Predicting invasive plant response to climate change: Prioritization and mapping of new potential threats to Alberta's biodiversity

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Preface

The Alberta Biodiversity Monitoring Institute (ABMI) is an arm's-length, not-for-profit scientific organization. The primary goal of the ABMI is to provide relevant scientific information on the state of Alberta's biodiversity to support natural resource and land-use decision making in the province.

In the course of monitoring terrestrial and wetland ecosystems across the province, the ABMI has assembled a massive biodiversity database, developed reliable measurement protocols, and found innovative ways to summarize complex ecological information.

The ABMI undertakes focused projects to apply this capacity to specific management challenges, and demonstrate the value of the ABMI's long-term monitoring data to addressing these challenges. In some cases, these applied projects also evaluate potential solutions to pressing management challenges. In doing so, the ABMI has extended its relevance beyond its original vision.

The ABMI continues to be guided by a core set of principles – we are independent, objective, credible, accessible, transparent and relevant.

This report was produced in support of the ABMI's Biodiversity Management and Climate Change Adaptation project, which is developing knowledge and tools to support the management of Alberta's biodiversity in a changing climate.

www.abmi.ca
www.biodiversityandclimate.abmi.ca

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Executive Summary

Climate change will result in more hospitable conditions in Alberta for new invasive species. We assessed 16 potentially new invasive plant species not yet present in Alberta for their invasiveness and climate change-related risk, demonstrating one approach to considering potential consequences of climate change for new non-native plant invasions in the province.

Invasiveness was evaluated based on four attributes: ecological impact, biological characteristics, dispersal ability and feasibility of control. Climate matching and habitat suitability modeling were used to predict potential invasion risk due to climate change in Alberta. Both approaches predicted an increase in potentially suitable climate space (climate matching) or habitat (habitat suitability modeling) in Alberta for 15 of 16 species between the historic/current climate (1961-1990) and projected future climate (2041-2070; the 2050s).

The top three new potential terrestrial invasive plant threats to Alberta's biodiversity are giant knotweed (*Fallopia sachalinensis*), tamarisk (*Tamarix chinensis*) and alkali swainsonpea (*Sphaerophysa salsula*). These species received the highest invasiveness score and showed the greatest increase in suitable high risk habitat in Alberta between current and future projected climate.

Ten of the 16 species we assessed are already listed (or have been proposed for listing) on the Alberta *Weed Control Act* as prohibited noxious species. Two of the species we assessed have 'not yet been assessed' by Alberta's Weed Regulatory Advisory Committee, globe thistle (*Echinops sphaerocephalus*) and European cotoneaster (*Cotoneaster integerrimus*), while a further four species assessed are not currently being considered by Alberta's Weed Regulatory Advisory Committee. They are: Syrian bean-caper (*Zygophyllum fabago*), gorse (*Ulex europaeus*), Scotch thistle (*Onopordum acanthium*), and Scotch broom (*Cytisus scoparius*). We provide suggestions for how climate change may be included in the consideration of these four, as yet unassessed, species under the *Weed Control Act*.

The climate change risk assessment indicated a high risk of invasion in the Grasslands Natural Region. Predictive models for the 2050s suggest that the Municipal Districts of Pincher Creek, Cardston and County of Forty Mile will be the top three municipalities/counties with suitable high risk habitat for the greatest number of new invasive species. Back country areas that are of conservation importance including Wilmore Wilderness Park, Jasper National Park and Banff National Park are also at high risk of invasion by more than one new invasive species.

From a regional perspective, more southerly parts of North America, regions within France and northern Spain may represent areas from which new non-native plant threats to Alberta's will emerge. Additionally, some regions around the world are predicted to have a higher climate match to Alberta by the 2050s than they do presently, including Newfoundland and Labrador, Turkey, Asia and Russia, which may facilitate new invasions from these regions.

Managing new non-native species that arrive as a result of climate change can range from eradication to tolerance to acceptance, and deciding on a management response should be done on a case by case basis. Management strategies will require increased coordination across jurisdictions, and should be formulated across wider geographic areas (regional perspectives) and over longer time frames.

1 Introduction

Climate change is likely to favour invasive species through decreased resistance of native communities to invasion, increased disturbance events such as fire, flood, storms and drought that favour traits of invasive species and more hospitable climates for invasive species to cross frontiers (Dukes & Mooney 1999, Mooney & Hobbs 2000, Stachowicz et al. 2002, Walther et al. 2009). Further, invasive plant traits generally predispose them to benefit from climate change; these include short generation time, good dispersal ability, broad environmental tolerance and rapid growth (Bradley et al. 2010). Global temperatures are predicted to be on average 3.7° Celsius warmer by the end of the 21st century compared to the 1986-2005 reference period, and warming is predicted to be most intense at high northern latitudes (IPCC 2013). This expands the range of suitable habitats for species that previously occupied warmer climates, and may facilitate poleward expansion of invasive species ranges (Kriticos 2012, Porter et al. 1991).

As with other climate change predictions, uncertainty remains in the expectations for invasive species due to the highly dynamic nature of the changes and the impact of human activities. Causal attribution of invasive plant distributions to climate change is complex because non-climatic factors such as biotic interactions, evolutionary change and dispersal influence local, short-term effects (Pearson & Dawson 2003). Nonetheless, climate has a strong influence on the distribution of plants, especially at regional or continental scales (Petitpierre et al. 2012) and climate change projections can inform predictions of the response of potentially invasive plant species (Kriticos 2012, Petitpierre et al. 2012, Sexton et al. 2002).

Expanding the spatial and temporal scales of investigation is essential to the study of climate change and biodiversity management issues (Hellman & Zavaleta 2008). Research on invasive species response to climate change, including the development of predictive models of invasive species ranges has proven valuable to orienting policies and decision-making, and identifying new potential areas of invasion (Mooney & Hobbs 2000, Beaumont et al. 2009, Dukes 2011). Managers of biological invasions require pre-emptive information on invasive species distributions so that risks can be assessed and suitable strategies can be formulated in a timely manner (Kriticos et al. 2003). Research to-date has, however, focused on modeling distributional changes of current invasive species, rather than predicting the arrival of new threats (Smith et al. 2012), even though preventing new invasions is regarded as the most efficient approach to managing invasive species (Tu 2009). For example, one recent report by the Government of Canada (2011) estimated that, for every dollar invested in prevention, economic returns are estimated at CAD $100. Conversely, for every dollar spent on reactive control, economic returns are significantly reduced to $1-$5.

The same Government of Canada report (2011) suggests that as a result of climate change, Canada can expect (1) new invasive species to establish and spread to new regions of Canada where they previously were unable to survive, (2) once non-threatening species to become invasive, (3) changes in the pathways of invasion, (4) managers to be required to find innovative strategies to control an increased number of invasive species, increasing the economic costs of control (Government of Canada 2011). In part, managing these new climate-related invasion risks requires both species-specific risk assessments that consider climate change-related risks, and a broader geographic perspective to identify potential sources of new invasive species.

Invasive species were highlighted as a climate change risk factor for Canadian protected areas (Lemieux et al. 2011), and their consideration in light of a changing climate has been identified as a research need in the province of Alberta (McClay et al. 2004). Alberta currently has an Invasive Alien Species Management Framework that includes a Risk Assessment Tool for assessing the potential impacts of new invasive species on biodiversity (Government of Alberta 2008). However, this risk assessment does not consider the possible consequences of climate change on the potential impact of new invasive species.

In this report, we demonstrate a risk assessment for invasive plants for Alberta that explicitly considers the potential consequences of climate change for new non-native plant invasions in the province. We use two complementary approaches to understand climate-related invasive plant risks to Alberta: identification of high-risk species from surrounding jurisdictions, and identification of potential novel source regions for new invasive plants globally. We rank potential new non-native plant threats to Alberta using an evaluation of both invasiveness and climate-related risk; invasiveness was evaluated with a trait-based invasiveness assessment (Carlson et al. 2008; Appendix 1) that includes a climate-screening component, and we evaluated climate-related risk in more detail with projections of change in suitable habitat between historic/current (1961-1990; i.e., 1975) and future (2041-2070; i.e., 2050s) climates in Alberta. We also highlight regions of the province most vulnerable to invasion by the assessed species, identify potential new geographic sources of invasive plant threats that may emerge as a result of climate change, and explore the management implications of including climate change in the assessment of invasive plant risks in Alberta.

2 Methods

2.1 Species assessed

We assessed the potential risk to Alberta from 16 non-native plant species based on their invasiveness and the projected change in suitable habitat between current and future climates in Alberta (Table 1). The set of species assessed was intended to represent the breadth of potential new non-native plant threats to Alberta, with a focus on species that have a high potential for altered invasion risk resulting from climate change; it was not intended to be a comprehensive set of all potential new non-native species to Alberta.

We selected species by examining regulated species present in states south of Alberta's border (Montana, North Dakota, South Dakota, Wyoming, Idaho, Washington, Oregon), and in provinces to the east (Manitoba, Saskatchewan, Ontario) and west of Alberta's border (British Columbia), but currently absent in Alberta (except for a few individuals planted in gardens). Limiting the list primarily (although not exclusively) to species regulated in jurisdictions south of Alberta emphasizes species that are more likely adapted to the warmer, drier conditions generally projected for Alberta in the 2050s (Schneider 2013). We also limited the list to include only one representative from any single genera under the assumption that congeneric species would share similar invasiveness rankings and responses to climate change.

Table 1. Non-native species assessed for climate-change-related risk and invasiveness in Alberta. None of these species are recorded in Moss (1992) or in the Alberta Conservation Information Management System (ACIMS)[1].

