell size was only constrained by processing power & considerations such as road width (i.e., without considering the Earth's curvature).

Suitability Criteria Weights

A pairwise comparison matrix was used to assign relative weights to the six criteria (Saaty, 1980). See Table 3 for the weightings. This method of assigning weight was selected as pairwise comparisons are effective when precise weightings are not known ahead of time, as was the case for our study (Saaty, 1980). This method allows for the comparison of relative importance of all factors by calculating the appropriate weightings based on these relative comparisons, making the user input in the decision-making process easier (Saaty, 1980). Previous habitat suitability modelling studies have used this pairwise method effectively (e.g., Store & Jokimäki, 2003), thus, we determined it appropriate to use it for our analysis.

Table 3. Pairwise comparison weightings for the six identified criteria (Sow Depth, Snow Interception – Tree Species, Food Source – Tree Species, Roads, Open Water Bodies, and Scheduled Forestry).

Criteria	Snow Depth	Tree Species – Snow Interception	Tree Species – Food Source	Roads	Open Water Bodies	Forestry (Scheduled Clearcut)
Snow Depth	1	1	2	4	4	0.5
Tree Species – Snow Interception	1	1	2	4	4	0.5
Tree Species – Food Source	0.5	0.5	1	0.5	3	0.25
Roads	0.25	0.25	2	1	3	0.33
Open Water Bodies	0.25	0.25	0.33	0.33	1	0.15
Scheduled Forestry (Clearcut)	2	2	4	3	6.66	1

Snow depth was given a high rank (see Table 3) as snow depths > 60 cm impede moose movement and result in an exponential increase in energy use (Renecker & Schwartz 1998), which can be deadly to adult moose, and even more so to moose calves (Keech et al., 2011). In Keech et al. (2011), it was found that snow depths > 90 cm result in 51% (n=39) of calves dying, while Kelsall (1969) found that snow depths of 60-70 cm impede moose movement, and snow depths of 70-99 cm severely restrict moose movement, leaving moose vulnerable to predators and hunters.

Interrelated with snow depth, tree species – snow interception capacity was also ranked highly (Table 3), as in snow depths >60 cm, moose prefer areas containing mature conifers, as they provide substantial shelter from snow and lateral protection from predators (Courtois & Crête, 1988; Dussault et al., 2005a; b; 2006). Different tree species provide different snow interception capabilities. The OMNR (2010) identified hemlock, red spruce, and cedar, as having high snow interception capability; while white spruce, balsam fir, white pine, and upland black spruce had moderate interception capability, and lowland black spruce, red pine; and jack pine, had low interception capability. Quantifiably, for 10 mm water equivalent in mild storm conditions, Schmidt and Gluns (1991) found that white spruce (moderate capability), balsam fir (moderate capability), and lodgepole pine, most like jack pine (low capability), intercepted 50%, 45%, and 30% of snowfall, respectively. Further, Storck et al., 2002, found that mature coniferous stands have been reported to intercept up to 60% (up to 40 mm water equivalent) of snowfall.

Tree species – food source preference was ranked low (see Table 3), as while strong foraging preference for birch and pine, intermediate preference for larch, alder, sallow/willow, juniper, rowan and aspen, and disinclination towards spruce and balsam fir, have been reported (Hörnberg, 2001; Kurttila et al., 2002; Milligan & Koricheva, 2013; Renecker & Schwartz, 1998), moose are habitat generalists, i.e., they can survive off a wide variety of tree species (OMNR, 2010). Further, moose densities have been more so reported to differ with stand regeneration age, as moose preferentially select 20- and 30- year-old regenerating mixed and deciduous stands with a dense understory shrub layer (Crête, 1989; Newbury et al., 2007; Peek 1998; Tendeng et al., 2016).

Distance from roads and developed areas was given a moderate rank (see Table 3). Moose are attracted to anthropogenic mineral licks, i.e., roadside muddy water ponds with high concentrations of dissolved highway salt. Naturally occurring mineral licks (e.g., mineral rich springs) are used by moose to supplement their dietary salt requirements (Fraser & Thomas, 1982; Laurian et al., 2010; OMNR, 2010; Rea et al., 2021). This has been found to likely be a cause of the increasing frequency of traffic accidents involving moose; for example, in Fraser & Thomas (1982), it was found that half of the accidents with moose that occurred along a 156 km section of the Trans-Canada Highway near Wawa, Ontario, were at or near actively used roadside licks.

Distance from open water bodies was included in the model due to their importance as a source of nutrients, including salt, for moose in the late spring to early fall months (Fraser et al., 1984; Timmermann & McNicol, 1988). Though they have limited use in winter months, open water bodies which are small, shallow, non-/slow-moving and are rich in aquatic vegetation can contain between 50-400 times more Na and 2-200 times more iron (Fe) in their forage than typical woody browse, making them important preferred feeding areas (Fraser et al., 1984).

