A Multi-Criteria Evaluation to Determine Habitat Suitability of Eastern Hemlock in Ontario

GEOG 4480: Final Report

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Abstract

Eastern hemlock (*Tsuga canadensis*) is a common conifer species in southern Ontario that is currently threatened by the northward spread of an invasive pest, the Hemlock Woolly Adelgid (HWA). The aim of this study was to estimate the location of suitable eastern hemlock habitats in Ontario to predict the spread of HWA and support conservation efforts to protect existing eastern hemlock stands. Using a Multi-Criteria Evaluation (MCE), two suitability maps were created, one which included soil type as a habitat-determining factor and one without due to the limited extent of soil data in Ontario. In the suitability model that included the soil type factor, areas considered to be most suitable were primarily located in central and southern Ontario, with lower suitability in northern Ontario. In the suitability raster omitting soil type, the greatest suitability was also in southern Ontario, although central Ontario around Algonquin park had the lowest suitability as the rock and clay content of the soil increased. Conservation efforts should be focused on areas with high habitat suitability scores to maintain abundance of eastern hemlock despite the threat of HWA infestation. To compare the difference in the resulting suitability rasters, an uncertainty analysis was conducted to examine areas that differ in their assigned suitability scores. Results of the study indicate the need for a province-wide soil survey to properly assess the distribution of eastern hemlock in Ontario.

1. Introduction

Eastern hemlock (*Tsuga canadensis)* fulfills a unique role in forest ecosystems as one of the few long-lived shade-tolerant species in North America (Orwig *et al.,* 2003). It holds ecological value by providing forage, habitat, and temperature regulation of nearby streams and understory (Ward *et al.* 2004). The loss of eastern hemlock can lead to a loss of local biodiversity and even change the microclimate of the area due to increased temperature and light penetration into the understory (Clark *et al*., 2012).

The Hemlock Woolly Adelgid (HWA) is an invasive insect that feeds on eastern hemlock and often kills the tree within 4-10 years following infestation (Orwig *et al.,* 2003). While the degree of eastern hemlock mortality and canopy thinning can vary between forest stands, HWA presence consistently results in stand deterioration (Orwig *et al.,* 2003). HWA have been migrating northward from the eastern USA and have been previously found in the Niagara region of Ontario (Orwig *et al.,* 2003; CFIA, 2022). In August 2022, HWA were found in Grafton, approximately 270 km from Niagara region and on the opposite side of Lake Ontario (CFIA, 2022). Most recently, HWA has also been found around Hamilton, indicating that HWA continues to spread into the province (Graham, 2023). Ontario is currently lacking a large-scale model of eastern hemlock distribution which is needed to facilitate province-wide management of HWA. Understanding the spatial distribution of the host tree species can assist efforts to monitor or treat areas that may be considered hotspots or corridors in the spread of the hemlock woolly adelgid infestation (Clark *et al.*, 2012).

Distinguishing eastern hemlock from other conifers in satellite images without ground truth data is difficult because it exists primarily in mixed forests where individual tree species are hard to decipher (Dunckel *et al.*, 2015). Previous studies assessing eastern hemlock habitat have used field sampling of hemlock stands and their properties to provide training data for maximum entropy algorithms (Williams *et al.,* 2016). Due to the lack of data on eastern hemlock distribution in Ontario, a Multi-Criteria Evaluation (MCE) was selected for this study to model suitability throughout the province using attributes of eastern hemlock habitat determined by previous studies. MCE incorporates factors —variables that describe an area in varying degrees of suitability based on a specific characteristic —and constraints — variables used to outline unsuitable locations (Eastman,1999). All factors are assigned weights to represent their relative importance and the output suitability is determined by multiplying each factor by its assigned weight and summing the results; the most suitable areas have higher values (Eastman,1999). In this analysis, regions were defined as suitable based on specific environmental conditions that characterize eastern hemlock habitat.

The purpose of this study was to estimate the locations of eastern hemlock in Ontario using an MCE model of habitat suitability. Determining the distribution of eastern hemlock in Ontario is essential to support conservation efforts to protect this species from the threat of hemlock woolly adelgid. The importance of soil type, the only factor without province-wide data, was assessed by recreating the suitability map without its input and calculating the resulting difference in suitability score.

2. Research Objectives

1. Identify the constraints and factors affecting habitat suitability of the eastern hemlock species in Ontario.

2. Develop and run a habitat suitability model for eastern hemlock in Ontario using a multi-criteria evaluation (MCE) approach to determine most ideal locations for this tree species within Ontario.

3. Perform uncertainty analysis by rerunning the suitability model with adjusted factor weightings, omitting the soil layer to test the sensitivity of the model to the soil type parameter.

4. Assess the strengths and weaknesses of including/omitting the soil type factor by comparing differences between the two suitability models.

3. Study Area

The province of Ontario has an area of approximately 1.076 million square kilometers, of which 66% is classified as forest (Government of Ontario, 2022b). Eastern hemlock is a common conifer species in southern Ontario and while pure stands of eastern hemlock do occur, it is typically found in mixed stands (Government of Ontario, 1995). HWA has been detected in British Columbia, Nova Scotia, and Ontario, but has not been reported in Manitoba or Quebec (Government of Canada, 2023b). The study area for the suitability map produced by the MCE model covers the entire province of Ontario. However, due to the limited extent of the soil survey data from

OMAFRA, the output of the MCE only covers the areas depicted in Figure 2 when soil type is included as a factor.

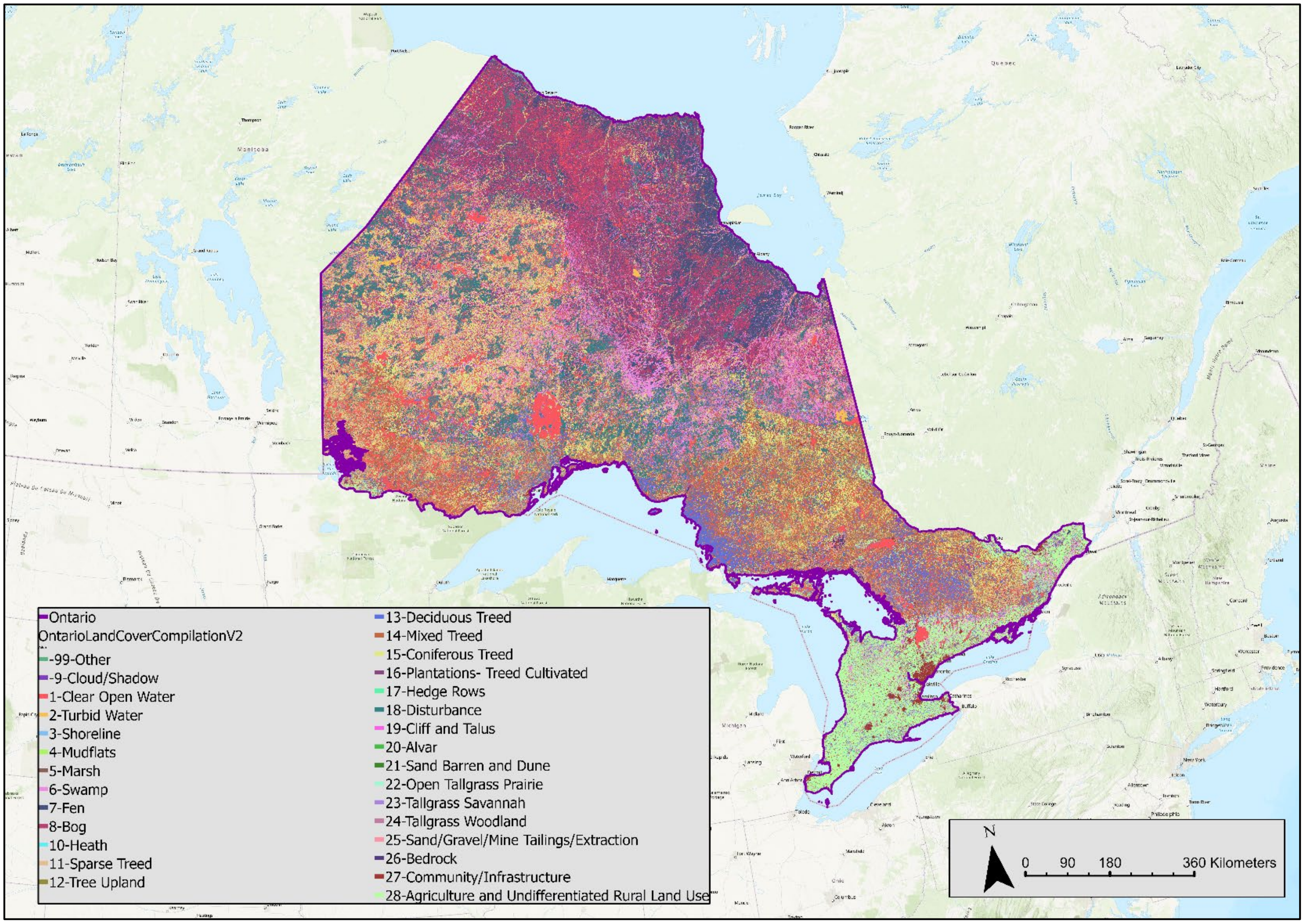

Figure 1: The provincial study site area of Ontario, Canada used to map habitat suitability of eastern hemlock. The boundary for the study site was created from the Government of Canada's Provinces/Territories, Cartographic Boundary File-2016 census dataset (Government of Canada, 2016). The land cover layer was sourced from the 2022 Land Information Ontario dataset and the map was created in ArcGIS pro.