Common name	Scientific name	Alberta designation	No. of provinces and states where regulated	ANPC rogues list[1]	NatureServe I-Rank[2]	Native range	Invaded range relative to Alberta
African rue	*Peganum harmala*	proposed prohibited noxious	6	present	not assessed	Eastern Iran to India	South of Alberta
alkali swainsonpea	*Sphaerophysa salsula*	proposed prohibited noxious	4	not found	not assessed	Asia	South and East of Alberta
autumn olive	*Elaeagnus umbellata*	prohibited noxious	1	present	high	Eastern Asia	South and East of Alberta
black swallow-wort	*Vincetoxicum nigrum*	proposed prohibited noxious	5	not found	high	Italy, France, Portugal, Spain	East of Alberta
European cotoneaster	*Cotoneaster integerrimus*	not yet assessed	0	present	not found	Central/Eastern Europe, Asia	West and South of Alberta
gorse	*Ulex europaeus*	none	5	not found	not assessed	Western and Central Europe	East of Alberta
knapweed, brown	*Centaurea jacea* (sensu lato)	prohibited noxious	1	present	unknown	Europe	Surrounds Alberta
knotweed, giant	*Fallopia sachalinensis*	prohibited noxious	4	present	med/high	Asia, Japan and Russia	Surrounds Alberta
medusahead	*Taeniatherum caput-medusae*	prohibited noxious	5	present	high	Europe	South and East of Alberta
puncturevine	*Tribulus terrestris*	prohibited noxious	12	present	not assessed	Europe, Asia, Africa, Australia	Surrounds Alberta
saltlover	*Halogeton glomeratus*	prohibited noxious	6		med/high	Russia and China	South of Alberta
Scotch broom	*Cytisus scoparius*	none	5	present	high	Western and Central Europe	Surrounds Alberta
Scotch thistle	*Onopordum acanthium*	none	13	not found	not assessed	Europe and Western Asia (Kazakhstan)	South of Alberta
Syrian bean-caper	*Zygophyllum fabago*	none	4	not found	not assessed	Asia, Middle East	South of Alberta
tamarisk, Chinese	*Tamarix chinensis* (sensu lato)	prohibited noxious	7	present	not assessed	China and Korea	South of Alberta
thistle, globe	*Echinops sphaerocephalus*	not yet assessed	0	present	not assessed	Eurasia	Surrounds Alberta

[1] Alberta Native Plant Council (ANPC) Rogues list is a list of non-native species present in Alberta (http://www.anpc.ab.ca/wiki/index.php/Main_Page)

[2] NatureServe I-Rank is an Invasive Species Impact Rank (I-Rank) of High, Medium, Low, or Insignificant used to categorize impact on natural biodiversity.

[1] http://www.albertaparks.ca/albertaparksca/management-land-use/alberta-conservation-information-management-system-(acims).aspx

Regulated species lists may be biased towards agricultural weeds, and may not include the most serious weeds if they are beyond control. Considering regulated lists from multiple jurisdictions surrounding Alberta, however, reduces the likelihood that a serious invasive plant was omitted from the list.

Species we assessed include those that are:

- already regulated or proposed for regulation in Alberta, but have not been detected in the province (*prohibited noxious* species and proposed *prohibited noxious* species)
- 'not yet assessed' for regulation in Alberta according to Alberta's Weed Regulatory Advisory Committee (http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/prm14073)
- regulated in neighbouring provinces or states, but have not yet been considered by Alberta's Weed Regulatory Advisory Committee.

2.2 Invasiveness ranking

We used a modified version of Alaska's *Invasiveness Ranking System for Non-native Plants of Alaska* to rank the invasiveness of the 16 species assessed (Carlson et al. 2008, Appendix 1). We selected this ranking system because it focuses on biodiversity impacts (rather than agricultural impacts), it contains a climate pre-screening component (see section 2.3) and allows assessment of species that are not yet present in the jurisdiction of interest. In this ranking system, species are assessed on 21 criteria, grouped into four attributes: ecological impact, invasive characteristics, dispersal ability, and feasibility of control. Assessments were peer-reviewed by species experts from outside of Alberta and are available at www.biodiversityandclimate.abmi.ca.

2.3 Assessing climate change-related risk

We represented to the future climate in Alberta using climate projections for the time frame 2041-2070 (2050s) because we expect to see pronounced effects of climate change by this timeframe (Schneider 2013) but it is still a reasonably close timeframe for which management planning can occur.

We used two approaches to assess climate change-related risk of each of the 16 assessed species to Alberta: climate matching and habitat suitability models. Climate matching was used to provide a simple assessment of the climatic similarity between the current species distribution and current and potential future climates in Alberta, by Natural Region, as part of the climate screening component of the invasiveness assessment. We developed more detailed spatial projections of potentially suitable habitat for each species in Alberta under current and future climates using habitat suitability models to assess the climate-related risk to Alberta of each potential new non-native plant species at a finer spatial scale.

2.3.1 Species observations

Both climate matching and habitat suitability modeling require distribution data (observed locations) for the species assessed. We obtained location data from the Global Biodiversity Information Facility, limiting our search to records with geographic coordinates (GBIF 2013). The Global Biodiversity Information Facility (GBIF, http://www.gbif.org) is a free, open-access database of natural history collections of a wide variety of species from around the world. Location data for two species (*Cotoneaster integerrimus* and *Halogeton glomeratus*) were supplemented with records requested from the Atlas Florae Europaeae. These data were obtained through personal communication with Alexander Sennikov, Secretary of the Committee for Mapping the Flora of Europe on August 30, 2013.

All records were examined and suspect points (e.g., those with coordinates (0, 0), or those where coordinate data and recorded place names were inconsistent) were removed. The final data set contained between 100 and 87,687 records for each species (Table 2). Location data from both native and invaded ranges were used to identify climate matches and to model habitat suitability because the combined data set is potentially more relevant for potential invasions into Alberta in the context of climate change than location data from the native range alone (Beaumont et al. 2009, Bradley et al. 2010).

Table 2. Species location data used in CLIMEX climate matching and habitat suitability modeling

Common name	Scientific name	Number of occurrence records	Data source
African rue	*Peganum harmala*	827	GBIF
alkali swainsonpea	*Sphaerophysa salsula*	100	GBIF
autumn olive	*Elaeagnus umbellata*	897	GBIF
black swallow-wort	*Vincetoxicum nigrum*	977	GBIF
European cotoneaster	*Cotoneaster integerrimus*	3,092	GBIF, AFE
gorse	*Ulex europaeus*	62,305	GBIF
knapweed, brown	*Centaurea jacea* (sensu lato)	62,232	GBIF
knotweed, giant	*Fallopia sachalinensis*	4,348	GBIF
medusahead	*Taeniatherum caput-medusae*	1,832	GBIF
puncturevine	*Tribulus terrestris*	4,065	GBIF
saltlover	*Halogeton glomeratus*	208	GBIF, AFE
Scotch broom	*Cytisus scoparius*	77,275	GBIF
Scotch thistle	*Onopordum acanthium*	10,701	GBIF
Syrian bean-caper	*Zygophyllum fabago*	262	GBIF
tamarisk, Chinese	*Tamarix chinensis*	326	GBIF
thistle, globe	*Echinops sphaerocephalus*	3,084	GBIF

GBIF: Global Biodiversity Information Facility
AFE: Atlas Florae Europaeae

2.3.2 CLIMEX climate matching

We used CLIMEX regional-climate matching (v.3; Hearne Scientific Software 2007; Sutherst et al. 2007) to determine the climate similarity between the current range of each non-native species and the current or projected future climate in each of Alberta's Natural Regions for use in the climate pre-screening component of the invasiveness ranking (Carlson et al. 2008; Appendix 1). The matching algorithm in the CLIMEX software calculates a Composite Match Index (CMI, range: 0-1) that describes the degree of matching between the climates in two regions or two time periods, based on temperature, precipitation, humidity and soil moisture variables which can optionally be weighted. Based on the climate data available, we used the variables weekly maximum, minimum, and average temperature, annual total rainfall and seasonality of rainfall (Sutherst et al. 2007; see Appendix 2 for a detailed description of the calculation of the CMI). A CMI value of 0.7 is generally accepted as the threshold for a biologically relevant climate match (Sutherst et al. 2007, Kriticos 2012). A CMI value of 0.7-1 therefore indicates that the climates of the two locations compared are a match, with higher values (closer to one) indicating climate matching to a greater degree.

Climate data

We used global historical/current (1961-1990, or 1975) and projected future (2041-2070, or the 2050s) gridded climate data from the CliMond[2] v 1.1 datasets at 0.5° resolution (Kriticos et al. 2012). The future climate data was from the CSIRO-Mk3.0 global climate model projection using the A2 SRES scenario (IPCC 2000). Of the two global climate models (CSIRO-Mk3.0 and MIROC-H) and SRES scenarios (A1B, A2) for which future projections are available from CliMond the combination of the CSIRO-Mk3.0 model and the A2 SRES scenario aligns best with the global climate model recommendations for Alberta and the approach taken by the Biodiversity Management and Climate Change Adaptation project at the Alberta Biodiversity Monitoring Institute (Stralberg 2012).

Matching climates based on species distributions

In the regional-climate matching algorithm in CLIMEX, two sets of locations (regions) are identified (termed 'Home' and 'Away'). To evaluate the climate match between locations in Alberta and the native and invaded ranges of the species assessed, we defined the 'Home' location set as the climate grid points nearest the geographic records for each species, and the 'Away' location s as the climate grid points within Alberta. We determined the degree of climate similarity between the current range of each target species and both historical/current (1961-1990) and projected future (2050s) climate in Alberta. The model returns the value of the Composite Match Index (CMI) for the best match among all of the 'Home' (current distribution) locations for each of the 'Away' (Alberta) locations.

The CMI values were averaged across: 1) the province, and 2) within each Natural Region, and used in the climate pre-screening section of the invasiveness ranking: Natural Regions for which CMI>0.7 are considered to have suitable climate for the establishment of the species (Appendix 1). For qualitative comparison with the more detailed spatial projections from the habitat suitability modeling approach (section 2.3.3) the CMI values were also averaged within each Municipal District in Alberta and mapped (Appendix 4).

2.3.3 Habitat suitability modeling

Species distribution model (SDM) approaches are commonly used to project suitable habitat for potential invasive plants in response to climate change (e.g., Peterson 2003). These models use a correlative approach between observed species locations and climate/environmental variables to predict habitat suitability outside of the observations; they assume climate equilibrium and strong climate dependency in determining the species distributions. The drawback to this approach for invasive species in particular is that species locations (distribution) observed today may not be in equilibrium with current climate; they may not be distributed over their full potential climate niche, due to factors such as dispersal limitation, competition, predation and human management, and may take centuries or

[2] www.climond.org

millennia to stabilise (Thomas 2011). Notwithstanding this caveat, habitat suitability models have been shown to be highly predictive in determining the point of invasion for species (Broennimann et al. 2007; Fitzpatrick et al. 2007; Hill et al. 2012).