As mentioned in the Study Area section of the report, GreenFirst uses the aerial application of glyphosate (herbicide) for tending post-planting of conifer seedlings in recently harvested areas (GreenFirst, 2022; RYAM, 2021). While the direct impacts of glyphosate on moose is still debated between TEK holders and the provincial and federal governments (Schreiber, 2016), the indirect impacts of glyphosate on moose have been widely reported in the scientific literature (Connor & McMillan, 1990; Cumming et al., 1996; Milner et al., 2013; Raymond et al., 1996). Glyphosate can influence the amount of preferred browse available to moose, resulting in moose having to expend more energy to find food in sprayed areas (Connor & McMillan, 1990). This in turn can leave them more vulnerable to other threats, e.g., wolves, hunters, and disease (Kayahara & Armstrong, 2015). Further, some plant species have been found to not return for several years post-herbicide application (Guiseppe et al., 2006), while others, which are not targeted by glyphosate, have been found to retain the chemical for up to 12 years post-application (Botten et al., 2021). In addition, while moose have been reported to prefer regenerated stands, this is highly dependent on the number of years since harvest (clearcut) or other disturbance, with moose selecting for 20- and 30- year-old regenerating stands over 5- and 10- year-old (recently cut) stands or mature forest (>150 years-old) (Courtois et al., 2002; Girard & Joyal, 1984; Newbury et al., 2007). These forest regeneration practices are included in our model in addition to areas scheduled for clearcutting. Because of these considerations, as well as the lack of forest cover in clearcut areas, distance from scheduled clearcuts or restoration practices for 2022 (GreenFirst, 2022) is ranked highly in our model.

Layers & Rasterization

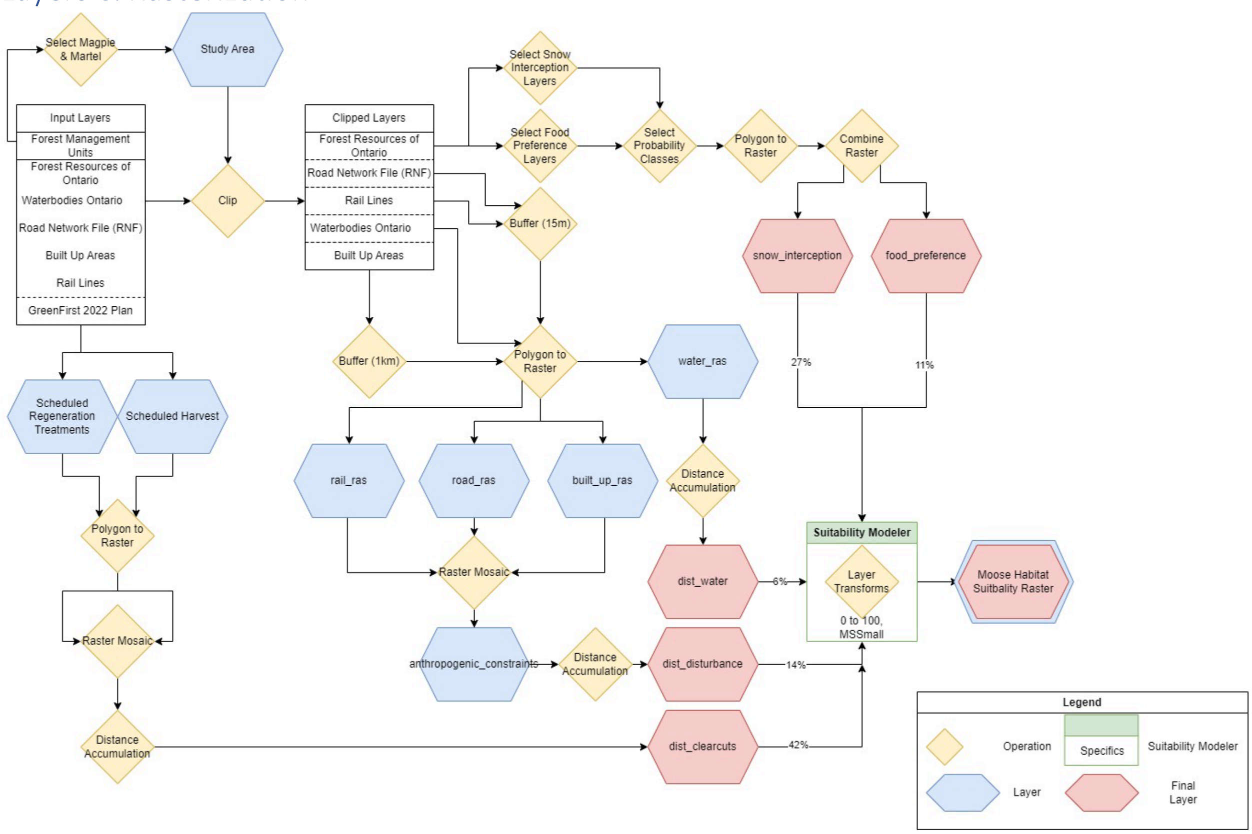

Figure 2. Flowchart representing the process of geospatial analysis. Outgoing arrows connect input layers to geoprocessing tools, or geoprocessing tools to output layers. Percentages on outgoing arrows represent the weighting of the given final layer in the suitability model.

Because of difficulty deriving snow depth from weather station data, we allowed snow interception to represent a general class for tree cover. The snow interception raster was generated using the Forest Resources of Ontario dataset (MNRF, 2021). This dataset supplied regions of Ontario in polygon vector format. Each section represented a probability of a tree species appearing in the specified region, which ranged from 0 (very unlikely) to 5 (very likely). These regions were then categorized into high, moderate, and low intercept ability, according to classes outlined in (OMNR, 2010). The probability classes were used to determine which intercept ability class was most likely to occur in any given space. Because of overlapping polygons for different tree species, classes were separated by probability, rasterized, and ultimately combined so that the highest probability value took priority in the raster (see Figure 2). The resulting raster represents the most likely intercept-ability class for any given cell (see Figure 3).