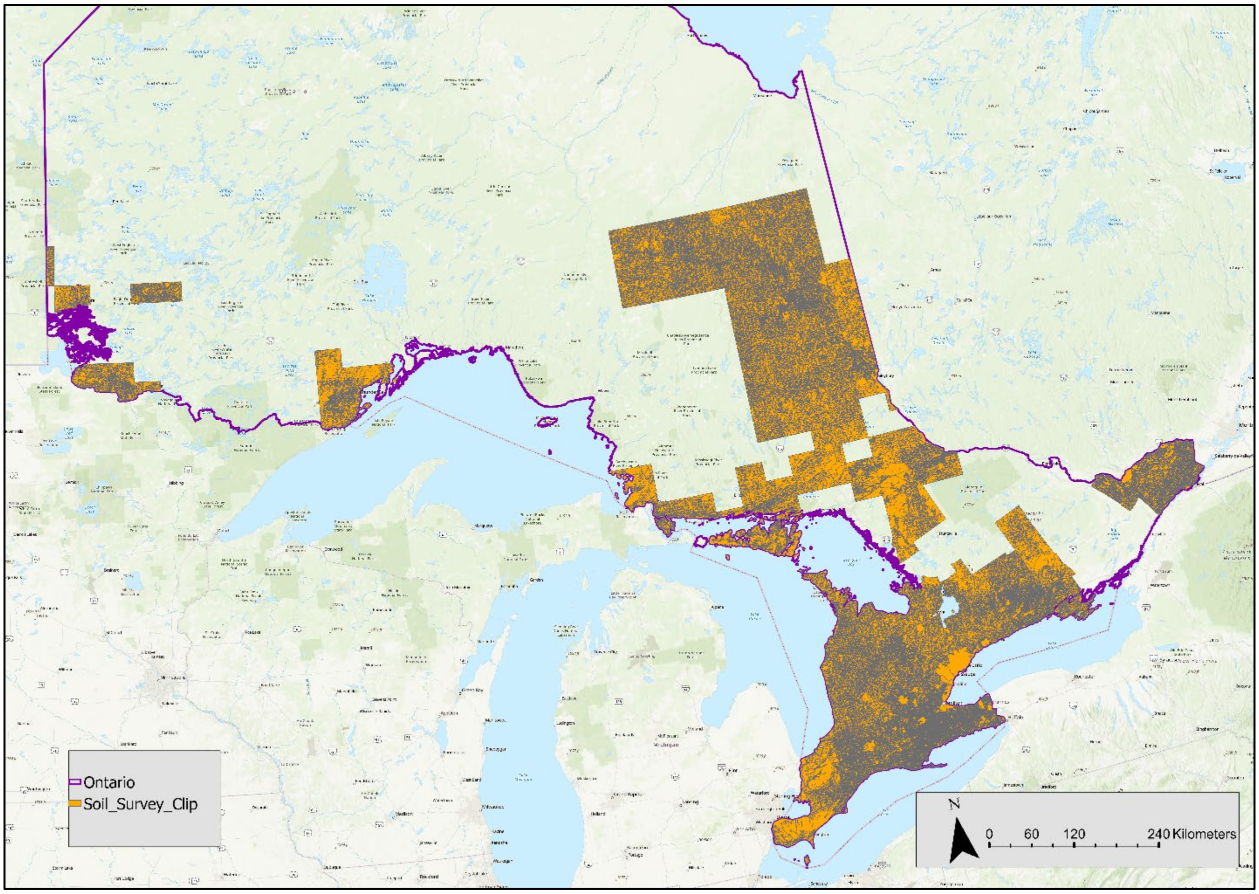

Figure 2: Map showing the extent of the individual soil survey layer. The orange polygons are areas that the soil survey has data for. Soil data gathered form OMAFRA, 2019.

4. Materials and Methods

4.1 Selection of Factors and Constraints

The constraints and factors that affect the suitability of an area for eastern hemlock habitat have been identified through literary research for input into the MCE model. In total, the model included one constraint and eight factors that affect the suitability of the location for eastern hemlock growth. The only constraint on eastern hemlock habitat in Ontario was the location of water bodies; since eastern hemlock is unable to grow in water, these areas are marked as inhospitable.

Land cover — Eastern hemlock was most often found in coniferous forests, although it can appear as a dominant species in some mixed-wood forests (Carey, 1993). It occurs rarely in urban areas and shrubland, including agricultural areas (Williams *et al.,* 2017). Occasionally hemlock can be found near wetland borders where the peat soils are shallow, but generally at low density (Carey, 1993; Williams *et al.*, 2017). These characteristics enable us to rank land cover types based on their reported suitability as eastern hemlock habitat (Appendix, Table 7).

Slope — Eastern hemlock prefers mid to low slopes over highly sloped areas, suggesting that as the slope increased the suitability of the location for eastern hemlock habitat decreased (Hart *et al.*, 2005).

Aspect — Eastern hemlock is preferentially found on northern-facing slopes, followed by northeastern, eastern, northwestern, and western aspects (Hart et al., 2005). It is least abundant on southern-facing slopes, potentially due to higher incident solar radiation affecting the soil and air temperatures and atmospheric humidity (Narayanaraj *et al.*, 2010). Refer to Appendix Table 8.

Precipitation — Increased average precipitation has been positively correlated with eastern hemlock growth in Maine; similarly, New England stands of eastern hemlock tend to occur in areas with annual precipitation ranging from 113-134 cm (Teets *et al.,* 2018; Orwig *et al.*, 2012). Areas with higher annual average precipitation values were considered more suitable for eastern hemlock.

Terrain Wetness Index (TWI) — TWI estimates water flow and accumulation and since eastern hemlock is often associated with areas of water accumulation, areas with higher TWI values were considered more suitable as eastern hemlock habitat (Embree, 2022).

Temperature — In New England, eastern hemlock stands had an average maximum July temperature of 27.4°C and a minimum January temperature of -11.21°C (Orwig *et al.*, 2012). Lower winter temperatures risk limiting moisture availability, which would be detrimental for eastern hemlock growth (Saladyga *et al*., 2015). Similarly, in the summer eastern hemlock prefers higher temperatures (Government of Ontario, 2022a; Stern *et al.,* 2021). Based on these values, higher July and January temperatures were considered more suitable.

Soil Type — In the Great Lakes region, eastern hemlock typically grows on sandy loams, silt loams, or loamy sands (Burns & Honkala, 1990). The location's suitability is expected to decrease as the soil's clay content increases, as the structure of clay negatively impacts drainage (OMARFA, 2019). Refer to Appendix Table 9.

4.2 Data Needs

Table 1. Description of the factor and constraint variables that will be used in the multi-criteria analysis to determine habitat suitability for the eastern hemlock.

Variable	**Data Type**	**Factor or Constraint**	**Source**	**Description**
Water bodies	Raster	Constraint	(Land Information Ontario, 2022)	Cannot grow in water
Slope	Raster	Factor	PDEM from (MNRF, 2020) using ArcGIS surface parameters tool	As slope increases suitability decreases
Minimum Temperature	Vector	Factor	(Government of Canada, 2023a)	Average January Minimum Temperature (2022) by weather station in Ontario, temperatures below -11.21°C are less suitable
Maximum Temperature	Vector	Factor	(Government of Canada. 2023a)	Average July Maximum Temperature (2022) per weather stations in Ontario, temperatures

				up to and including 27.4°C are more suitable
Precipitation	Raster	Factor	(Government of Canada. 2023a)	Average precipitation in 2022 by Ontario weather station. Prefers moist conditions, areas with greater precipitation will be most suitable.
Soil Type	Vector	Factor	(OMAFRA, 2019)	Prefers loamy soils, as soil type contains higher clay percentages suitability decreases
Aspect	Raster	Factor	PDEM from (MNRF, 2020) using ArcGIS surface parameters tool	Primarily prefers north-facing slopes, suitability decreases as aspect becomes increasingly south-facing
Land Cover	Raster	Factor	(Land Information Ontario, 2022)	Coniferous forest is most suitable, with scrubland and urban areas less suitable.

Topographic Wetness Index (TWI)	Raster	Factor	PDEM from (MNRF, 2020) using various ArcGIS pro tools described in 4.3	Prefers moist soils, suitability increases with increasing TWI values.

4.3 *Data Cleaning and Pre-processing*

All input data layers were first reprojected to Canada Lambert Conformal Conic, as Lambert conformal conic projections are commonly used by Statistics Canada (Statistics Canada, 2021). The Ontario land cover raster and the Ontario soil survey layers were clipped to the Ontario boundary since they both extended past the provincial boundary in some areas. To produce the constraint layer, the Ontario land cover raster was reclassified to give areas of water (clear open water and turbid water) a value of zero while all other land cover types had a value of one.

The DEM files representing northern and southern Ontario were joined using the mosaic to new raster tool; slope and aspect rasters were then derived from this provincial DEM using the surface parameters tool in ArcGIS pro. To calculate the Topographic Wetness Index (TWI), flow direction was first calculated from the DEM and then flow accumulation was derived from the flow direction raster using the ArcGIS pro tools of the same names. Flow accumulation was rescaled using the following equation:

Equation 1. $F = (accumulation + 1) \cdot cellsize$

Where the cell size of the flow accumulation raster was 30 meters. The slope calculated earlier was converted to radians, then the tangent of the slope was taken using the raster calculator. The TWI was then calculated using the following equation:

Equation 2. $TWI = \ln\left(\frac{F}{S}\right)$

Where F represents the rescaled flow accumulation and S represents the tangent of the slope.

To derive the provincial temperature rasters, comma-separated values (csv) files containing the average temperatures in January and July 2022 were each joined to a 2022 vector layer of Ontario weather stations (Lesack, 2016). The temperature values for Ontario were interpolated for the rest of the province using the Inverse Distance Weighted (IDW) technique and the output raster was clipped to the provincial boundaries. Average annual precipitation for each weather station was calculated in a separate csv file using monthly precipitation values per station from the Government of Canada Monthly Climate Summaries for 2022. As with provincial maximum and minimum temperature, the annual precipitation csv file was joined to the weather stations vector layer, interpolated using the IDW tool, and then clipped to the Ontario boundary.