Compared to the climate matching approach (section 2.3.2), habitat suitability modeling uses a larger set of environmental variables, including additional climate variables and other classes (e.g., edaphic) of variables, and allows for more complex, non-linear responses to environmental variables, and interactions among them when projecting suitable habitat (Peterson 2003). The habitat suitability models are therefore more nuanced spatial predictions of habitat suitability in the present and future climates for each of the species assessed than the predictions from climate matching.

Environmental data

We used a combination of climate (current or future) and soil variables to model habitat suitability for the 16 potentially new non-native species in Alberta:

- Historic/current climate (1961-1990): Nineteen bioclimatic variables at 2.5 arc minute (nearly 4.6 km) resolution from Worldclim[3] (Hijmans et al. 2005).
- Future climate (2041-2070): CliMond 10′ gridded climate data from CISRO Mk3.0, A2 scenario (Kriticos et al. 2012).
- Soil variables: Global data set of derived soil properties (0.5-degree grid)[4]. Variables included total available water capacity, soil pH (0-30 cm depth range) and soil pH (30-100 cm depth range).

Some of the predictor variables were highly correlated. To reduce multi-collinearity among variables, Pearson correlation and VIF (variance inflation factor) were used for variable selection (Marquardt 1970). A pairwise Pearson correlation coefficient (absolute value) of 0.7 was used as a threshold of correlation, and a VIF greater than 10 was used as an indication of collinearity. From the set of 19 climate and three soil variables, we selected eight climatic variables and two soil variables that were uncorrelated based on these criteria:

1) Annual Mean Temperature
2) Mean Diurnal Range: Mean of monthly (max temp - min temp)
3) Isothermality: Mean Diurnal Range/Temperature Annual Range
4) Max Temperature of Warmest Month
5) Mean Temperature of Driest Quarter
6) Annual Precipitation
7) Precipitation Seasonality (Coefficient of Variation)
8) Precipitation of Warmest Quarter
9) Total available water capacity
10) Soil pH (0-30 cm depth range)

[3] www.worldclim.org
[4] http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=546

Species distribution modeling

We used maximum entropy modeling to predict habitat suitability for each of the 16 potential invasive species in both current and future Alberta climates (Phillips et al. 2006; Merow et al. 2013). This approach is appropriate for modeling habitat suitability based on "presence-only" data, such as data from herbaria where species absences are not explicitly recorded (Elith et al. 2011). The analyses were conducted using the MaxEnt[5] (Version 3.3.3k; Phillips et al. 2006) and R package 'dismo' (Hijmans et al. 2013).

To model each species' distribution using presence-only location data, each set of observations was divided into a training dataset, used to develop the model and a testing dataset, used to evaluate the performance of the model. Model performance was evaluated using the area under the curve (AUC) of a receiver operating characteristic (ROC; Manel et al. 2001). An AUC value of 0.5 implies random predictive discrimination, while values above 0.7, 0.8 and 0.9 represent good, very good and excellent discrimination, respectively (Swets 1988, Manel et al. 2001). We used these models to predict distributions of suitable habitat for all 16 species under both current and future climates for Alberta.

Habitat suitability was initially predicted as a continuous variable. To convert the continuous prediction of habitat suitability for each model into categories representing low risk (low suitability) and high risk (high suitability) habitat, we used model specific probability thresholds (Peterson et al. 2011). The low threshold, identifying low risk habitat, was chosen using the least training presence threshold (Pearson et al. 2007); the relatively higher threshold, identifying habitat most likely to be at risk of invasion (i.e., *suitable high risk habitat*), was defined by sensitivity-specificity sum maximization (e.g., Liu et al. 2013).

Individual predictions for the 16 species for either the current or future climate were combined to identify overlapping areas of predicted *suitable high risk habitat* among species and to highlight potential new high risk areas in Alberta resulting from climate change.

2.4 Combining invasiveness rankings and climate-related risk

To consider invasiveness and climate-related risk in combination, we qualitatively ranked species to identify the top three species that are both 1) ranked as "Extremely" or "Highly Invasive", and 2) have the largest relative increases in projected *suitable high risk habitat* of the species assessed, as determined by the habitat suitability models.

2.5 Regional climate matching

To investigate potential new sources of non-native species to Alberta under climate change from a global perspective, we examined the similarity of current and future climatic conditions between Alberta and the rest of the globe (Kriticos 2012).

We applied the CLIMEX regional climate-matching algorithm to a factorial combination of historical and projected future climate in Alberta and the rest of the world to represent four risk scenarios (Table 3):

[5] http://www.cs.princeton.edu/~schapire/maxent/

1. Geographic origins of present risk: current risk areas identified by matching historical reference climate in Alberta with the same reference climate for the rest of the world. This is the baseline scenario that can be compared to all future risk scenarios.
2. Geographic origins of future risk: regions that represent the present locations of species that could pose a risk to Alberta in the future. These areas have historic climate conditions that are similar to Alberta's future climate.
3. Geographic origins of transient risk: regions that represent the locations of species that may pose a transient risk to Alberta in the future. As climate changes, these areas will become more climatically similar to Alberta's historical climate. If the relative rate of climate change in Alberta lags behind other regions of the globe, species adapting to the new conditions in their native ranges could pose a transient threat to Alberta.
4. Geographic origins of future equilibrium risk: regions that represent the potential future locations of species that may pose a risk to Alberta in the future. These areas have projected future climate conditions that are similar to those projected for Alberta in 2050.

We used the 0.7 CMI threshold to map climate similarity for each of the four scenarios.

Table 3. Combinations of historical and projected future climates in Alberta compared with the world representing four risk scenarios (adapted from Kriticos 2012)

		World	
		Historical	Future
Alberta	Historical	Current risk areas	Transient risk areas
	Future	Current location of future risk species	Future equilibrium risk areas

3 Results

Of the 16 species assessed, the top three new potential terrestrial invasive plant threats to Alberta are giant knotweed (*Fallopia sachalinensis*), tamarisk (*Tamarix chinensis*), and alkali swainsonpea (*Sphaerophysa salsula*). These species were all ranked as either 'extremely' or 'highly invasive' and had the greatest increases in *suitable high risk habitat* in Alberta between historic and future projected climate, as projected by the habitat suitability models. Two of these species (tamarisk and giant knotweed) are currently managed in Alberta through regulation as *prohibited noxious* species on the *Weed Control Act*. The third species, alkali swainsonpea, has been proposed for inclusion as a *prohibited noxious* species in 2014.

The climate matching analysis indicated an increase in climate similarity of the current species ranges and Alberta's climate between the current and 2050s climates for all species assessed (Table 1). Similarly, the habitat suitability models projected an increase in *suitable high risk habitat* in Alberta between the 1975 reference climate and the 2050s future climate for all 16 species, except for saltlover (*Halogeton glomeratus*), where a 46% decline in *suitable high risk habitat* was projected between the two climates (Table 4, Appendix 3).

From the predicted distributions of the 16 species assessed, Alberta's southern region (Grasslands Natural Region) is the most at-risk region to new invasive species in both the historic and future climate; this result is consistent with the outcome of the climate matching analysis. Specifically, within the Grasslands Natural Region under the historic climate[6], Cypress County and County of Forty Mile are the municipalities/counties with *suitable high risk habitat* for the greatest number of new invasive species (five species, Figure 1a). In future projected climate, the Municipal Districts of Pincher Creek and Cardston and County of Forty Mile are predicted to be the top three municipalities/counties with *suitable high risk habitat* for the greatest number of new invasive species (six to seven species, Figure 1b). Back country areas in the Rocky Mountains including Wilmore Wilderness Park, Jasper National Park and Banff National Park also showed *suitable high risk habitat* for more than one new invasive species.

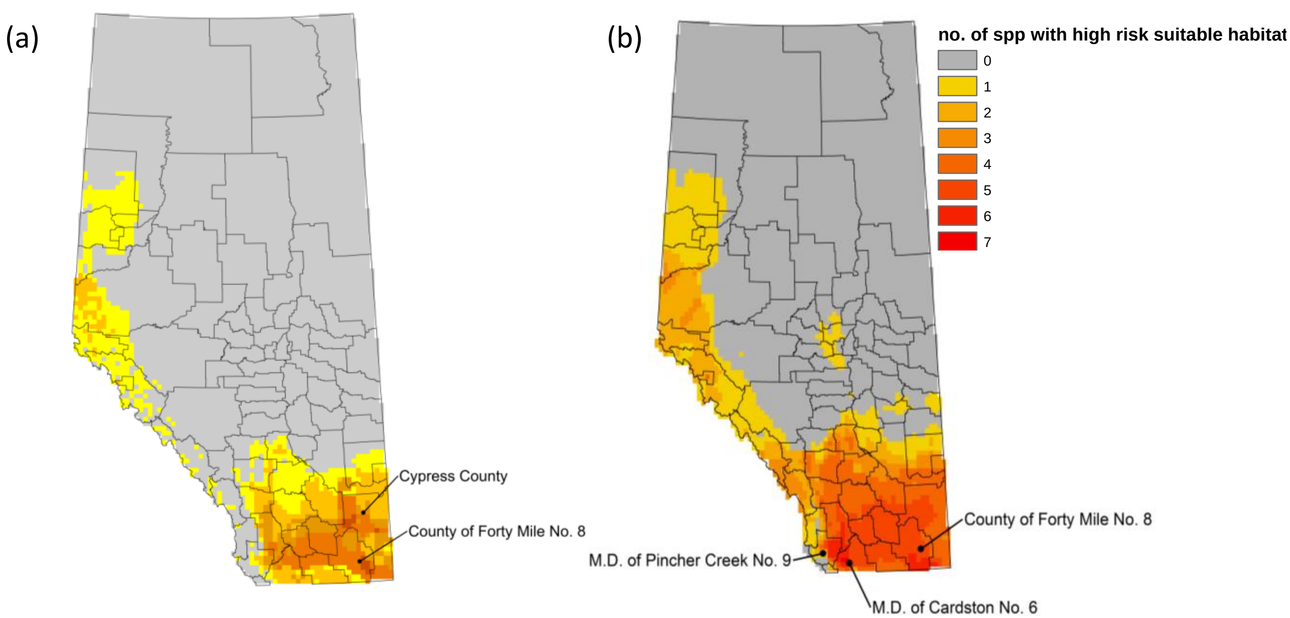

Figure 1. Municipality Districts/Counties with *suitable high risk* habitat for the greatest number of potentially new invasive species (a) under current climate (b) in future climate

[6] S*uitable high risk habitat* and high CLIMEX matches were observed under current climate even though the species are not yet present in Alberta because models indicate the *potential climate match* or *habitat suitability* for the species rather than the actual or realised range.