In our model, the raster representing tree species - food preference was created using a similar method to the one described above for snow interception (see Figure 2). Tree species were classified by 'low', 'moderate', and 'high' food preference based on the findings in Renecker & Schwartz (1998), Hörnberg (2001), Kurttila et al. (2002) and Milligan & Koricheva (2013), as mentioned in the previous section. The following output raster represents the most likely species to occur in any one cell in terms of low, moderate, and high food preference (see Figure 3).

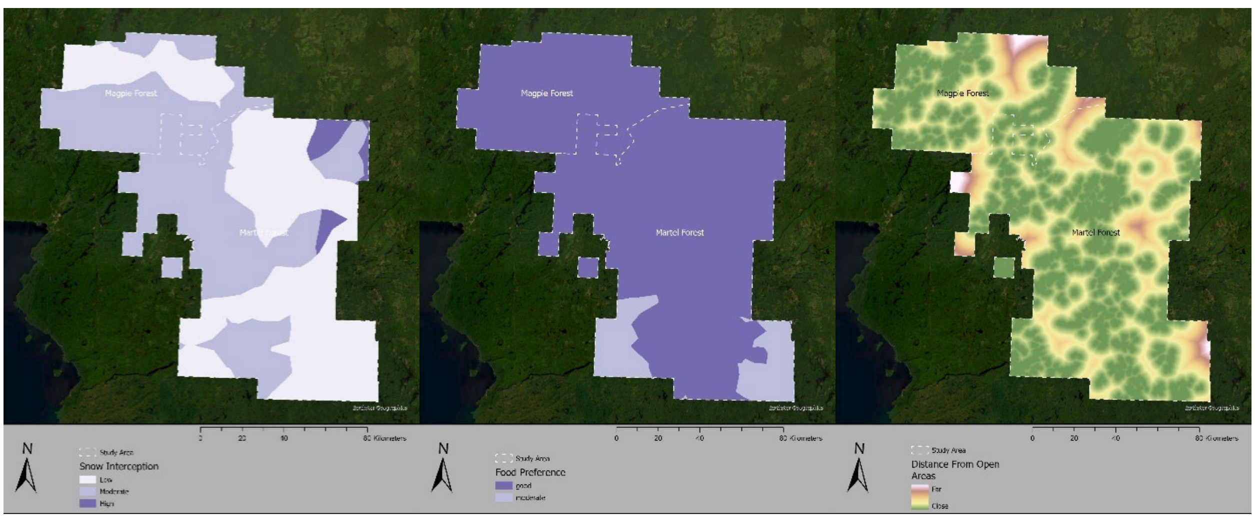

Figure 3. Intermediate Layers. Left: Snow Interception Capability; each cell represents the most likely class of tree to occur. Middle: Food Preference – Tree Species; each cell represents the most likely class of tree to occur. Right: Distance Accumulation raster from areas scheduled for clearcutting or restoration practices.

Additional layers involved considering the distance from elements in the study area, such as, anthropogenic disturbances (roads, developed areas), areas scheduled for clearcutting or restoration in 2022 (GreenFirst, 2022), or water bodies. Our 'clearcut areas' layer is derived from shapes provided to us by (GreenFirst, 2022), specifically polygon layers representing 'Scheduled harvest', which will be clearcut by the end of the 2022 harvest season, and 'Scheduled Regeneration Treatments', which would have been clearcut going into the 2022 season and are scheduled to have herbicide treatments as described in the previous sections (GreenFirst, 2022; OMNR, 2010). Figure 4 compares the final HSI with the base clearcut areas raster overlayed with satellite imagery of the same area. It can be noted that while the clearcut areas correspond with defoliated tracts of land, the raster does not cover all areas that are open in the imagery, since not all layers provided by (GreenFirst, 2022) were able to be considered due to poor documentation (see data limitations below). Further, our raster may not cover the full extent of disturbance from forestry operations as aerial herbicide (glyphosate) application to remove competing vegetation post-planting of conifer seedlings would only be happening in the year or two post-harvest (GreenFirst, 2022). Thus, given that moose tend to select for 20- and 30- year-old regenerating stands over 5- and 10- year-old (recently cut) stands (Courtois et al., 2002; Girard & Joyal, 1984; Newbury et al., 2007), disinclination of moose towards stands harvested in 2019 and further back, will probably not factor into our model. A distance accumulation tool (see Figure 3) was applied to the clearcut areas raster to allow some distance from the clearcut areas to have an effect on the model (see Figure 2. Flowchart representing the process of geospatial analysis. Outgoing arrows connect input layers to geoprocessing tools, or geoprocessing tools to output layers. Percentages on outgoing arrows represent the weighting of the given final layer in the suitability model.Figure 2).