The categorical input factors— land cover, soil type, and aspect— were standardized using the reclassify tool in ArcGIS pro. The continuous input factors were standardized to a common numeric scale of 1-10 using the rescale by function in ArcGIS pro. Both precipitation and maximum temperature were transformed using

MsLarge, slope was transformed using the MsSmall function, and minimum temperature was transformed using the linear function due to the negative temperature values.

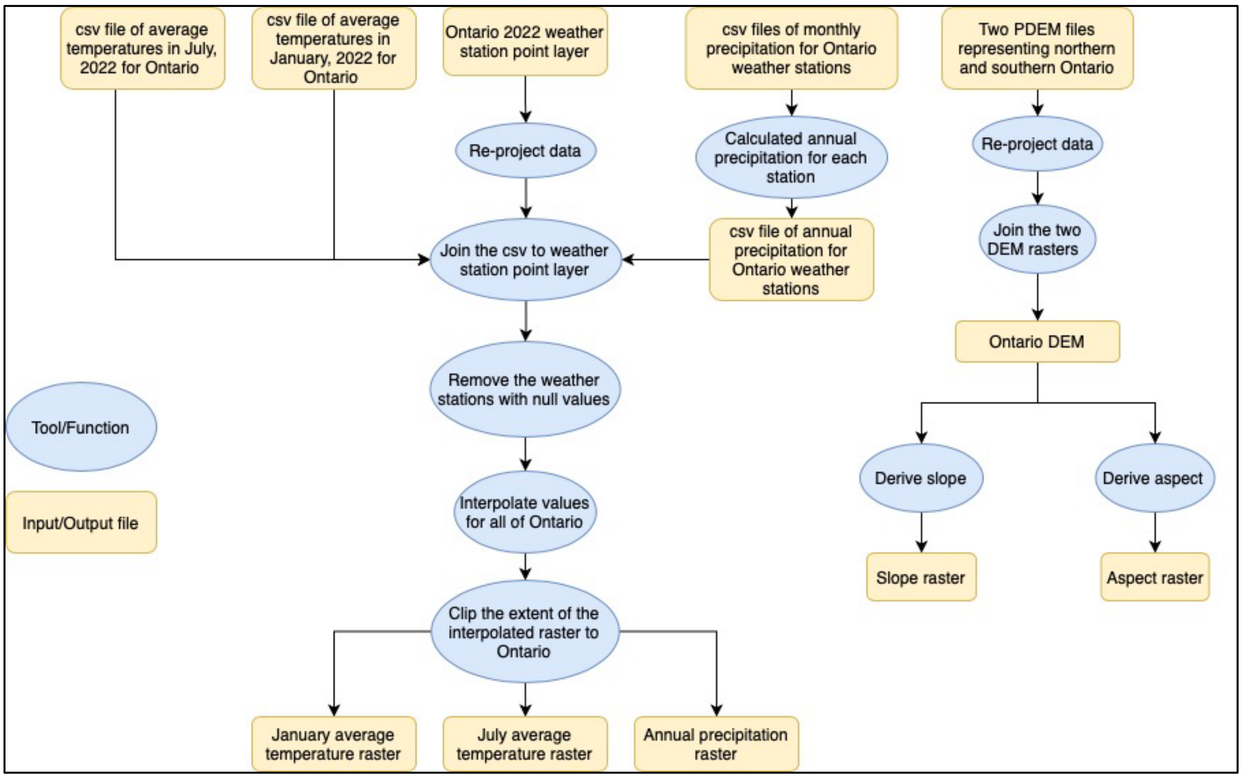

Figure 3. Part one of the project workflow for the pre-processing of the factors for the MCE model.

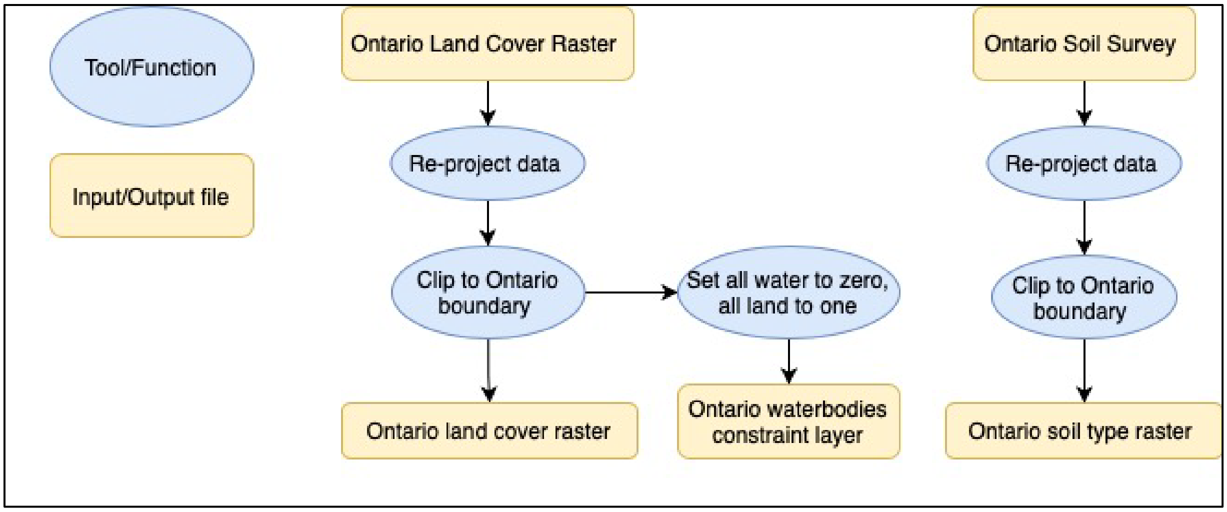

Figure 4. Part two of the project workflow for the pre-processing of the factors and constraint for the MCE model.

4.4 Multi-Criteria Evaluation (MCE)

Multi-criteria evaluation is a common method of assessing the suitability of land for a specific purpose based on a variety of attributes of that location (Eastman, 1999). Therefore, a suitability model was designed to reflect where eastern hemlock is most likely to thrive in Ontario based on a literature review. The suitability model was run twice: once including the soil type factor and once without, as it is the only factor to not cover the entire province.

To determine the relative importance of the different factors, a pairwise comparison matrix was used to assign each factor's weight based on similar models of eastern hemlock habitat suitability from the literature. Williams *et al.* (2016), and Clark *et al*. (2012) conducted similar studies on factors affecting eastern hemlock habitat and each established a basis for the relative importance between factors (Table 2). Factor importance was ranked based on the average weighting of the two papers, with a value of eight representing least important and one being the most. This ranking scheme was then used in a Saaty 9-point scale pairwise comparison matrix to determine the factor weightings that were used in the suitability model (Table 3). Full Pairwise Comparison Matrix found in Appendix, Table 9.

Table 2. Evaluation of factor weights in related literature of factors affecting the location of eastern hemlock in North America.

Evaluating Factor	**Abbreviation**	**Weighting from Williams *et al.* 2017**	**Weighting from Clark *et al.* 2012**	**Average of Papers**	**Ranking Based on Paper Average**
Aspect	Asp.	0.5%	1.2%	1.45%	5
Slope	-	2.1%	1.6%	1.85%	4
Minimum Temperature	Min. Temp.	0.6%	3.1%	1.85%	4
Maximum Temperature	Max. Temp.	0.3%	0.5%	0.4%	8
Soil Type	-	11.6%	42.8%	27.2%	2
Annual Precipitation	Precip.	1.3%	N/A	1.3%	6
Land Cover	LC	59.5 %	N/A	59.5%	1

Topographic Wetness Index	TWI	0.4%	1.1%	0.75%	7

Table 3. Pairwise Comparison Matrix Total Weights

Factor	Asp.	Slope	Min. Temp.	Max. Temp.	Soil Type	Precip.	LC	TWI
Total Weight	0.0805	0.2013	0.2013	0.0134	0.2013	0.0403	0.2416	0.0201

With the weights assigned, the suitability model was generated using the raster calculator to multiply the standardized factors by the assigned weights. These values were then summed and multiplied by the map constraint to create the suitability raster. This process is shown in the following equation:

Equation 3. Hemlock habitat suitability = $(\sum w_i X_i)(\prod C)$

where w_i = the weight assigned to factor i

X_i = the criteria score of factor i

C = final map constraints

4.5 Uncertainty Analysis

As the soil layer does not cover the full extent of the study area, suitability maps were generated with and without the inclusion of soil type. The factors were re-weighted to account for the exclusion of soil type (Table 4). For the full pairwise comparison matrix including individual weights, see appendix table 10. The output suitability maps were compared to assess the strengths and weaknesses of including the limited soil data in the assessment of eastern hemlock location across Ontario. To depict this change, the Compute Change function was used to produce a raster image showing the relative difference in suitability values between the models with and without the soil type factor.