Table 4. Summary of invasiveness ranks and change in habitat suitability for 16 potentially new non-native species in Alberta. A qualitative combination of Invasiveness rank and change in suitable high risk area (km^2) was used to rank giant knotweed (*Fallopia sachalinensis*), tamarisk (*Tamarix chinensis*), and alkali swainsonpea (*Sphaerophysa salsula*) as the top three potentially new invasive species threats in Alberta.

			Habitat Suitability Model		Climate Match	
Common name	Species name	Invasiveness rank*	Change in suitable high risk area 1975-2050s (km^2)	Change in suitable high risk area (% over 1975)	Change in climate match index for Alberta (% over 1975)	Alberta designation
African rue	*Peganum harmala*	Moderately Invasive	59,472	139	3.5	proposed prohibited noxious 2014
alkali swainsonpea	***Sphaerophysa salsula***	**Highly invasive**	**16,331**	**21**	**0.5**	**proposed prohibited noxious 2014**
autumn olive	*Elaeagnus umbellata*	Extremely Invasive	0	0	6.1	prohibited noxious
black swallow-wort	*Vincetoxicum nigrum*	Moderately Invasive	4,413	(0-4,413 km^2)	6.8	proposed prohibited noxious 2014
European cotoneaster	*Cotoneaster integerrimus*	Weakly Invasive	40,369	87	3.9	not yet assessed
gorse	*Ulex europaeus*	Highly invasive	0	0	7.1	none, regulated in 2 nearby states
knapweed, brown	*Centaurea jacea*	Modestly Invasive	28,858	523	9.1	prohibited noxious
knotweed, giant	***Fallopia sachalinensis***	**Extremely Invasive**	**19,510**	**2,100**	**4.2**	**prohibited noxious**
medusahead	*Taeniatherum caput-medusae*	Highly invasive	232	(0-232 km^2)	7.1	prohibited noxious
puncturevine	*Tribulus terrestris*	Moderately Invasive	51,082	222	2.6	prohibited noxious
saltlover	*Halogeton glomeratus*	Modestly Invasive	-2,003	-46	0.3	prohibited noxious
Scotch broom	*Cytisus scoparius*	Highly invasive	1,161	(0-1,161 km^2)	5.4	none, regulated in 4 nearby states
Scotch thistle	*Onopordum acanthium*	Modestly Invasive	2,932	918	5.7	none, regulated in 6 nearby states
Syrian bean-caper	*Zygophyllum fabago*	Modestly Invasive	28,800	(0-28,800 km^2)	2.7	none, regulated in 2 nearby states
tamarisk, chinese	***Tamarix chinensis* (sensu lato)**	**Extremely Invasive**	**28,176**	**64**	**3.8**	**prohibited noxious**
thistle, globe	*Echinops sphaerocephalus*	unknown	200	(0-200 km^2)	5.9	not yet assessed

*Possible invasiveness ranks (decreasing invasiveness): Extremely, Highly, Moderately, Modestly, Weakly Invasive.

3.1 Invasiveness ranks

Tamarisk (*Tamarix chinensis*), autumn olive (*Elaeagnus umbellata*) and giant knotweed (*Fallopia sachalinensis*) are the three species that were given the highest invasiveness scores based on their traits alone, and were categorised as 'extremely invasive' (sensu Carlson et al. 2008, Table 5). Detailed invasiveness assessments based on species traits can be found at: www.biodiversityandclimate.abmi.ca. Ecological impacts of these species include:

- Tamarisk: potential to lower the water table, alter floristic composition and increase wildfires
- Autumn olive: potential to become dominant in forest understories, alter nutrient cycles and reduce prairie habitat
- Giant knotweed: out-competes grasses and other pasture species, low palatability to grazers and is difficult to control due to its extensive root system

Although scored as 'extremely invasive', autumn olive was not predicted to have *suitable high risk habitat* in Alberta in the climate of the 2050s (section 3.3), and so was not included in the top three high-risk non-native plants for Alberta.

Alkali swainsonpea (*Sphaerophysa salsula*), medusahead (*Taeniatherum caput-medusae*) and Scotch broom (*Cytisus scoparius*) also possess highly invasive traits and were categorised as 'highly invasive'. Because of its large projected increase in *suitable high risk habitat* between the current and future Alberta climates, alkali swainsonpea was identified in the top three high-risk species. Ecological impacts of alkali swainsonpea include potential impacts on nutrient cycling, invasion of wetland habitats, and low palatability to grazers.

Most of the other species we assessed (nine species) had moderate rankings of risk, being categorised as either 'moderately' or 'modestly invasive'. European cotoneaster (*Cotoneaster integerrimus*) was categorised as the least invasive species assessed and was categorised as 'weakly invasive'.

Table 5. Invasiveness scores for 16 potentially new non-native species in Alberta based on ecological impact, biological characteristics and feasibility of control (sensu Carlson et al. 2008, Appendix 1).

Common name	Scientific name	Ecological impact, e.g. on ecosystem processes, community composition	Biological characteristics, e.g. dispersal, germination	Distribution, e.g. in natural areas, regions invaded	Control, e.g. feasibility, effort required	Invasiveness score (Relative score based on questions answered*)	**Category**
African rue	*Peganum harmala*	27	15	16	6	66	***Moderately Invasive***
alkali swainsonpea	*Sphaerophysa salsula*	28	18	19	9	74	***Highly Invasive***
autumn olive	*Elaeagnus umbellata*	37	20	16	6	81	***Extremely Invasive***
black swallow-wort	*Vincetoxicum nigrum*	28	20	13	5	68	***Moderately Invasive***
European cotoneaster	*Cotoneaster integerrimus*	9	17	8	6	44	***Weakly Invasive***
gorse	*Ulex europaeus*	31	14	11	9	65	***Moderately Invasive***
knapweed, brown	*Centaurea jacea*	20	13	18	7	58	***Modestly Invasive***
knotweed, giant	*Fallopia sachalinensis*	31	18	23	6	80	***Extremely Invasive***
medusahead	*Taeniatherum caput-medusae*	37	17	21	3	78	***Highly Invasive***
puncturevine	*Tribulus terrestris*	16	17	16	5	54	***Modestly Invasive***
saltlover	*Halogeton glomeratus*	20	10	15	7	52	***Modestly Invasive***
Scotch broom	*Cytisus scoparius*	37	17	16	8	78	***Highly Invasive***
Scotch thistle	*Onopordum acanthium*	20	13	13	7	54	***Modestly Invasive***
Syrian bean-caper	*Zygophyllum fabago*	24	6	10	6	56	***Modestly Invasive***
tamarisk, Chinese	*Tamarix chinensis*	40	21	21	5	87	***Extremely Invasive***
thistle, globe	*Echinops sphaerocephalus*	6	13	17	5	52	***Modestly Invasive***

*Some traits of species are unknown; Invasiveness score was calculated based only on known traits. The score ranges from 0-100.

3.2 Climate matching

Across all species assessed, there was a climate match (CMI ≥ 0.7) between the current ranges and at least one of Alberta's Natural Regions for the historic (1975) climate (Table 6). Furthermore, there was an increase in CMI in Alberta between the historic and the 2050s climate across all 16 potentially new non-native species (Table 6). In the climate-screening component of the invasiveness ranking, all species were therefore considered a climate-related risk. We relied on the results from the habitat suitability modeling to further refine our assessment of climate-related risk.

Among species, there was some variation in the degree of climate match to Alberta's climates, presently and in the future (Appendix 4). Species with the highest climate matches to Alberta in the 2050s were: European cotoneaster, tamarisk, brown knapweed (*Centaurea jacea*), and puncturevine (*Tribulus terrestris*). Those with the lowest climate match were: black swallow-wort (*Vincetoxicum nigrum*), autumn olive, and alkali swainsonpea. Alberta's southern region (Grasslands Natural Region) is the most vulnerable region to new potential invasive species in both the current and future climate with respect to the average climatic similarity to the current ranges of the species assessed (Table 6).

Table 6. Climate Match Index (CMI) means for 16 species by Natural Region. CMI ≥ 0.7 indicate a mean climate match between Alberta and the 16 species assessed

	Grassland	Parkland	Foothills	Boreal	Rockies	Shield
1975	**0.820**	0.806	0.806	0.759	0.754	0.697
2050	**0.838**	0.831	0.826	0.793	0.766	0.743

3.3 Habitat suitability modeling

The habitat suitability models provide more detailed projections of the current and future climate-related risk of the species assessed. Projections for most species show an increase in *suitable high risk habitat* in Alberta in the 2050s climate compared with 1975 (current/reference climate). Species with the largest increases in *suitable high risk habitat* were: African rue (*Peganum harmala*; 59,472 km^2), puncturevine (51,082 km^2), and European cotoneaster (40,369 km^2; Table 4; species-specific projections provided in Appendix 3).

Five species are predicted to move from having no *suitable high risk habitat* in the current climate to having up to 28,800 km^2 in *suitable high risk habitat* in the 2050s. These are: Syrian bean-caper (*Zygophyllum fabago*), medusahead, globe thistle (*Echinops sphaerocephalus*), Scotch broom and black swallow-wort. Two species, gorse (*Ulex europaeus*) and autumn olive, remained without any *suitable high risk habitat* in Alberta in the 2050s, but are predicted to show an increase in *suitable low risk habitat*.

One species, saltlover, experienced a decrease of 2,003 km^2 in *suitable high risk habitat* between 1975 and 2050. The predicted suitable habitat of saltlover was more strongly related to precipitation variables (e.g., Precipitation Seasonality and Precipitation of Warmest Quarter) than any other species assessed, which likely contributed to the unique pattern of change in *suitable high risk* *habitat* for this species. In addition, the data set used for modeling this species was among the smallest of all the species assessed (Table 2).