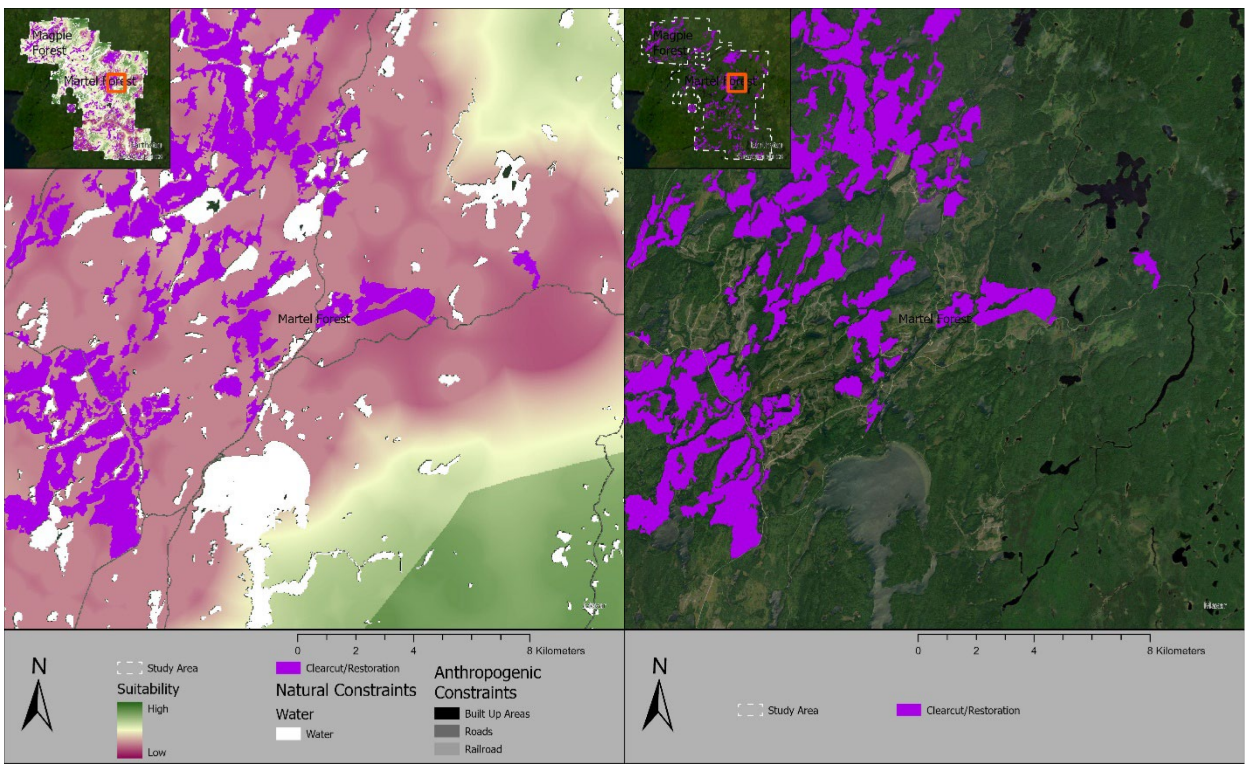

Figure 4. Close-up of the Missinaibi Forest. Left: The HSI, an area representing low suitability, with scheduled clearcut or restoration practice areas overlayed. Right: Satellite imagery representing the same extent, with scheduled clearcut or restoration practice areas overlayed. It can be noted that the overlayed areas do not completely cover areas that are clearly clearcut in the imagery.

The anthropogenic constraints are a combination of the Road Network File (RNF) dataset (Statistics Canada, 2017) and the built-up areas dataset (DMTI Spatial Inc., 2020) to represent human settlements. The RNF dataset was in line format and had a 15m buffer applied before being converted to raster format. The built-up areas dataset was in polygon format and had a 1km buffer applied before conversion to raster format to account for error in the dataset against satellite imagery. The rasters of these were then combined to create the constraint layer. A distance accumulation was applied to the constraint to create the final 'dist_disturbance' layer that was used in the suitability model (see Figure 2). Natural constraints consisted of water bodies, the raster layer of which was derived from a clip of the Waterbodies Region dataset (DMTI Spatial Inc., 2020). A distance accumulation operation was applied to the rasterized water bodies layer to create the criteria layer (see Figure 2).

Suitability Model

Our final HSI is a combination of the intermediate raster layers relative to the assigned weights which were determined using the pairwise comparison matrix detailed in previous sections (Saaty, 1980). Each raster layer was standardized to a uniform range of values, which could then be transformed using the ArcGIS pro suitability modeler. For layers such as Snow Interception and Food Preference, suitability values were assigned linearly. Distance accumulation layers were transformed using MSSmall functions. Disturbance and clearcut distance layers were transformed such that greater distance meant higher suitability, while distance from water bodies was transformed so that distance from the water bodies lowered suitability. The calculated weights were then assigned to the transformed layers, which were combined to produce the final HSI (see Figure 5). Suitability scores in the final raster are from 0 to 100, where 0 is low suitability and 100 is high suitability.

A second raster was produced as output, which represents areas with either less than 50% suitability or greater (Figure 6). This raster was created by reclassifying the HSI to a binary raster based on the associated range of values. The binary suitability raster allowed us to analyze the distribution of high suitability areas relative to low suitability areas.