Table 4: Pairwise Comparison Matrix Total Weights for Uncertainty Analysis

Factor	Precip.	Slope	Min. Temp.	Max. Temp.	Asp.	LC	TWI
Total Weight	0.0353	0.2118	0.2118	0.0118	0.1412	0.2824	0.1059

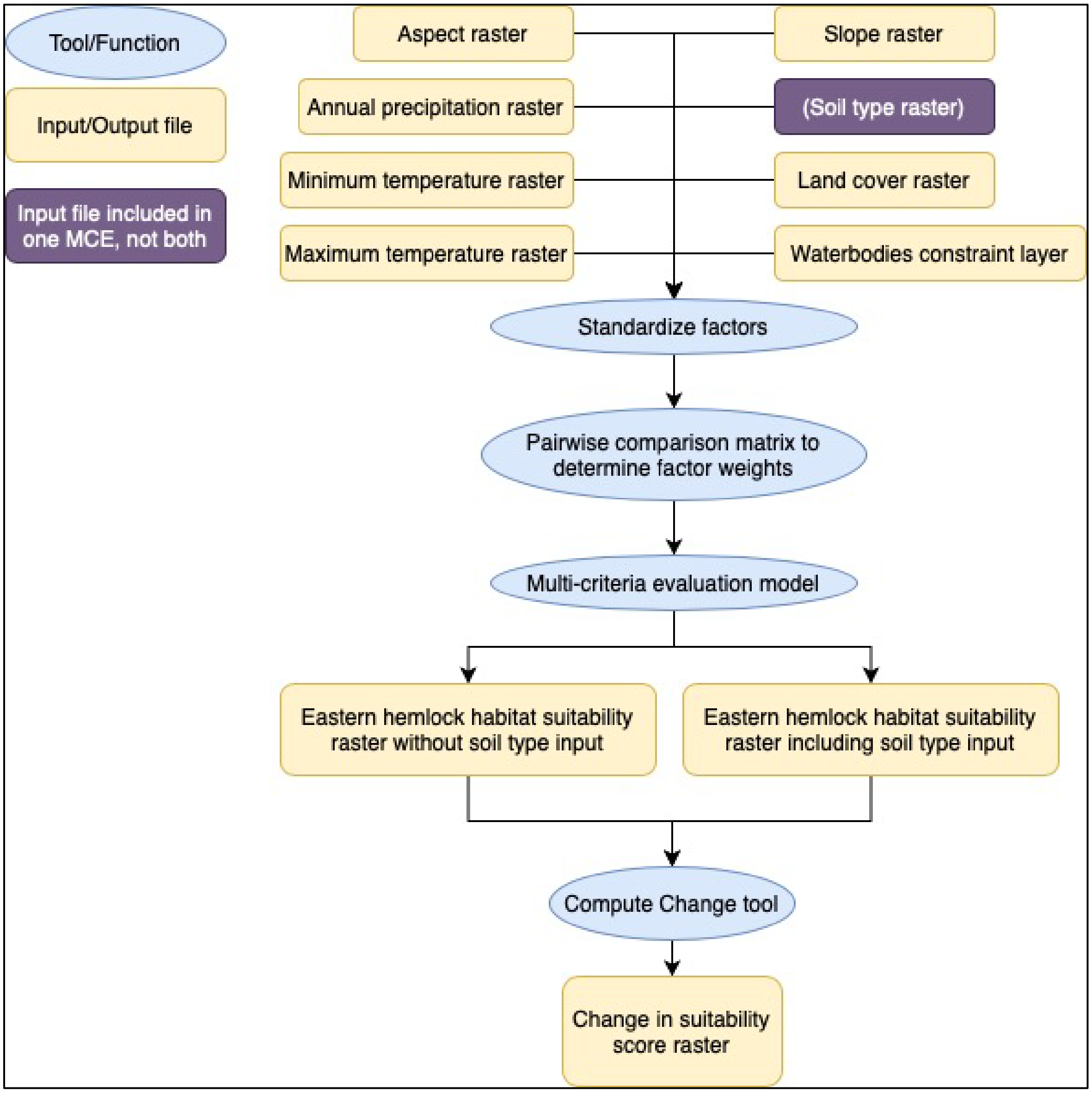

Figure 5. The project workflow for the MCE model.

5. Results

5.1 Suitability Including Soil Type

The suitability raster that included soil type encompassed areas of Ontario where there was soil data available. The suitability scores were grouped into five levels ranging from most to least suitable, as described in Table 5, to provide a better visual representation of suitability.

The suitability map created by including soil type (Figure 6) was restricted to the extent of the soil type layer within Ontario. Unfortunately, this limited the extent of the suitability map to primarily southern Ontario, particularly along the Great Lakes. As shown in Figure 6, both Manitoulin Island and the area south of Timmins show some of the high suitability values, while the Sudbury area had some of the lowest suitability values for eastern hemlock habitat.

Table 5. Labelling of easter hemlock habitat suitability scores.

Descriptive Label	**Suitability Score**
Least suitable	≤ 1.820
Less suitable	≤ 4.124
Moderately suitable	≤ 5.163
More suitable	≤ 6.353
Most suitable	≤ 9.473

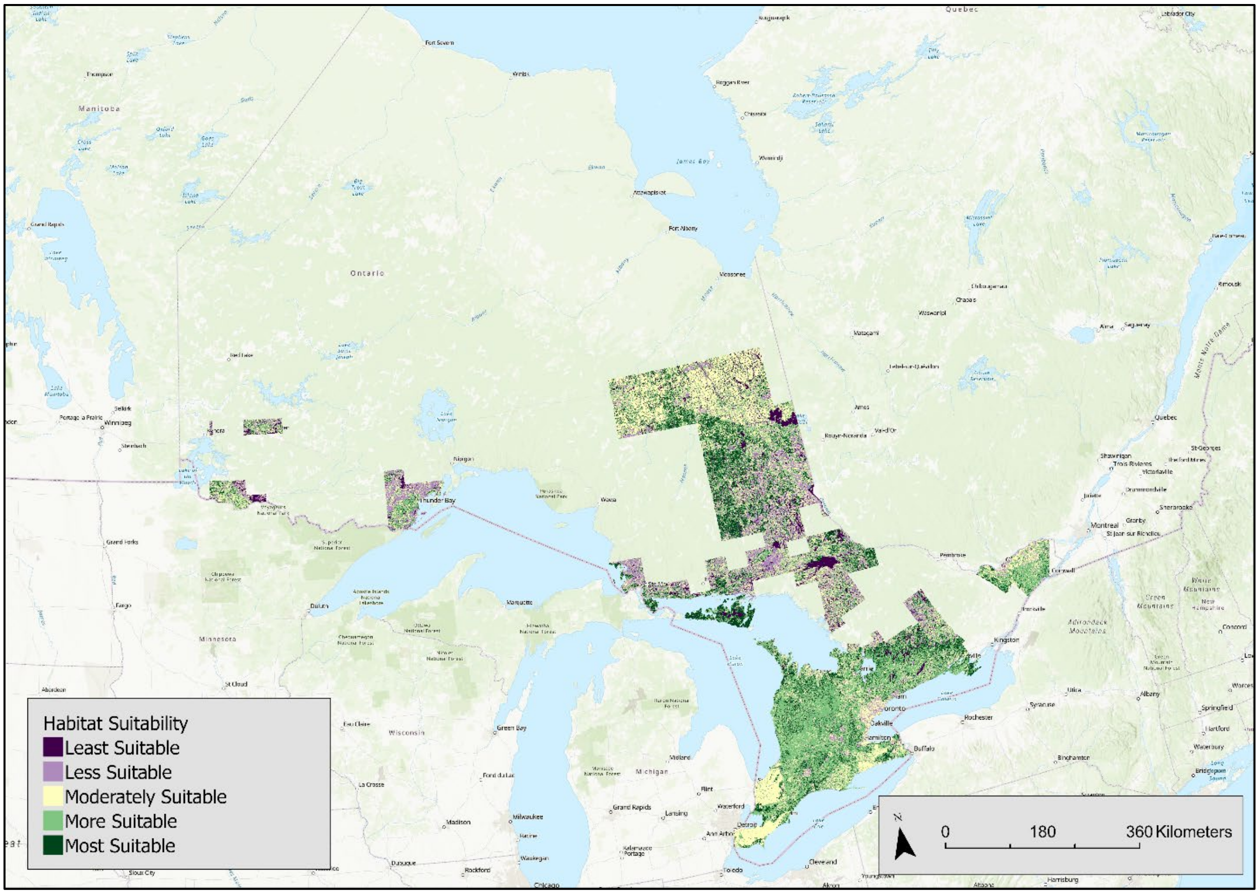

Figure 6. Suitability map of the most and least suitable areas for eastern hemlock when soil type is considered as a factor. Dark green are areas of more suitability, while dark purple are areas that are least suitable for the growth of the species.

5.2 Suitability Omitting Soil Type

When soil type was not included in the suitability raster, the output suitability map encompassed the entire province of Ontario. The grouping of the suitability scores was the same as in Table 5.

Omission of the soil type factor produced a dramatically different suitability map, shown in Figure 7. Windsor and the Kawartha highlands have some of the highest suitability values, while northern Ontario especially near Hudson Bay have some of the lowest values for eastern hemlock habitat suitability.