Predictive performance of the habitat suitability models ranged from 0.682 to 0.984, with most species showing excellent discrimination (AUC > 0.9; Table 7).

Table 7. Predictive performance of species distribution modeling

Common name	Scientific name	Area under curve (AUC)*
African rue	*Peganum harmala*	0.957
alkali swainsonpea	*Sphaerophysa salsula*	0.982
autumn olive	*Elaeagnus umbellata*	0.966
black swallow-wort	*Vincetoxicum nigrum*	0.973
European cotoneaster	*Cotoneaster integerrimus*	0.929
gorse	*Ulex europaeus*	0.769
knapweed, brown	*Centaurea jacea*	0.682
knotweed, giant	*Fallopia sachalinensis*	0.890
medusahead	*Taeniatherum caput-medusae*	0.952
puncturevine	*Tribulus terrestris*	0.945
saltlover	*Halogeton glomeratus*	0.983
Scotch broom	*Cytisus scoparius*	0.695
Scotch thistle	*Onopordum acanthium*	0.823
Syrian bean-caper	*Zygophyllum fabago*	0.984
tamarisk, Chinese	*Tamarix chinensis*	0.962
thistle, globe	*Echinops sphaerocephalus*	0.913

*An AUC value of 0.5 implies random predictive discrimination, while values above 0.7, 0.8 and 0.9 represent good, very good and excellent discrimination respectively (Swets 1988, Manel et al. 2001).

3.4 Regional climate matching

In Alberta’s current climate, new non-native species are most likely to originate from coloured regions shown in Figure 2a. These regions possess a climate match with Alberta (CMI ≥ 0.7). New regions of the world that may provide a source of non-native plant threats to Alberta in the 2050s include more southerly parts of North America and additional areas in France and northern Spain (Figure 2b). Additionally, some regions are predicted to have a higher climate match to Alberta by the 2050s than they do currently, including Newfoundland and Labrador, Turkey, Asia and Russia. There are also new climate matches in the 2050s between Alberta and more northern latitudes such as Nunavut, Northwest Territories and the Yukon. These northerly regions pose a ‘transient risk’ because they possess projected future climate conditions that are similar to Alberta’s current climate.

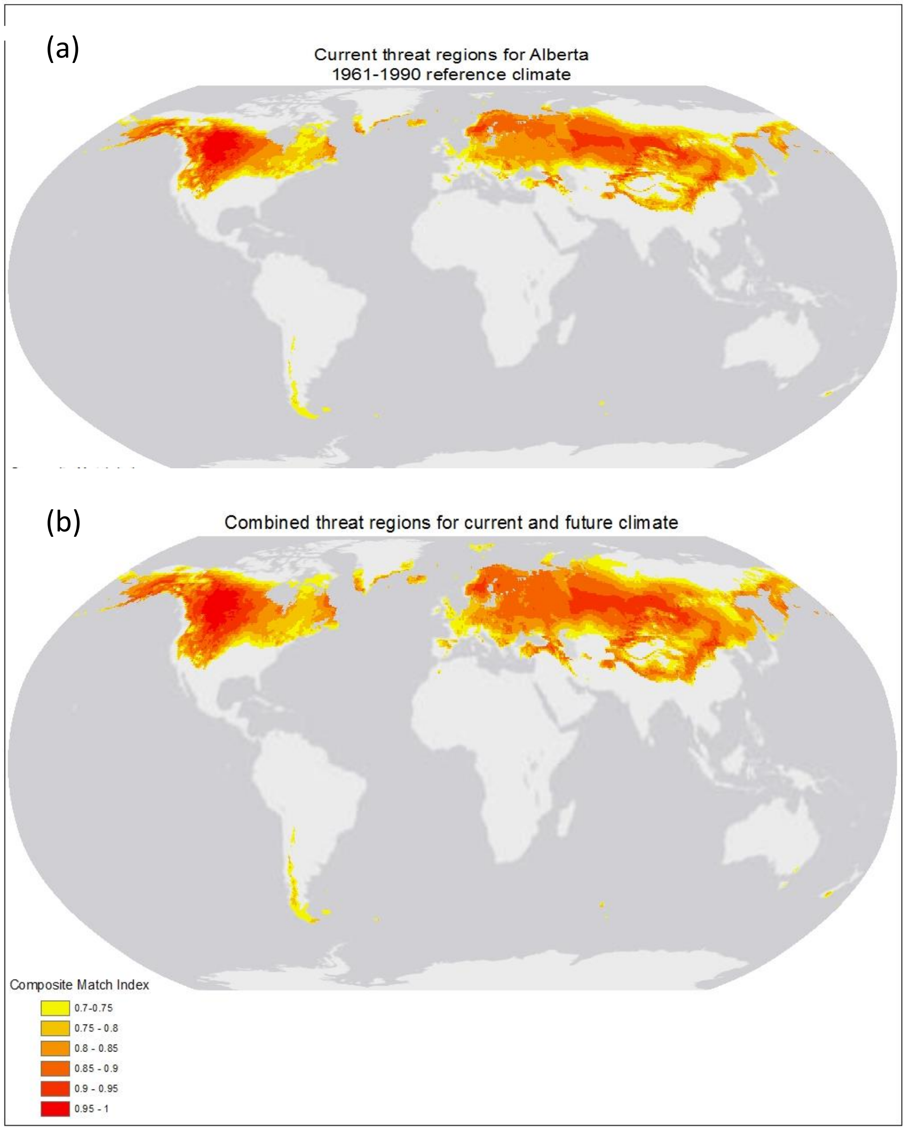

Figure 2. Regions from where potentially new invasive species to Alberta may originate, based on climate similarity to Alberta. The Composite Match Index (CMI) is shown for (a) Alberta and the rest of the globe under reference climate, (b) combined present and potential future threat areas in 2050.

4 Discussion

4.1 Implications for invasive species management in Alberta under climate change

Invasive species are managed in Alberta primarily through regulation on the *Weed Control Act* as *noxious*[7] or *prohibited noxious* species. Ten of the 16 species we assessed are already listed on the *Weed Control Act* as *prohibited noxious species* (or have been proposed for listing). These are invasive species that are recognised as being absent or present in very low numbers in Alberta. For these species, the regulation stipulates that they be eradicated. Importantly, the three species for which we identified the combination of invasiveness and climate-related risk to be greatest (alkali swainsonpea, giant knotweed and tamarisk) are already listed or proposed listed as *prohibited noxious species.*

Two of the species we assessed in this report have 'not yet been assessed' by Alberta's Weed Regulatory Advisory Committee (globe thistle and European cotoneaster). A further four species assessed are not currently being considered by Alberta's Weed Regulatory Advisory Committee: Syrian bean-caper, gorse, Scotch thistle (*Onopordum acanthium*) and Scotch broom. Thus, we have provided invasiveness rankings and climate-related risk for six new species not yet assessed in Alberta, and demonstrated a methodology that can be used to appraise current management of invasive species for conservation purposes in the context of climate change (though we recognise that the *Weed Control Act* also lists species that threaten agriculture). The following are specific suggestions within the management framework of the *Weed Control Act* and including evaluation of climate-change risk for the four species not currently being considered in Alberta:

1. Family Zygophyllaceae, contains *moderately* to *modestly* invasive species such as Syrian bean-caper (*Zygophyllum fabago*), African rue (*Peganum harmala*) and puncturevine (*Tribulus terrestris*) (Table 7). While African rue and puncturevine are listed as proposed *prohibited noxious* and *prohibited noxious* in Alberta respectively, Syrian bean-caper is not noted in any way in Alberta. Syrian bean-caper is predicted to undergo a substantial increase in *suitable high risk habitat* in Alberta by 2050 (Figure 3). As such, Syrian bean-caper could be regulated in a manner similar to other species in the family, and could be considered for listing as a *prohibited noxious* species.
2. Gorse has no *suitable high risk habitat* in Alberta in 2050, although it is ranked as a *highly invasive* species. Based on this information, gorse may not be a good candidate for inclusion on the *Weed Control Act*.
3. Scotch thistle and Scotch broom are *modestly invasive* and *highly invasive* respectively, with a relatively small *suitable high risk area* predicted in 2050 that lies in the Municipality of Pincher Creek (Figure 4). These species could be considered for inclusion in the by-law[8] provision of the *Weed Control Act* as *prohibited noxious species* within the municipality.

[7] *Noxious* species on the *Weed Control Act* are already present in Alberta in abundance. Control is stipulated for this category of invasive species; eradication would not be feasible given their abundance.
[8] The *Weed Control Act* has a by-law provision whereby Municipalities can elevate invasive species as *prohibited noxious* or *noxious* within that municipality.

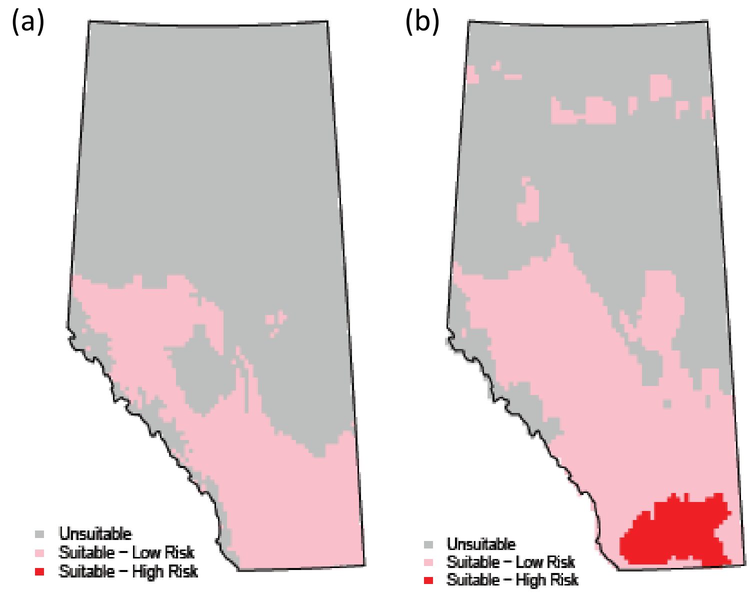

Figure 3. Species distribution models for Syrian Bean-caper under (a) current climate and (b) in 2050. A substantial increase in suitable high risk habitat is predicted by 2050.