Results & Discussion

The HSI Model Results and Interpretation

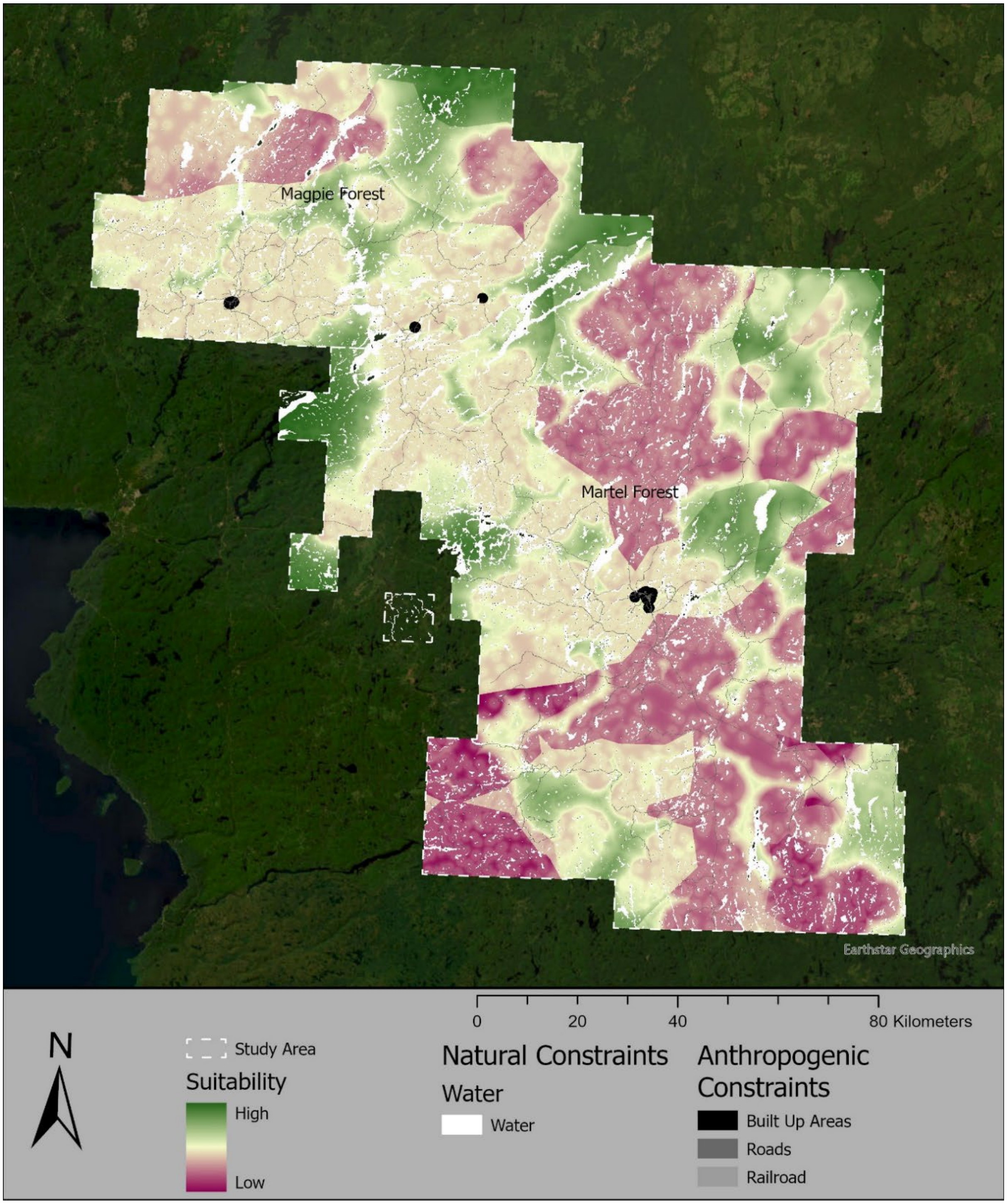

Figure 5. Map of moose habitat suitability index (HSI) model for the Missinaibi FMU (Magpie & Martel forests). Model was built in ArcGIS pro using constraints & criteria identified using literature. Suitability is ranked as a percentage, from 0 suitability rating to 100 suitability rating. Cells that are represented by constraints are solid colour rasters, where moose are unable to habituate.