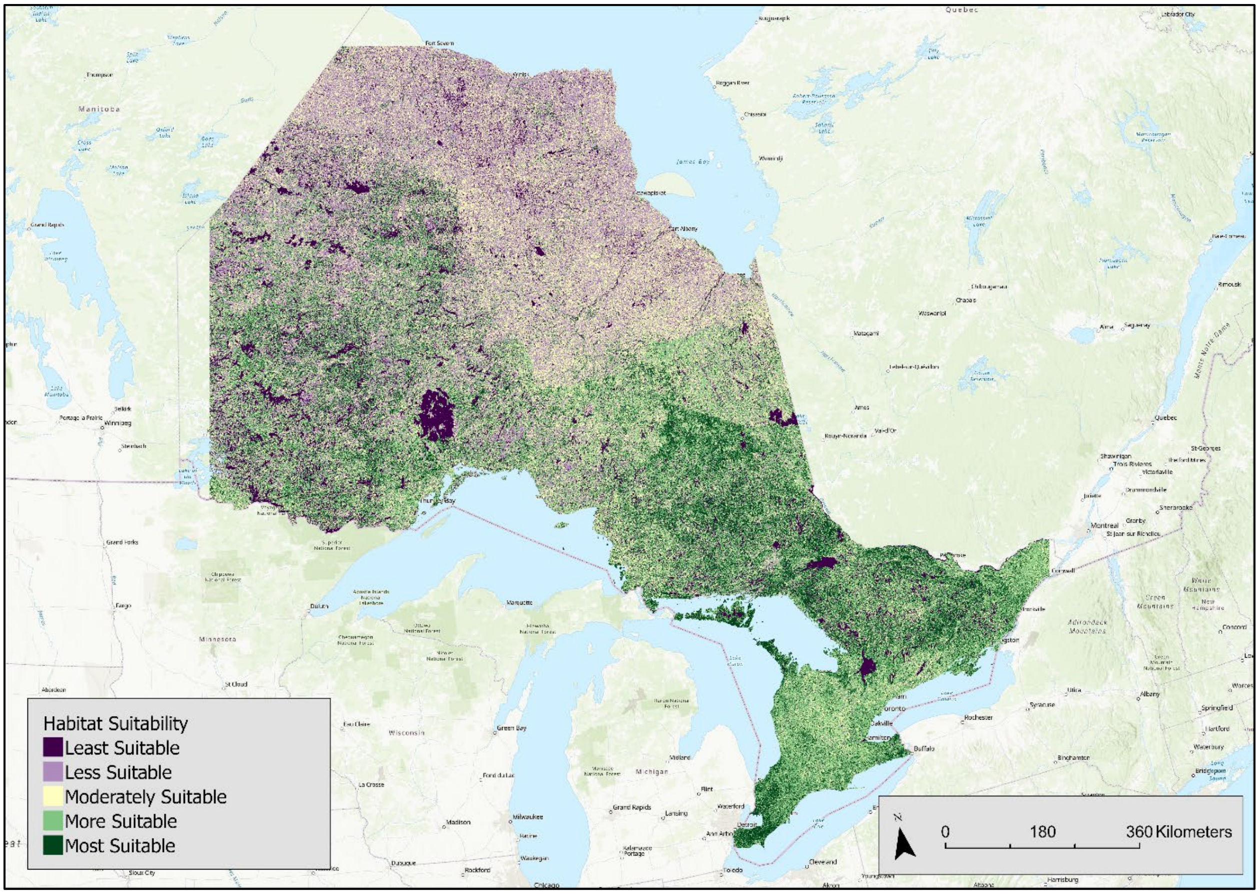

Figure 7. Suitability map of the entire province without the soil type factor. Areas of darker green are more suitable and areas of dark purple are least suitable.

5.3 Uncertainty Analysis: Comparison of Suitability Models with and without Soil Type

By comparing the side-by-side visual differences of the two suitability maps it is apparent that when soil type is considered as a factor there is significantly less data and large differences in the suitability values assigned to certain area. Specific locations that display this best are highlighted in Figures 9, 10, and 11.

The output of the Compute Change Raster tool (Figure 8) in ArcGIS pro visually displayed the areas of the study site that differ the greatest between the two suitability rasters. This raster only covers the extent of the soil type raster. Differences between the two suitability rasters were categorized into five different categories that range from No Difference to Most Difference (Table 6). Areas with the greatest difference in suitability are near Algonquin Park, Sault Ste. Marie, London, Sarnia, and Windsor. In all cases, the suitability of these locations increased greatly when soil type was not considered.

Table 6: Labelling of the Change Compute Raster scores

Descriptive Label	**Difference Between Suitability Rasters**
No Difference	≤ -0.166281
Some Difference	≤ -0.067962
Moderate Difference	≤ 0.036913
More Change	≤0.128678
Most Change	≤ 0.344981

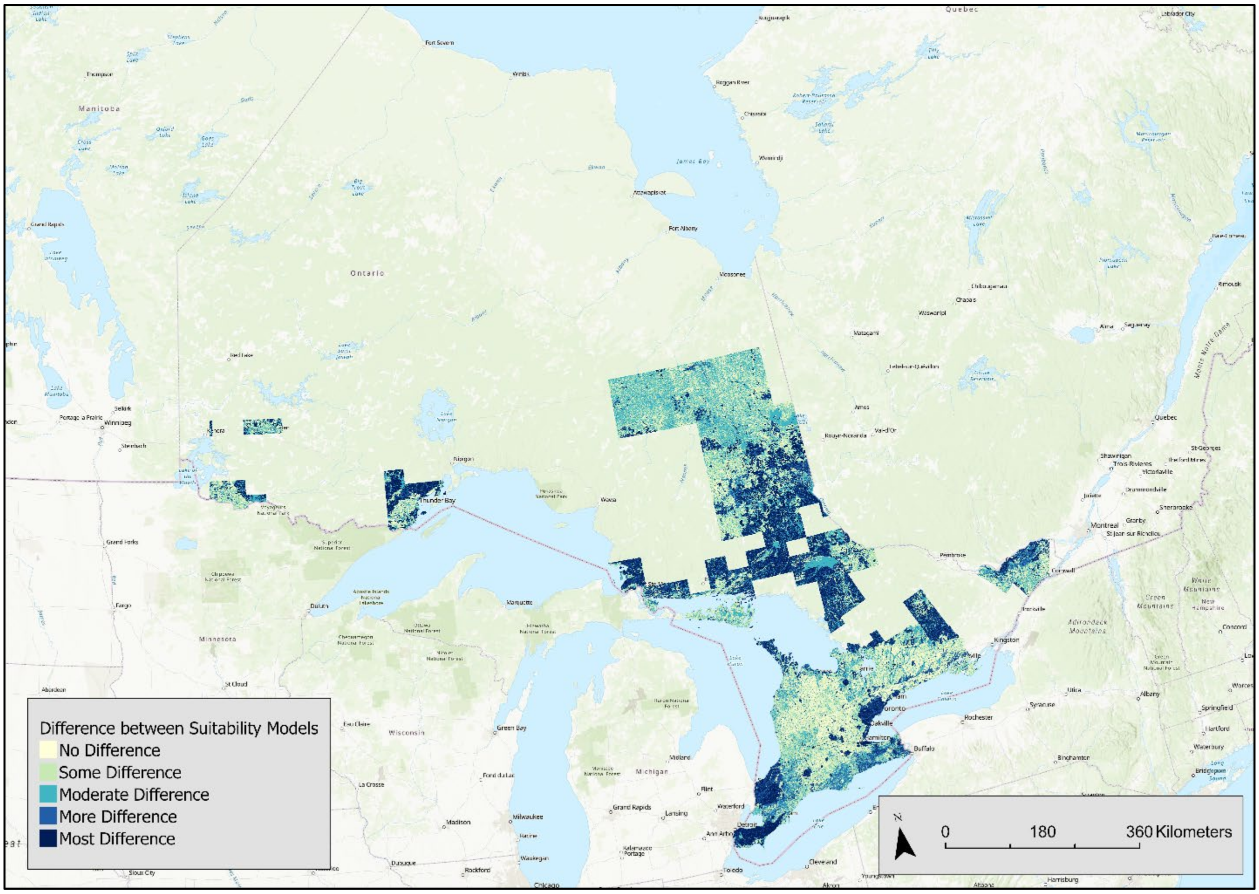

Figure 8: Map depicting the difference in suitability value between the suitability model that included soil type as a factor and the model that omitted soil type.

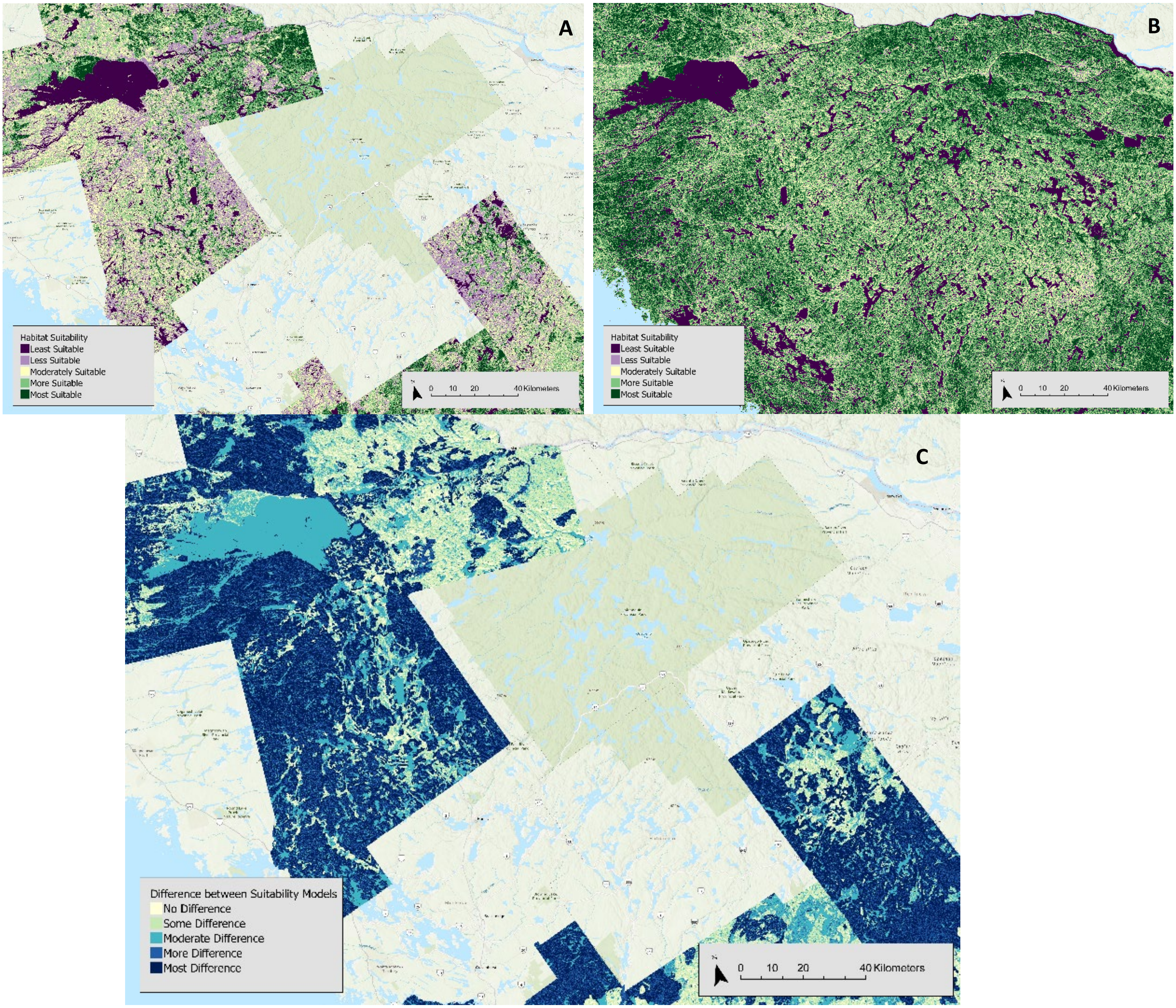

Figure 9. Suitability map over Algonquin Park A) with the soil type factor included, B) without the soil type factor, and C) depicting the difference in suitability score between maps A) and B).