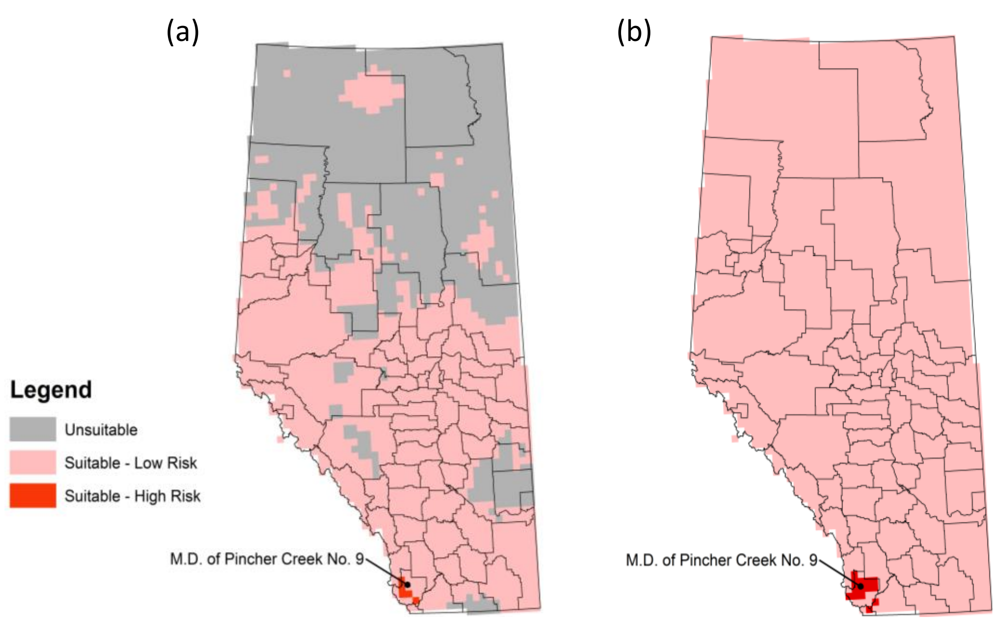

Figure 4. Species distribution maps for (a) Scotch broom and (b) Scotch thistle showing predicted suitable high risk areas in 2050 for both species.

There was a high level of overlap between regulated species in Alberta and in jurisdictions that surround Alberta. By examining regulated invasive plant lists in nearby provinces and states, we found no other terrestrial species besides the 16 species we assessed that are (1) currently absent in Alberta, (2) not on Alberta's *Weed Control Act* (or noted by Alberta's Weed Regulatory Advisory Committee) and (3) have published distribution data. This suggests that our list is complementary to the *Weed Control Act* and that we have assessed most of the new terrestrial plant species threats to the province that have high potential to invade due to climate change.

Currently, like most other jurisdictions (Groves et al. 2002, Hannah et al. 2002), the Government of Alberta does not consider climate change in managing invasive plant species. The rationale is that government works at a localised scale (county scale) on invasive plant management, where there are more dominant factors (other than climate) influencing invasive plants, such as disturbance, dispersal and competition. However, our study has demonstrated that climate change will likely result in an increase in suitable habitat for new non-native plants, and the methodology we present could be used to make pre-emptive interventions to manage invasive species in response to climate change; a consistent theme in climate change adaptation (Hellman & Zavaleta 2008). Both approaches (using localised factors and climate) working in tandem could increase management effectiveness for invasive species. Surveillance monitoring to enhance the chances of early detection and rapid response for new invasive species should also be emphasized.

4.2 Assessing climate-related risk: climate matching and habitat suitability modeling

We implemented two approaches to assessing climate-related risk to Alberta for the species assessed: climate matching and habitat suitability models. Quantitatively, the outcomes from the two approaches are quite different: the climate matching outcomes generally indicate high climatic suitability (CMI ≥ 0.7) in Alberta for all species assessed, whereas the habitat suitability modeling did not predict *suitable high risk habitat* for all species in either the current or future climates (e.g., for globe thistle and autumn olive only *suitable low risk habitat* was predicted; Appendix 3).

The differences relate to both the modeling approaches themselves, and the definition of thresholds in each approach. Climate matching provides a measure of the similarity in climates between two regions, but only a limited set of climate variables is considered and the outcome is limited to the best match between any of the locations in the observed species range and the Alberta locations. In contrast, habitat suitability modeling considers a wider set of both climate and edaphic variables and allows for more complex, non-linear responses to environmental variables, and interactions among them, and therefore provides more nuanced projections of potentially suitable habitat.

In implementing both approaches here, we imposed thresholds on the projections of climate similarity (CMI ≥ 0.7) and habitat suitability (to define "suitable low risk" and "suitable high risk" habitats). Changing the definition of either threshold would impact the quantitative, but not the qualitative outcomes.

The difference in quantitative outcomes between the two approaches suggests that the climate matching outcomes are more liberal projections of potentially suitable regions of Alberta for the set of species assessed than the outcomes from the habitat suitability modeling.

The two approaches produced similar relative results, however, with respect to the general suitability of the climates in Alberta for the set of potential invasive species assessed. Both approaches predicted a relative increase in habitat or suitable climate in Alberta in the 2050s for almost all species, as well as the highest risk to invasion in the southern region of the province. Furthermore, even at a smaller scale, there was high similarity in the spatial predictions of relative climate similarity and relative habitat suitability for many of the species assessed: Scotch broom, globe thistle, autumn olive, African rue, alkali swainsonpea, medusahead, gorse and Syrian bean-caper (compare maps in Appendix 3, Appendix 4).

4.3 Which non-native species should we consider invasive in the context of biodiversity conservation?

Managing new species that arrive in a jurisdiction as a result of climate change can range from eradication to tolerance to acceptance, and deciding on a management response should be done on a case by case basis (Walther et al. 2009). For example, those species that alter ecosystem processes (through nitrogen fixation, altering fire regimes and water cycles) could be ranked a higher priority for management. Blanket removal of non-native species would require increasingly unsustainable efforts and promote ecosystems that are not suitable to emerging climatic conditions (Millar et al. 2007). In managing non-native species for conservation purposes under climate change, the management objective should be focused more on managing change than retaining past community composition. Managers can ask 'how can we maximise our contribution to global conservation within our region?', rather than 'how can we keep things as they are?' (Thomas 2011).

New strategies to cope with invasive species under climate change will include the incorporation of climate change scenarios into planning and management for invasive species. Management strategies will also need to be formulated across wider geographic areas (regional perspectives) and longer time frames, which require increased coordination across jurisdictions (Hellman & Zavaleta 2008). Scenario planning (e.g., modeling) to identify and prioritize climate change risks coupled with science-based monitoring of indicators is an appropriate framework for managing invasive species under climate change (Baron et al. 2009; Bradley et al. 2010; Dukes 2011). Scenario planning should be developed through partnerships with other agencies and interest groups, and plans should be adapted based on monitoring results (Bradley et al. 2010; Dukes 2011). Data and information on invasive species impacts should be shared across scales and jurisdictions to facilitate risk assessments (Bradley et al. 2010; Crosman et al. 2011; Dukes 2011).

Climate change adaptation, including the management of invasive species, is still based on ecological reasoning at the general principles or idea stage rather than specific actionable strategies for the management of invasive species (Hellman & Zavaleta 2008). General conservation principles such as mitigating species loss from invasive species, maintaining large areas of high quality habitat and connectivity for example, that were developed pre-climate change continue to hold and are perhaps even more crucial under climate change to protecting biodiversity (Thomas 2011).

5 Conclusion

Climate change in Alberta will result in more suitable habitat for 15 of the 16 potentially new invasive species identified in this report. Of the 16 new species assessed, the top three species with the highest invasiveness score which also showed the greatest increase in *suitable high risk area* within Alberta were: giant knotweed (*Fallopia sachalinensis*), tamarisk (*Tamarix chinensis*) and alkali swainsonpea (*Sphaerophysa salsula*). The Grasslands Natural Region is the most at-risk region to new invasive species in both current and future climates. Predictive models show that the Municipal Districts of Pincher Creek, Cardston and County of Forty Mile will be the top three municipalities/counties in the 2050s that contain *suitable high risk habitat* for the greatest number of new invasive species. Back country areas that are of conservation importance and also at high risk for invasion by more than one new invasive species include Wilmore Wilderness Park, Jasper National Park and Banff National Park. Our methodology can be used to appraise current management of invasive species for conservation purposes in the context of climate change.

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Appendix1. Invasiveness ranking system for Alberta

Alberta non-native plant invasiveness ranking form
(Adapted from Carlson et al. 2008)

Scientific name:	
Common name:	
Assessor:	
Reviewers:	
Date:	

Outcome score:

A. Climatic Comparison

This species is present or may potentially establish in the following natural regions:

	Collected in Alberta regions	CLIMEX similarity in current climate	CLIMEX similarity in 2050
Boreal			
Parkland			
Foothills			
Grassland			
Rocky Mountains			
Shield			

B. Invasiveness Ranking

	Total (Total answered[1] points possible)	Total score
1. Ecological impact	40()	
2. Biological characteristic and dispersal ability	25()	
3. Ecological amplitude and distribution	25()	
4. Feasibility of control	10()	
Outcome score	100()[b]	[a]
Relative maximum score[2]		

[1]For questions answered ‘unknown’ do not include point value for the question in parentheses for ‘Total answered points possible.’

[2]Calculated as a/b x 100.