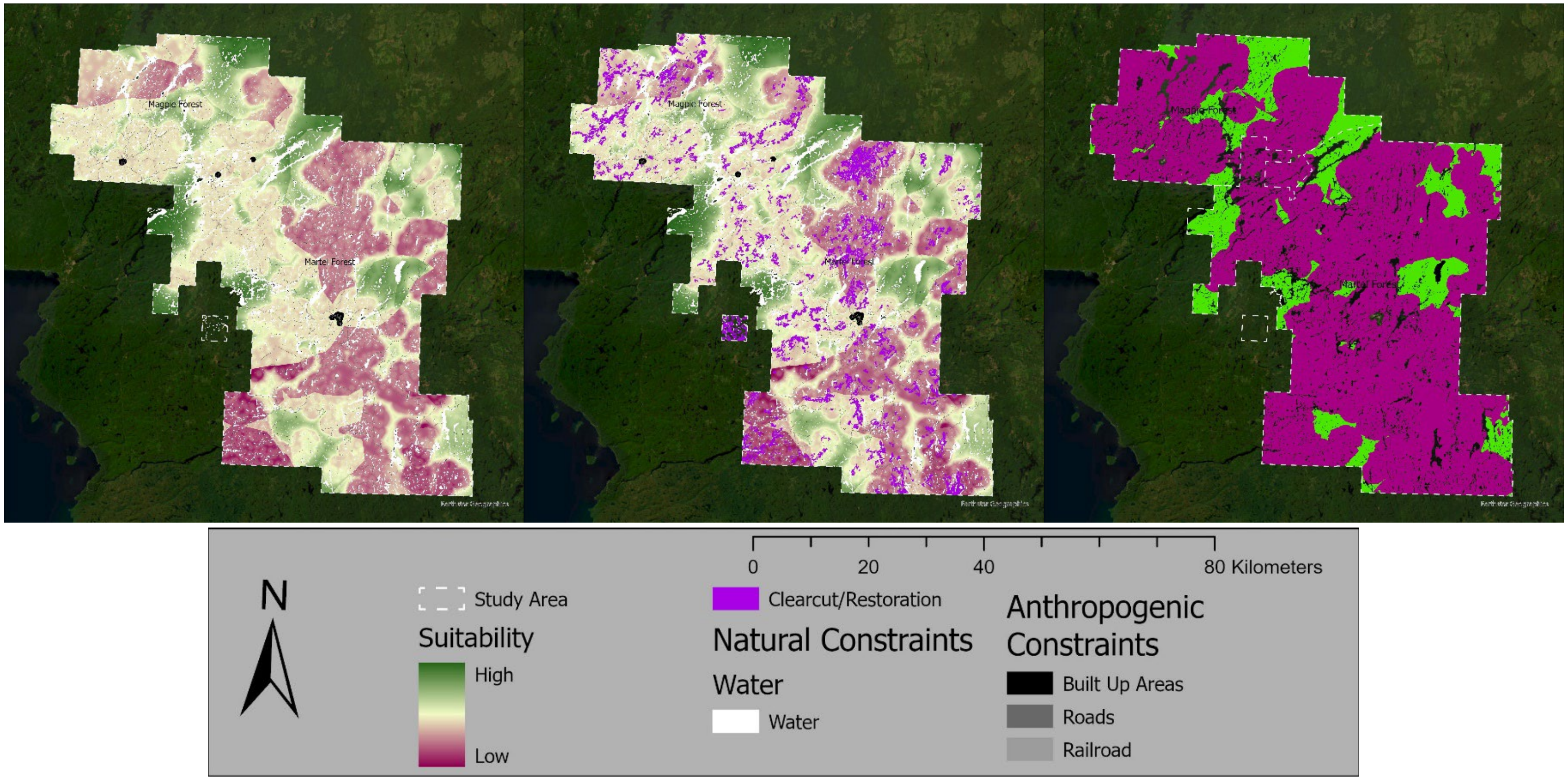

Figure 6. (Left to Right) 1, A map of the output Moose Habitat HSI for the Missinaibi forest. 2, A map of the Moose Habitat HSI including cells where clearcutting or restoration treatment for previously clearcut areas is scheduled. 3, A binary raster representing areas that are either < 50% suitable for moose habitation, (Purple) or >= 50% suitable (Green) based on out HSI model.

From the HSI model results, it is of interest how much of the Missinaibi FMU gets clearcut. While the 37,910 ha scheduled for harvest of the total 1,200,466 ha of productive forest in the Missinaibi FMU is not that substantial (~ 3.2%), what is interesting is the wide distribution of clearcuts across the FMU, see Figure 3,4 (RYAM, 2021). As previously mentioned, moose do not prefer recently harvested areas, as they do not provide adequate food sources or protection from predators (Newbury et al., 2007), thus, it is of concern and of interest to further examine larger and clustered areas of scheduled harvest.

Further of interest, is the areas of low suitability that are unbroken across some expanses of the map. While moose are not restricted to the FMU boundary, these areas do pose a threat to young calves and even adult moose as they may be forced to traverse these areas in search of resources, in the case of plant disease outbreaks, forest fires, or new human/hunter establishments (Price et al., 2013). To negate possible negative impacts, e.g., inbreeding depression due to the presence of a geographic barrier, the establishment of human-made wildlife corridors could help to ensure habitat connectivity (Courbin et al., 2014).

From our binary suitability raster (see Figure 6), which classifies areas as either greater or less than 50% suitability, it is important to note that only 17.74% of the Missinaibi FMU is classified as more than 50% suitable according to our model. Further, these patches are quite secluded, often surrounded my large expanses of unsuitable habitat, which can have negative impacts on moose population dynamics (geographic (allopatric) separation, inbreeding depression), as previously mentioned, as moose may be unable to safely traverse between patches (Courbin et al., 2014). To further contextualize this, within a given season, an adult moose home range may be up to 10 km^2, with annual home ranges for migratory moose being much larger, up to 30,000 ha (300 km^2) (Addison et al., 1980; Crête, 1988; Environmental Protection and Sustainability, n.d.; Taylor & Ballard, 1979). Visually, looking at Figure 6, we can see how narrow corridors and small secluded patches may not be able to support self-sustaining moose populations.

Returning to an earlier point regarding habitat connectivity, the importance of wildlife (migration) corridors is further increasing in the face of worsening climate change (Keeley et al. 2018). As a result of anthropogenic climate change, the Canadian boreal forest ecozone range is expected to shift northwards increasingly rapidly, meaning that if species are the persist, they need to be able to migrate north in pace with preferred abiotic conditions (weather) (Price et al., 2013). For this to occur, species need to both a) have the dispersal abilities to travel the distance required, at an in-keeping-with or faster pace than abiotic conditions and b) have access to corridors which allow for migration (Price et al., 2013). Looking at our suitability model, see Figure 5 and 6, our results raise the concern that the moose populations living in southernmost fragmented suitable patches may not be able to "keep pace" with climate change, due to the lack of suitable habitat between them and more northern suitable patches. This is something that moving forwards must be taken into consideration by GreenFirst and the

OMNR in putting forth guidelines and best management practices for conserving biodiversity at the stand and site scales.