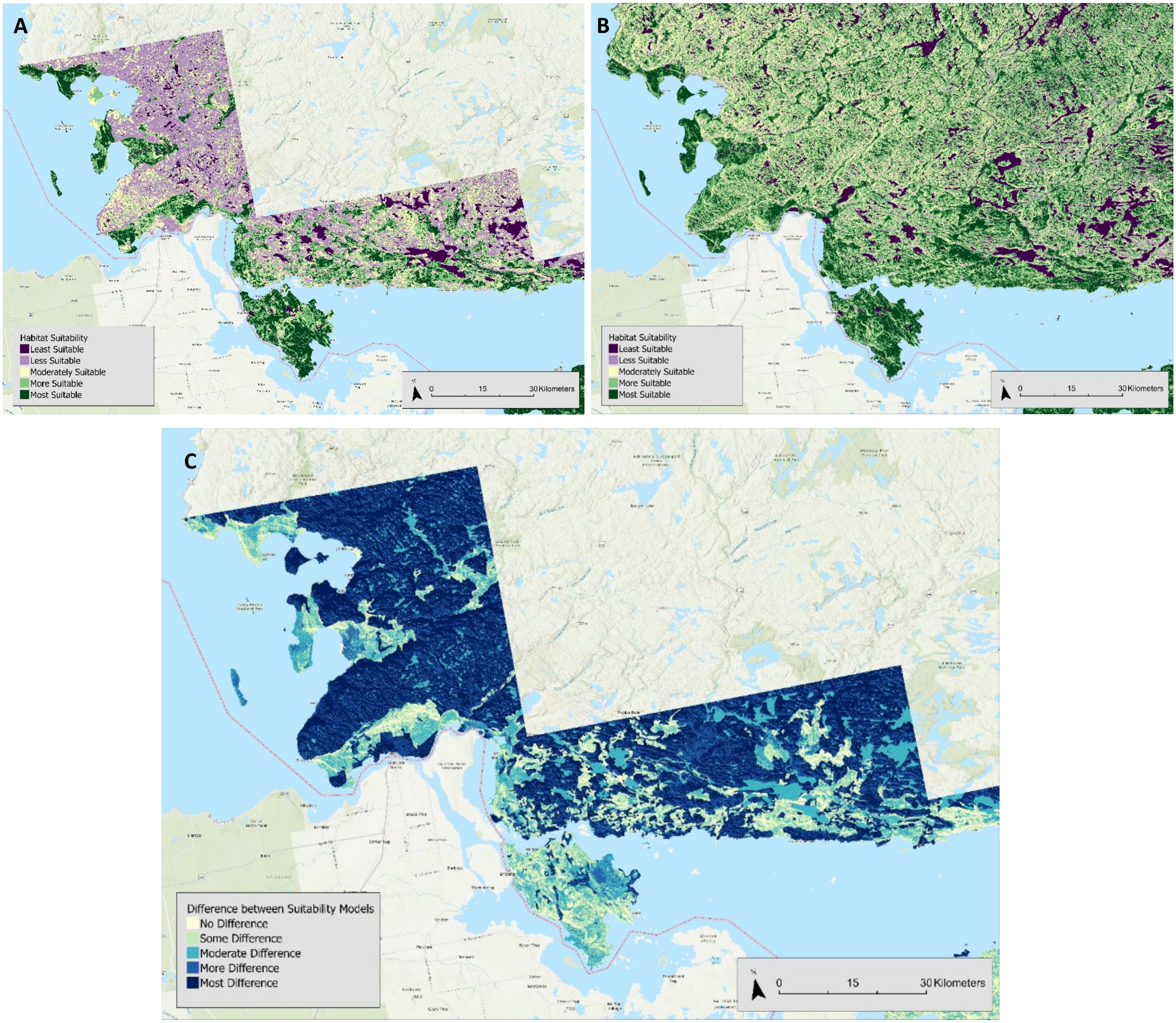

Figure 10. Suitability map over Sault Ste. Marie A) with the soil type factor included, B) without the soil type factor, and C) depicting the difference in suitability score between maps A) and B).

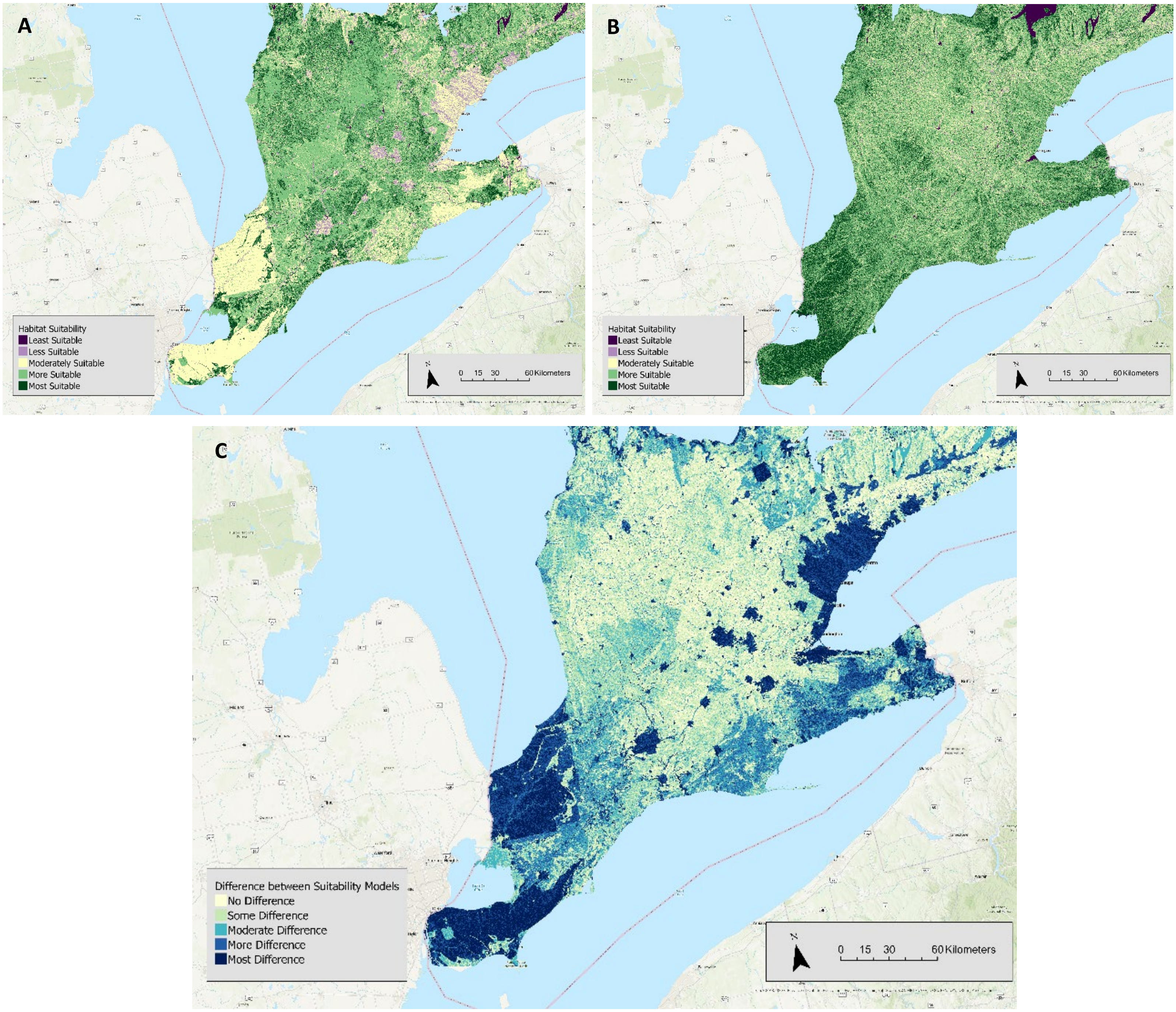

Figure 11. Zoomed in extent of suitability map over London, Sarnia, and Windsor A) with the soil type factor included, B) without the soil type factor, and C) depicting the difference in suitability score between maps A) and B).

6. Discussion

6.1 Interpreting Suitability at Specific Regions

The results presented in A) and B) of Figure 9 demonstrate an area where the extent covered by the suitability models that included and omitted soil type differ greatly. The suitability model without soil type classified most of Algonquin Park and the surrounding area as more or most suitable since this area is classified as deciduous, mixed, and coniferous forests and has a high January minimum temperature. However, when soil is included the suitability of areas to the west and south of Algonquin Park decreased to less suitable since most of this area is rockland soil (OMAFRA, 2019). Vasiliauskas and Aarssen (1999) described a hemlock stand in the western part of Algonquin park and noted that the soil in this area was primarily loamy sands. The suitability model without soil depicts this area as ranging between moderately and most suitable, and the presence of loamy sands suggests that if soil type was included, this area would be predicted as suitable for eastern hemlock growth by both models (Vasiliauskas and Aarssen, 1999).