A. Climatic Comparison:

1.1 Has this species ever been collected or documented in Alberta?

__Yes – continue to 1.2

__ No – continue to 2.1

1.2 Which natural region has it been collected or documented? Proceed to section B. Invasiveness Ranking.

__Boreal

__Rockies

__Grassland

__Foothills

__Parkland
__Shield

Documentation:
Sources of information:
2.1 Is there a high degree of climate similarity (CMI >0.7) between climates anywhere the species currently occurs and
a. Boreal
b. Rockies
c. Grassland
d. Foothills
e. Parkland
f. Shield

-If 'no' is answered for all regions, reject species from consideration

Documentation:
Sources of information:

B. Invasiveness Ranking

1. Ecological Impact

1.1 Impact on Natural Ecosystem Processes

a. No perceivable impact on ecosystem processes 0
b. Has the potential to influence ecosystem processes to a minor degree (e.g., has a perceivable but mild influence on soil nutrient availability) 3
c. Has the potential to cause significant alteration of ecosystem processes (e.g., increases sedimentation rates along streams or coastlines, reduces open water that are important to waterfowl) 7
d. May cause major, possibly irreversible, alteration or disruption of ecosystem processes (e.g., the species alters geomorphology; hydrology; or affects fire frequency, altering community composition; species fixes substantial levels of nitrogen in the soil making soil unlikely to support certain native plants or more likely to favor non-native species) 10
u. Unknown

Score:

Documentation:
Identify ecosystem processes impacted:
Rationale:
Sources of information:

1.2 Impact on Natural Community Structure

a. No perceived impact; establishes in an existing layer without influencing its structure 0
b. Has the potential to influence structure in one layer (e.g., changes the density of one layer) 3
c. Has the potential to cause significant impact in at least one layer (e.g., creation

of a new layer or elimination of an existing layer) 7
d. Likely to cause major alteration of structure (e.g., covers canopy, eradicating most or all layers below) 10
u. Unknown

Score:

Documentation:
Identify type of impact or alteration:
Rationale:
Sources of information:

1.3 Impact on Natural Community Composition
a. No perceived impact; causes no apparent change in native populations 0
b. Has the potential to influence community composition (e.g., reduces the number of individuals in one or more native species in the community) 3
c. Has the potential to significantly alters community composition (e.g., produces a significant reduction in the population size of one or more native species in the community) 7
d. Likely to cause major alteration in community composition (e.g., results in the extirpation of one or several native species, reducing biodiversity or change the community composition towards species exotic to the natural community) 10
u. Unknown

Score:

Documentation:
Identify type of impact or alteration:
Rationale:
Sources of information:

1.4 Impact on higher trophic levels (cumulative impact of this species on the animals, fungi, microbes, and other organisms in the community it invades)
a. Negligible perceived impact 0
b. Has the potential to cause minor alteration 3
c. Has the potential to cause moderate alteration (minor reduction in nesting/foraging sites, reduction in habitat connectivity, interference with native pollinators, injurious components such as spines, toxins) 7
d. Likely to cause severe alteration of higher trophic populations (extirpation or endangerment of an existing native species/population, or significant reduction in nesting or foraging sites) 10
u. Unknown

Score:

Documentation:
Identify type of impact or alteration:
Rationale:
Sources of information:

Total Possible:

Total:

2. Biological Characteristics and Dispersal Ability

2.1 Mode of reproduction

a.	Not aggressive reproduction (few [0-10] seeds per plant and no vegetative reproduction)	0
b.	Somewhat aggressive (reproduces only by seeds (11-1,000/m2)	1
c.	Moderately aggressive (reproduces vegetatively and/or by a moderate amount of seed, <1,000/m2)	2
d.	Highly aggressive reproduction (extensive vegetative spread and/or many seeded, >1,000/m2)	3
u.	Unknown	

Score:

Documentation:

Describe key reproductive characteristics (including seeds per plant):

Rationale:

Sources of information:

2.2 Innate potential for long-distance dispersal (bird dispersal, sticks to animal hair, buoyant fruits, wind-dispersal)

a.	Does not occur (no long-distance dispersal mechanisms)	0
b.	Infrequent or inefficient long-distance dispersal (occurs occasionally despite lack of adaptations)	2
c.	Numerous opportunities for long-distance dispersal (species has adaptations such as pappus, hooked fruit-coats, etc.)	3
u.	Unknown	

Score:

Documentation:

Identify dispersal mechanisms:

Rationale:

Sources of information:

2.3 Potential to be spread by human activities (both directly and indirectly – possible mechanisms include: commercial sales, use as forage/revegetation, spread along highways, transport on boats, contamination, etc.)

a.	Does not occur	0
b.	Low (human dispersal is infrequent or inefficient)	1
c.	Moderate (human dispersal occurs)	2
d.	High (there are numerous opportunities for dispersal to new areas)	3
u.	Unknown	

Score:

Documentation:

Identify dispersal mechanisms:

Rationale:

Sources of information:

2.4 Allelopathic

a. no 0
b. yes 2
u. unknown

Score:

Documentation:
Describe effect on adjacent plants:
Rationale:
Sources of information:

2.5 Competitive ability

a. Poor competitor for limiting factors 0
b. Moderately competitive for limiting factors 1
c. Highly competitive for limiting factors and/or nitrogen fixing ability 3
u. Unknown

Score:

Documentation:
Evidence of competitive ability:
Rationale:
Sources of information:

2.6 Forms dense thickets, climbing or smothering growth habit, or otherwise taller than the surrounding vegetation

a. No 0
b. Forms dense thickets 1
c. Has climbing or smothering growth habit, or otherwise taller than the surrounding vegetation 2
u. Unknown

Score:

Documentation:
Describe growth form:
Rationale:
Sources of information:

2.7 Germination requirements

a. Requires open soil and disturbance to germinate 0
b. Can germinate in vegetated areas but in a narrow range or in special conditions 2
c. Can germinate in existing vegetation in a wide range of conditions 3
u. Unknown

Score:

Documentation:

Describe germination requirements:
Rationale:
Sources of information:

2.8 Other species in the genus invasive in Alberta or elsewhere

a.	No	0
b.	Yes	3
u.	Unknown	

Score:

Documentation:
Species:
Sources of information:

2.9 Aquatic, wetland, or riparian species

a. Not invasive in wetland communities	0
b. Invasive in riparian communities	1
c. Invasive in wetland communities	3
u. Unknown	

Score:

Documentation:
Describe type of habitat:
Rationale:
Sources of information:

Total Possible:
Total:

3. Distribution

3.1 Is the species highly domesticated or a weed of agriculture

a.	No	0
b.	Is occasionally an agricultural pest	2
c.	Has been grown deliberately, bred, or is known as a significant agricultural pest	4
u.	Unknown	

Score:

Documentation:
Identify reason for selection, or evidence of weedy history:
Rationale:
Sources of information:

3.2 Known level of ecological impact in natural areas

a. Not known to cause impact in any other natural area 0
b. Known to cause impacts in natural areas, but in dissimilar habitats and climate zones than exist in regions of Alberta 1
c. Known to cause low impact in natural areas in similar habitats and climate

zones to those present in Alberta 3
d. Known to cause moderate impact in natural areas in similar habitat and climate zones 4
e. Known to cause high impact in natural areas in similar habitat and climate zones 6
u. Unknown

Score:

Documentation:
Identify type of habitat and states or provinces where it occurs:
Sources of information:

3.3 Role of anthropogenic and natural disturbance in establishment
a. Requires anthropogenic disturbances to establish 0
b. May occasionally establish in undisturbed areas but can readily establish in areas with natural disturbances 3
c. Can establish independent of any known natural or anthropogenic disturbances 5
u. Unknown

Score:

Documentation:
Identify type of disturbance:
Rationale:
Sources of information:

3.4 Current global distribution
a. Occurs in one or two continents or regions (e.g., Mediterranean region) 0
b. Extends over three or more continents 3
c. Extends over three or more continents, including successful introductions in arctic or subarctic regions 5
u. Unknown

Score:

Documentation:
Describe distribution:
Rationale:
Sources of information:

3.5 Extent of the species Canada range and/or occurrence of formal state or provincial listing
a. 0-5 percent of the states/provinces 0
b. 6-20 percent of the states/provinces 2
c. 21-50 percent, and/or state/province listed as a problem weed (e.g., 'Noxious,' or 'Invasive') in 1 state or Canadian province 4
d. Greater than 50 percent, and/or identified as 'Noxious' in 2 or more states or Canadian provinces 5
u. Unknown

Score:

Documentation:
Identify provinces invaded:
Rationale:
Sources of information:

Total possible:
Total:

4. Feasibility of Control

4.1 Seed banks

a. Seeds remain viable in the soil for less than 3 years 0
b. Seeds remain viable in the soil for between 3 and 5 years 2
c. Seeds remain viable in the soil for 5 years and more 3
u. Unknown

Score:

Documentation:
Identify longevity of seed bank
Rationale:
Sources of information:

4.2 Vegetative regeneration

a. No resprouting following removal of aboveground growth 0
b. Resprouting from ground-level meristems 1
c. Resprouting from extensive underground system 2
d. Any plant part is a viable propagule 3
u. Unknown

Score:

Documentation:
Describe vegetative response:
Rationale:
Sources of information:

4.3 Level of effort required

a. Management is not required (e.g., species does not persist without repeated anthropogenic disturbance) 0
b. Management is relatively easy and inexpensive; requires a minor investment in human and financial resources 2
c. Management requires a major short-term investment of human and financial resources, or a moderate long-term investment 3
d. Management requires a major, long-term investment of human and financial resources 4
u. Unknown

Score:

Documentation:
Identify types of control methods and time-term required:
Rationale:
Sources of information:

Total Possible:
Total:
Total for 4 sections Possible:
Total for 4 sections:

References:

Notes:

Score Interpretation:
While different users will have different concepts of what constitutes various levels of invasiveness (e.g., what is 'highly invasive' vs. 'moderately invasive' may differ among management agencies), we divided the ranks into six blocks in Appendix A. We consider species with scores ≥80 as 'Extremely Invasive' and species with scores 70–79 as 'Highly Invasive;' both of these groups are composed of species estimated to be very threatening to Alberta. Species with scores of 60–69 as 'Moderately Invasive' and scores of 50–59 represent 'Modestly Invasive' species; both of these groups still pose significant risks to ecosystems. Species with scores of 40–49 are 'Weakly Invasive', and <40 are considered 'Very Weakly Invasive.' These last two groups generally have not been shown to significantly alter ecosystem processes and communities elsewhere and probably do not require as much attention as the other species.