Another significant observation from our suitability model is that many of the high suitability areas are found towards the edges of the Missinaibi FMU, see Figure 5. This is an important observation as our map does not take into consideration the forestry practices of surrounding FMUs, nor human settlements and roads that lay outside the boundaries of our study, and thus, these areas may be less suitable than our model shows them to be. Further, moose, like all other wildlife, do not necessarily respect FMU “boundaries”, unless there are actual physical barriers to movement (e.g., fencing). Therefore, even if suitable habitat does indeed exist along the boundaries of the Missinabi FMU, moose populations could decline due to exposure to hunters, roads, etc. along and across the boundary edge.

While multiple criteria were considered in the creation of the HSI map (Figure 5), certain criteria were determined to be more impactful on the habitat suitability of a given region for moose (Table 3). Snow depth, tree species – snow interception, and forestry (scheduled clearcut) are major driving agents in this determination, while open water bodies was considered to be a less important factor, for example. The maps shown in Figures 3 and 6 indicate that an arc-shaped region along the north and eastern portions of the study area had low snow interception values, as well as more clearcut regions. Unsurprisingly, the high weighting importance assigned to forestry resulted in generally low suitability in these regions (Figure 5). Conversely, the western portion of the study area generally showed the opposite trend, with greater snow interception, less forestry, and overall greater habitat suitability. The consideration of multiple factors is made evident when considering the most south-west portion of the study area, where this had short distances from open areas and large swaths of clearcuts (Figures 3 and 6), which contributed to it being considered as a low suitability region.

Previous researchers has not focused on the Missinaibi FMU, nor have they considered forestry as a major factor in their habitat suitability models. Further, while many studies considered tree species as a proxy for snow interception, only some considered true snow depth measurements, roads/development, and open water bodies (Table 1). The inclusion of these factors in this study sets it apart from previous studies and places it in alignment with modern research that considers many factors in HSI models (Zhi et al., 2022). With the chosen threshold, Zhi et al. (2022) found that 13.6% of their study area in China was suitable for moose, while considering many of the same factors as were considered in this study. However, research which included regions used by Algonquin moose hunters found that approximately 80% of the study areas had good or high habitat suitability (Tendeng et al., 2016), and research which monitored forest dynamics and types over several decades in the northeastern United States found similarly high habitat suitability in certain regions, with as low as 50% suitability in others, particularly if those regions had been damaged by ice storms (Koitzsch, 2002). The approximately 18% suitability across the entire Missinaibi FMU according to our 50% threshold is notably lower than that of other studies; however, the region studied is much more akin to the one in Zhi et al. (2022), where a large ecoregion region is considered rather than a smaller (larger scale) region with known high suitability or moose density, as in Koitzsch (2002) or Tendeng et al. (2016). Further, we included more environmental variables than these studies with higher suitability findings, which may contribute to the observed difference in overall suitability of the study area.

Data Limitations & Improvements

While the Scheduled Forestry dataset (GreenFirst, 2022) provided insight and areas of scheduled harvest, it was lacking in proper documentation. For e.g., while it provides polygon layers that are considered ‘areas of concern’, such as ‘nests’ and ‘reserves’, there is no definition of these areas in the accompanying documentation. Another point layer lacking an accompanying definition was those assigned to be ‘aggregate pits’, which based off satellite imagery appear to be clear-cut areas, but there was no reliable way to confirm that based on the data and documentation we had access to. Further, due to the time constraints of the project and the depth of understanding required to thoroughly consider the Forestry Management Plans, we were not able to derive as much information about herbicide use and harvest practices out of the data as we had hoped. These factors can be considered given more time to improve the model. Future work should consider following the (OMNR, 2010) more closely and with higher specificity.

The forest resource inventory was also lacking in documentation as there was no indication that probability classes represented specific probability values, and information had to be derived from outside sources and data visualization tools. The non-continuous nature of the dataset also lends to error in our model by creating artificial borders between areas where snow interception or food preference differs (see Figure 7). An improved model would include a more detailed analysis of tree species distribution in the Missinaibi forest region, as well as stand measurements, age, and other factors deemed relative to moose habitat selection by our literature review. For example, as previously mentioned, moose prefer older cuts over more recent clear cuts, due to their preferred food availability (Courtois et al., 2002; Girard & Joyal, 1984). Stand age is mentioned throughout the OMNR (2010) guidelines and in many of the previous moose HSI model papers, including Puttock et al. (1996), Rempel et al. (1997), and Dussault et al. (2006). The lack of forest stand age data could be remedied using ground-level techniques, as identified in Koivuniemi & Korhonen (2006) and Maltamo et al. (2020).