Figure 10 covers Sault Ste. Marie and demonstrated a dramatic difference in suitability score between the two models. Areas farther from shore are classified as least suitable when soil type is included and moderately to most suitable when soil was not included. The suitability score is lower when soil type is included because this area is also primarily rockland soil, where 25-90% of the soil is characterized by rock outcrops and the remaining soil is shallow, suggesting it is not well suited to support eastern hemlock (OMAFRA, 2019). The suitability scores were also affected by high annual precipitation, mainly deciduous land cover, lower maximum July temperatures, and mid-range minimum January temperatures. High levels of precipitation and the land cover type increase the suitability, while the other factors limit the suitability of the Sault Ste. Marie region for eastern hemlock habitat.

In Figure 11, the difference in suitability values is greatest near Sarnia and Windsor; with soil type included, these regions are considered only moderately suitable as eastern hemlock habitat while the model without soil type ranks these locations as more and most suitable. Including the soil type in this area lowered the suitability of the location due to the predominantly Caistor and Brookston clay soil types and the suitability of the area decreased with increasing clay content due to its negative influence on soil drainage (OMAFRA, 2019). Downtown urban centers such as Guelph and Kitchener-Waterloo are marked as less suitable when soil type was included due to the imperviousness of predominantly compacted soils and concrete surfaces in cities; these areas are designated as built-up areas and are given no further soil classification (Craul, 1991; OMAFRA, 2019). The region's suitability was lowered since it is primarily urban, and this region experienced little precipitation (mostly values of 1). However, the location's maximum and minimum temperature values are high, which increase the suitability for eastern hemlock. The surrounding areas saw fewer changes in suitability since loam soils are most common and are considered suitable for eastern hemlock habitat (OMAFRA, 2019; Burns & Honkala, 1990). Overall, the region pictured in Figure 11 was favoured by the suitability model. Porter *et al.* (2008) described a hemlock-dominated forest plot in the Koffler Scientific Reserve, located to the west of Newmarket, Ontario. In Figure 11 the approximate area of the Koffler Scientific Reserve appears to have been classified as more and most suitable by both models.

6.2 Limitations of the study

Some limitations of this study must be considered if using the suitability models to locate eastern hemlock in Ontario. The lack of soil type data in some areas of the province is one issue with data reliability, but it is also important to note that interpolation of the climate variables from weather station data will reduce the accuracy of regions with low weather station density. Another limitation stems from the lack of known hemlock stand locations to test the accuracy of our suitability models' predictions. The weighting system, which weighs soil type highly as demonstrated by Williams *et al.* (2017) and Clark *et al*.'s (2012) findings, and the unknown sensitivity of eastern hemlock to soil type also pose limitations. The ideal soil texture for eastern hemlock habitat is described in multiple papers as moderately coarse textures and this is attributed to sandy loams, loamy sands, and silty loams (Carey, 1993; Bonneau *et al.,* 1999; Clark *et al.,* 2012; Burns *et al.,* 1990). The weighting of soil type in our model was based on these literary sources, however it remains unclear whether eastern hemlock is equally sensitive to all soil types and in all locations.

7. Conclusions

Based on the stark differences between the suitability models produced with and without soil type, the need for a provincial wide soil type survey is clear. The large difference in suitability values is partly due to how heavily soil type was weighted (0.2013/1.00) as recommended by Williams *et al.* (2017) and Clark *et al*. (2012). Once a provincial soil type survey is complete, the MCE to predict the location of eastern hemlock habitat can be rerun to properly estimate eastern hemlock distribution in Ontario.

There are few previous reports of eastern hemlock habitat in Ontario other than a few research papers that occurred in specific, small hemlock stands. An avenue of future study could be to assess eastern hemlock abundance in an area of Ontario that differs in the suitability for eastern hemlock predicted by the two models above and assess how the models performed based on the field survey results. If a field study is not feasible, it could still be valuable to test the accuracy of these models against eastern hemlock observations collected from citizen science programs such as iNaturalist. The suitability maps could also be used in combination with satellite imagery to locate eastern hemlock in existing forested areas. However, satellite imagery alone cannot accurately assess the locations of eastern hemlock without supporting on-site visits or reference maps, which is why the estimations of hemlock suitable habitat in Ontario are necessary (Bonneau *et al.,* 1999; Dunckel *et al.*, 2015).

With the current and advancing threat of the invasive hemlock woolly adelgid species migrating into Ontario from the eastern USA, locating areas that are suitable and can sustain eastern hemlock growth are essential (Orwig *et al.,* 2003; CFIA, 2022). The suitability maps produced by the MCE models in this study have important potential conservation applications as these maps can be used to discern areas where eastern hemlock can grow, and the protection of these habitats will help maintain the abundance of this old growth species in Ontario. Areas on the maps that indicate high suitability are potential habitats where a greater abundance of eastern hemlock could be currently growing and thus become a hotspot for HWA. Conservation efforts to limit or minimize the spread of this invasive species should be focused on the regions that were indicated by the highest suitability scores.

References

Bonneau, L.R., Shields, K.S., and Civco, D.L. (1999). Using satellite images to classify and analyze the health of hemlock forests infested by the hemlock woolly adelgid. *Biological Invasions* 1, 255-267. https://doi-org.subzero.lib.uoguelph.ca/10.1023/A:1010021629127

Burns, R.M., and Honkala, B.H., (tech. coords.) (1990). *Agriculture Handbook 654*: *Silvics of North American: Conifers: 1.* U.S. Department of Agriculture, Forest Service. https://www.srs.fs.usda.gov/pubs/misc/ag_654/volume_1/vol1_table_of_contents.htm

Canadian Food Inspection Agency (CFIA) (2022). *Hemlock woolly adelgid confirmed in Grafton, ON.* Government of Canada News Release. https://www.canada.ca/en/food-inspection-agency/news/2022/08/hemlock-woolly-adelgid-confirmed-in-grafton-on.html?fbclid=IwAR13utZsFcyjYO_gEMv_i_hSmThcyFBoNGrdZ-lzaq0CfJGSqL9-v2z046g

Carey, J.H. (1993). *Tsuga canadensis.* Fire Effects Information System (FEIS). U.S. Department of Agriculture. https://www.fs.usda.gov/database/feis/plants/tree/tsucan/all.html

Clark, J.T., Fei, S., Liang, L., and Rieske, L.K. (2012). Mapping eastern hemlock: comparing classification techniques to evaluate susceptibility of a fragmented and valued resource to an exotic invader, the hemlock woolly adelgid. *Forest Ecology and Management*, 266, 216-222. https://doi.org/10.1016/j.foreco.2011.11.030

Craul, P.J. (1991). Urban soil: problems and promise. *Arnoldia* 51. https://arboretum.harvard.edu/stories/urban-soil-problems-and-promise/

Dunckel, K., Weiskittel, A., Fiske, G., Sader, S., Latty, E., and Arnett, A. (2015). Linking remote sensing and various site factors for predicting the spatial distribution of eastern hemlock occurrence and relative basal area in Maine, USA. *Forest Ecology and Management* 358, 180-191. DOI: 10.1016/j.foreco.2015.09.012

Eastman, J.R. (1999). Multi-criteria evaluation and GIS. In Longley, P.A., Goodchild, M.F., Maguire, D.J., Rhind, D.W. (Eds.), *Geographical information systems (*pp. 493–502). New York: John Wiley and Sons.

Embree, G. M., (2022). Classifying the 2022 status of *Tsuga canadensis* (eastern hemlock) along the Kentucky portion of the Pine Mountain wildlands corridor. *Electronic Theses and Dissertations.* Paper 3972. https://doi.org/10.18297/etd/3972

Government of Ontario (1995). *Eastern hemlock.* Extension notes. http://www.lrconline.com/Extension_Notes_English/pdf/hmlck.pdf

Government of Ontario (2016). *Provinces/Territories, Cartographic Boundary File-2016 Census* [Dataset]. Retrieved from https://open.canada.ca/data/en/dataset/a883eb14-0c0e-45c4-b8c4-b54c4a819edb/resource/12c03de6-c3f7-4f5f-bb5c-d479f2332842

Government of Ontario (2022a). *Eastern Hemlock*. Tree Atlas. https://www.ontario.ca/page/eastern-hemlock#:~:text=The%20eastern%20hemlock%20grows%20in,range%20of%20different%20soil%20types.

Government of Ontario (2022b). *About Ontario.* https://www.ontario.ca/page/about-ontario

Government of Canada. (2023a). *Monthly Climate Summaries*. Historical Climate Data. https://climate.weather.gc.ca/prods_servs/cdn_climate_summary_e.html

Government of Canada. (2023b). *Hemlock woolly adelgid – Adelges tsugae (Annand).* Invasive species. https://inspection.canada.ca/plant-health/invasive-species/insects/hemlock-woolly-adelgid/eng/1325610383502/1325610993895

Graham, C. (2023). *Communication update: invasive spread of urban forest pests: hemlock woolly adelgid identified on city property (city wide) (ES23005).* https://www.hamilton.ca/sites/default/files/2023-03/comm-update_Hemlock-Woolly-Adelgid-Identified-on-City-Property.pdf

Hart, J.L., and Shankman, D. (2005). Disjunct eastern hemlock *(Tsuga canadensis*) stands at its southern range boundary. *The Journal of the Torrey Botanical Society* 132, 602-612. https://doi.org/10.3159/1095-5674(2005)132[602:DEHTCS]2.0.CO;2

Land Information Ontario (2022). *Ontario land cover compilation v.2.0.* Ontario Geohub. https://geohub.lio.gov.on.ca/documents/7aa998fdf100434da27a41f1c637382c/about

Lesack, P. (2016). *Environment Canada weather station data, April 2016.* Abacus Data Network. https://hdl.handle.net/11272.1/AB2/DIYFBI

Ministry of Natural Resources and Forestry (MNRF) (2020). *Provincial Digital Elevation Model.* Ontario Data Catalogue. https://data.ontario.ca/dataset/provincial-digital-elevation-model

Narayanaraj, G., Bolstad, P.V., Elliott, K.J., and Vose, J.M. (2010). Terrain and landform influence on *Tsuga canadensis* (L.) Carrière (eastern hemlock) distribution in the southern Appalachian Mountains. *Castanea* 75, 1-18. https://doi.org/10.2179/08-049.1

OMAFRA GIS. (2019). *Soil Survey Complex*. Ontario Geohub. https://geohub.lio.gov.on.ca/datasets/ontarioca11::soil-survey-complex/explore?location=46.447110%2C-79.835511%2C9.31

Orwig, D.A, Foster, D.R., & Mausel, D.L. (2003) Landscape patterns of hemlock decline in New England due to the introduced hemlock woolly adelgid. *Journal of Biogeography,* 29 (10-11), 1475- 1487. https://doi-org.subzero.lib.uoguelph.ca/10.1046/j.1365-2699.2002.00765.x

Orwig, D.A., Thompson, J.R., Povak, N.A., Manner, M., Niebyl, D., Foster, D.R. (2012). A foundation tree at the precipice: *Tsuga canadensis* health after the arrival of *Adelges tsugae* in central New England. *Ecosphere* 3, 1-16. https://doi.org/10.1890/ES11-0277.1

Porter, T.M., Skillman, J.E. and Monclavo, J.M. (2008). Fruiting body and soil rDNA sampling detects complementary assemblage of *Agaricomycotina* (*Basidiomycota*, Fungi) in a hemlock-dominated forest plot in southern Ontario. *Molecular Ecology* 17, 3037-3050. https://doi.org/10.1111/j.1365-294X.2008.03813.x

Saladyga, T., and Maxwell, R.S. (2015). Temporal variability in climate response of eastern hemlock in the central Appalachian region. *Southeastern Geographer* 55, 143-163. doi:10.1353/sgo.2015.0014.

Statistics Canada (2021). *Map Projection.* Dictionary, Census of Population, 2021. https://www12.statcan.gc.ca/census-recensement/2021/ref/dict/az/Definition-eng.cfm?ID=geo031

Stern, R.L., Schaberg, P.G., Rayback, S.A., Murakami, P.F., Hansen, C.F., and Hawley, G.J. (2021) Eastern white pine and eastern hemlock growth: possible tradeoffs in response of canopy trees to climate. *Canadian Journal of Forest Research*, 51(12), 1926-1938. https://doi.org/10.1139/cjfr-2020-051

Teets, A., Fraver, S., Weiskittel, A.R., and Hollinger, D.Y. (2018). Quantifying climate-growth relationships at the stand level in a mature mixed-conifer species forest. *Global Change Biology* 24, 3587-3602. https://doi-org.subzero.lib.uoguelph.ca/10.1111/gcb.14120

Vasiliauskas, S.A., and Aarssen, L.W. (1999). *The effects of moose (Alces alces L.) on hemlock (Tsuga canadensis (L.) Carr.) seedling establishment in Algonquin provincial park, Ontario, Canada.* Proceedings: Symposium on Sustainable

Management of Hemlock Ecosystems in Eastern North America, 148-153. https://www.nrs.fs.usda.gov/pubs/gtr/gtr_ne267/gtr_ne267.pdf

Ward, J.S., Montgomery, M.E., Cheah, C.A.S.J., Onken, B.P., and Cowles, R.S. (2004). *Eastern hemlock forests: guidelines to minimize the impacts of hemlock woolly adelgid*. Morgantown, WV: USDA Forest Service Northeastern Area and Private Forestry.

Williams, J., Hanavan, R.P., Rock, B., Minocha, S., and Linder, E. (2016). Low-level *Adelges tsugae* infestation detection in New England through partition modeling of Landsat data. *Remote Sensing of Environment,*190, 13-25. https://doi.org/10.1016/j.rse.2016.12.005

Appendix

Table 7. Reclassification/Standardization of Land Cover Dataset

Suitability Ranking (1– least suitable. 10 – most suitable. 0 – no suitability)	**Grouped Land Cover Category**	**Individual Land Cover Classes**
0	Other	Other, Cloud/Shadow, Turbid Water, Open Water
1	Low Veg	Open Cliff & Talus, Sand Barren & Dune, Sand/Gravel/Mine, Bedrock, Heath, Mudflat, Shoreline, Fen
2	Agri/Pasture, Urban, Water Adjacent	Community/Infrastructure, Plantations, Hedge Rows, Disturbance, Alvar, Open Tallgrass Prairie, Tallgrass Savannah, Agriculture/Undifferentiated, Bog, Marsh, Swamp
3	-	-
4	Other Treed	Treed Upland, Sparse Treed, Tallgrass Woodland
5	-	-
6	Deciduous	Deciduous
7	-	-
8	Mixed Forest	Mixed Forest
9	-	-
10	Coniferous	Coniferous

Table 8. Reclassification/Standardization of Aspect Dataset based on Hemlock Stand Distribution values from Orwig *et al.,* 2003.

Suitability Ranking (1- least suitable; 10 – most suitable)	**Slope Aspect (Direction; Degrees)**
1	S (157.5-202.5)
2	-
3	SW (202.5-247.5)
4	SE (112.5-157.5)
5	E (67.5-112.5)
6	N (337.5-22.5)
7	NE (22.5-67.5)
8	-
9	W (247.5-292.5)
10	NW (292.5-337.5)

Table 9. Reclassification/Standardization of Soil Type Dataset based on Loam Texture Contribution

Suitability Ranking (1- least suitable; 10 – most suitable; 0 – no suitability)	**‘A’ Horizon Soil Texture**
0	NA (Not Applicable); VA (Variable Area); R (Rivers); WA (Water Area)
1	S (Sand); C (Clay); G (Gravel)
2	SIC (Silty Clay)
3	VAR (Variable); FS (Fine Sand); GS (Gravelly Sand)
4	LFS (Loamy Fine Sand); LS (Loamy Sand); VFS (Very Fine Sand)
5	LVFS (Loamy Very Fine Sand); GSL (Gravelly Sandy Loam); LCS (Loamy, Clay Sand)
6	GL (Gravelly Loam); SCL (Sandy Clay Loam)
7	ORG (Organic); CL (Clay Loam); SICL (Silty Clay Loam); CSL (Clayey Sandy Loam)
8	FSL (Fine Sandy Loam)
9	SL (Sandy Loam); SIL (Silty Loam); VFSL (Very Fine Silty Loam)
10	L (Loam)

Table 10. Pairwise Comparison Matrix used for the suitability map containing the soil type factor.

	Pairwise Ranks								Individual Weights								Total Weight
	Precip	**Slope**	**Min Temp**	**Max Temp**	**Asp**	**Soil Type**	**LC**	**TWI**	**Precip**	**Slope**	**Min Temp**	**Max Temp**	**Asp**	**Soil Type**	**LC**	**TWI**	
Precip	1.00	0.20	0.20	3.00	0.50	0.20	0.17	2.00	0.04	0.02	0.02	0.08	0.03	0.05	0.06	0.07	**0.0403**
Slope	5.00	1.00	1.00	5.00	2.00	0.33	0.25	4.00	0.20	0.09	0.10	0.14	0.13	0.08	0.10	0.14	**0.2013**
Min. Temp.	5.00	1.00	1.00	5.00	2.00	0.33	0.25	4.00	0.20	0.09	0.10	0.14	0.13	0.08	0.10	0.14	**0.2013**
Max. Temp.	0.33	0.20	0.20	1.00	0.25	0.13	0.11	0.50	0.01	0.02	0.02	0.03	0.02	0.03	0.04	0.02	**0.0134**
Asp.	2.00	2.00	0.50	4.00	1.00	0.25	0.20	3.00	0.08	0.17	0.05	0.11	0.07	0.06	0.08	0.11	**0.0805**
Soil Type	5.00	3.00	3.00	8.00	4.00	1.00	0.50	6.00	0.20	0.26	0.30	0.22	0.27	0.23	0.19	0.21	**0.2013**
LC	6.00	4.00	4.00	9.00	5.00	2.00	1.00	8.00	0.24	0.34	0.39	0.24	0.33	0.45	0.38	0.28	**0.2416**
TWI	0.50	0.25	0.25	2.00	0.33	0.17	0.13	1.00	0.02	0.02	0.02	0.05	0.02	0.04	0.05	0.04	**0.0201**
SUM	**24.83**	**11.65**	**10.15**	**37.00**	**15.08**	**4.41**	**2.60**	**28.50**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 11. Pairwise Comparison Matrix used for the suitability map omitting the soil type factor.

	Pairwise Ranks							Individual Weights							Total Weight
	Precip	**Slope**	**Min Temp**	**Max Temp**	**Asp**	**LC**	**TWI**	**Precip**	**Slope**	**Min Temp**	**Max Temp**	**Asp**	**LC**	**TWI**	
Precip	1.00	0.17	0.17	3.00	0.25	0.13	0.33	0.04	0.03	0.03	0.08	0.02	0.06	0.02	**0.0353**
Slope	6.00	1.00	1.00	8.00	4.00	0.33	5.00	0.21	0.17	0.17	0.21	0.27	0.15	0.24	**0.2118**
Min Temp	6.00	1.00	1.00	8.00	4.00	0.33	5.00	0.21	0.17	0.17	0.21	0.27	0.15	0.24	**0.2118**
Max Temp	0.33	0.13	0.13	1.00	0.20	0.11	0.25	0.01	0.02	0.02	0.03	0.01	0.05	0.01	**0.0118**
Asp.	4.00	0.25	0.25	5.00	1.00	0.20	3.00	0.14	0.04	0.04	0.13	0.07	0.09	0.15	**0.1412**
LC	8.00	3.00	3.00	9.00	5.00	1.00	6.00	0.28	0.52	0.52	0.24	0.34	0.44	0.29	**0.2824**
TWI	3.00	0.20	0.20	4.00	0.33	0.17	1.00	0.11	0.03	0.03	0.11	0.02	0.07	0.05	**0.1059**
SUM	**28.33**	**5.74**	**5.74**	**38.00**	**14.78**	**2.27**	**20.58**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.0000**