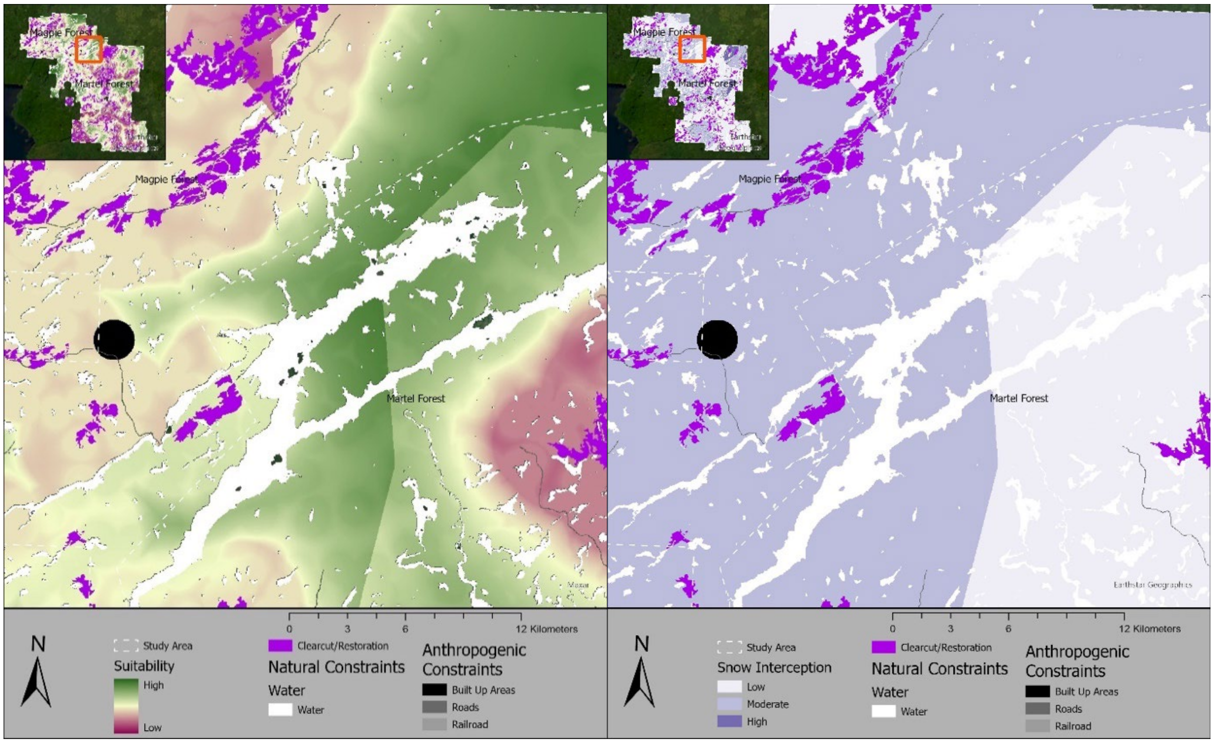

Figure 7. Close-up view of one section of the Missinaibi forest (Near Missinaibi Provincial Park). Left: Shows the moose HSI with scheduled clear cut or regeneration areas overlayed. Includes examples of constraints, as well as both very low and very high suitability areas. Right: The same extent with the snow interception raster layer instead of the HSI, shows a border area between low and moderate interception. (Note: This border is not real, it only represents the most common tree for the area as indicated by the Forest Resources dataset (MNRF,2021)).

Although we determined snow depth to be a highly significant factor relating to winter moose habitat selection, data availability and processing power limitations prevented us from creating an accurate snow depth raster that could be used in the model. From Ontario weather station data (Environment Canada, 2022), only two weather stations fell within the study area, and a worthwhile interpolation of snow depth measurements over the entire area would be unlikely to reflect real-world conditions. An improved model would require more refined snow-depth data which could also take elevation and slope into consideration.

Further, while our findings provide a preliminary model for moose habitat suitability in the Missinaibi FMU, unlike other similar studies (Dussault et al., 2006; Tendeng et al., 2016; Zhi et al., 2021), we were unable to assess the validity of our model in relation to real-time moose population numbers and habitat use in the Missinaibi FMU due to lack of available data. Going forward, we suggest the collection of moose population and habitat use data via global positioning system (GPS) telemetry, as used in Dussault et al. (2006), surveys, as used in Zhi et al. (2021), or consultation with local hunters, as used in Tendeng et al. (2016).

Finally, it is important to note that nature is highly connected across space, as well as time (Bartley, T., & Gutgesell, M., lecture notes, BIOL*3060, 2023). This suitability map uses datasets from a range of dates with little specificity. The carrying capacity of ecosystems changes through time, with population dynamics typically lagging in their response (Bartley, T., & Gutgesell, M., lecture notes, BIOL*3060, 2023). Thus, while outside the scope of this project, going forward it would be of interest to include time-related elements such as the employment of a time series analysis to consider habitat suitability over time, as used Porzig et al. (2014) and Arenas-Castro & Sillero (2021) to map bird and other wildlife populations.

Conclusions

The results of this study add to the growing body of studies that are recognizing the importance of bringing together Western science and TEK to understand wildlife habitat needs and properly account for them in forest management. With our HSI we have shown that while the OMNR (2010) guidelines have managed to identify a substantive number of criteria which affect moose habitat suitability, more focus on the impact of clear-cuts and glyphosate application on moose habitat is needed as these forestry practices can significantly impact moose's ability to travel across the landscape and find preferred food sources. Further, while our study does provide a good preliminary model for moose habitat suitability in the Missinaibi FMU, further data collection is needed to fine-tune the model and be able to apply it at a greater spatial extent, which is necessary to better understand the effects of forestry and other variables on moose population-level dynamics.

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