Appendix 2. Calculation of the Composite Match Index in CLIMEX

We selected weekly minimum, maximum, and average temperature, annual rainfall total and seasonality of rainfall, each with a weight of 1, as the climate variables for use in the calculation of the Composite Match Index (CMI) in CLIMEX . With these variables selected, the CMI is calculated as follows (refer to Sutherst et al. 2007 for additional details):

Maximum, Minimum and Average Temperature Match Indices, I_{tmax}, I_{tmin}, and I_{tav}

$I_{tmax} = exp(-k_T T_{dmax})$
$I_{tmin} = exp(-k_T T_{dmin})$
$I_{tav} = exp(-k_T T_{dav})$

where T_{dmax}, T_{dmin}, and T_{dav} are the means of the weekly absolute differences in maximum, minimum and average temperatures, respectively between the two locations.

The constant k_T is set to 0.1 such that a mean weekly difference of 1 °C results in an index value of 0.9, and a mean weekly difference of 5 °C results in an index value of 0.6.

Total Rainfall Match Index, I_{rtot}

$I_{rtot} = exp(-k_R R_d)$
where, $R_d = abs(R_T - R_M)/(1+a(R_T+R_M))$,

R_T = annual rainfall at 'Home' location
R_M = annual rainfall at 'Away' location

R_d is the difference in annual rainfall between the two locations, adjusted so that a small difference in rainfall is more significant for locations with lower rainfall. The constants a and k_R are set to 0.001 and 0.004, respectively. A difference in rainfall of 200 mm per year between two locations results in an index value of 0.64 if the average rainfall for the two locations is 400 mm, and an index value of 0.85 if the average rainfall is 2000 mm.

Rainfall Pattern Index, I_{rpat}

$I_{rpat} = exp(-k_P R_D)$

R_D is the mean of the absolute difference between the weekly rainfall of the 'Home' and 'Away' locations, after the weekly rainfall of the 'Home' location has been multiplied by R_M/R_T (defined above). The constant k_P is set to 0.005 such that a mean weekly difference of 20 mm results in an index value of 0.9, and a mean weekly difference of 100 mm results in an index value of 0.6.

Composite Match Index, CMI

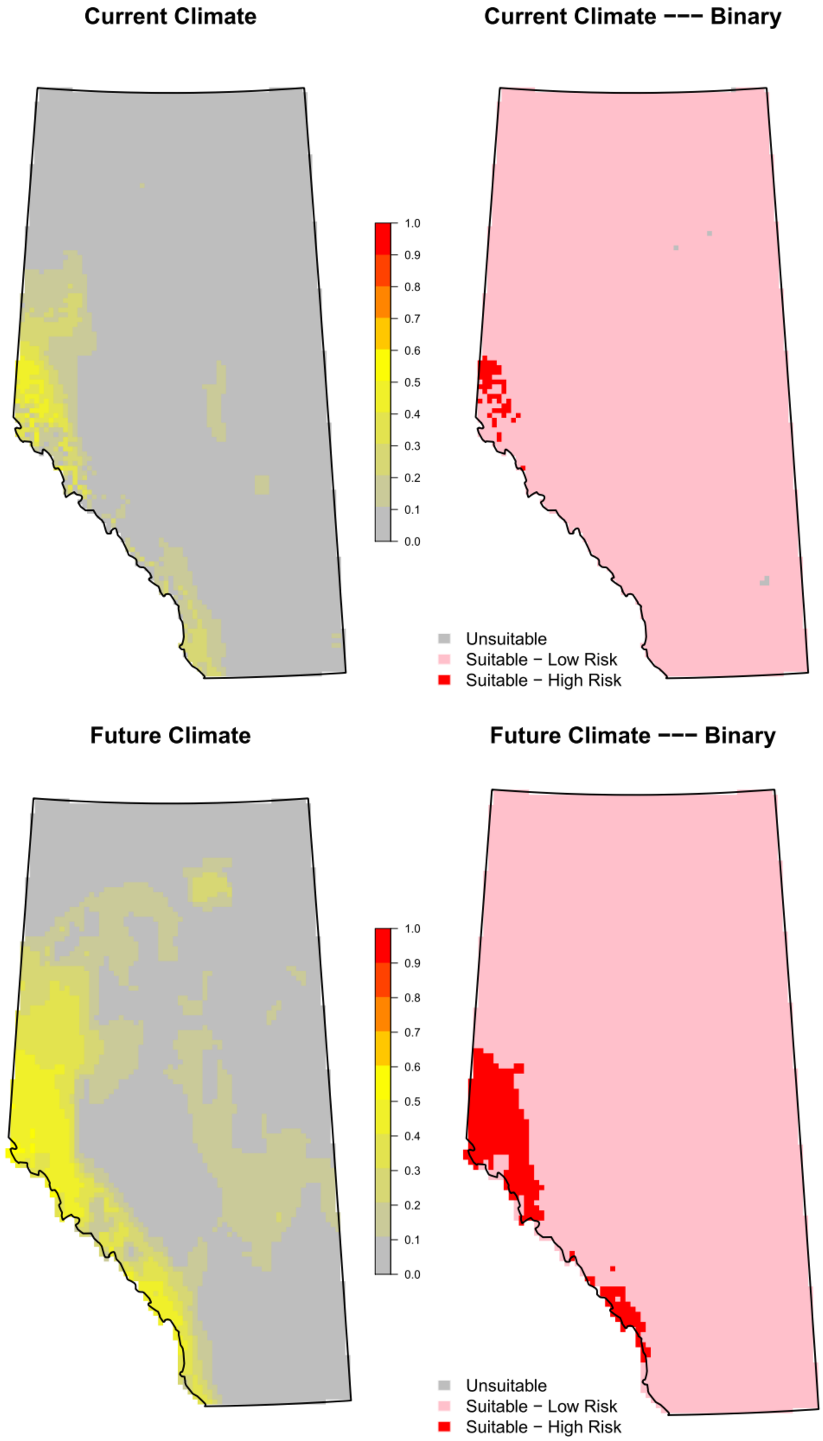
$CMI = (I_t \times I_{rtot} \times I_{rpat}) \times 100$
where, $I_t = (I_{tmin}+I_{tmax}+I_{tav})/3$

In the regional-climate matching algorithm, the CMI is calculated for each of the 'Home' locations compared to all of the 'Away' locations. For each 'Away' location, the CMI value calculated for that location associated with the best match to a 'Home' location is retained (i.e., the *best* match CMI value is retained for each 'Away' location).

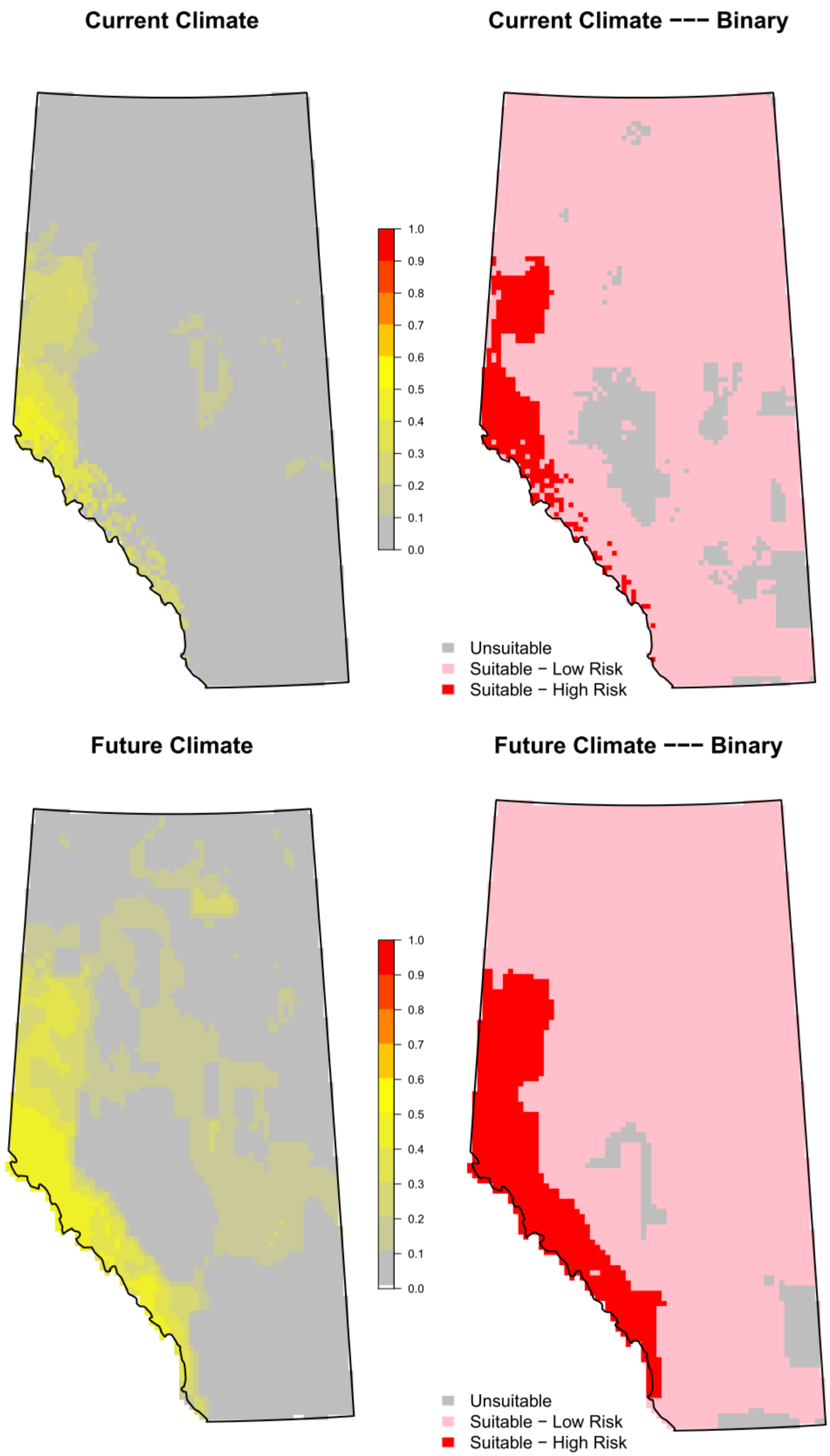
Appendix 3. Habitat suitability modeling for 16 potentially new invasive species in Alberta

Figures on the left indicate the probability of habitat suitability for the species. Figures on the right show a larger area of potentially suitable habitat for the species (suitable low risk habitat) as well as sites which are more likely to be at high risk of invasion (suitable high risk habitat).

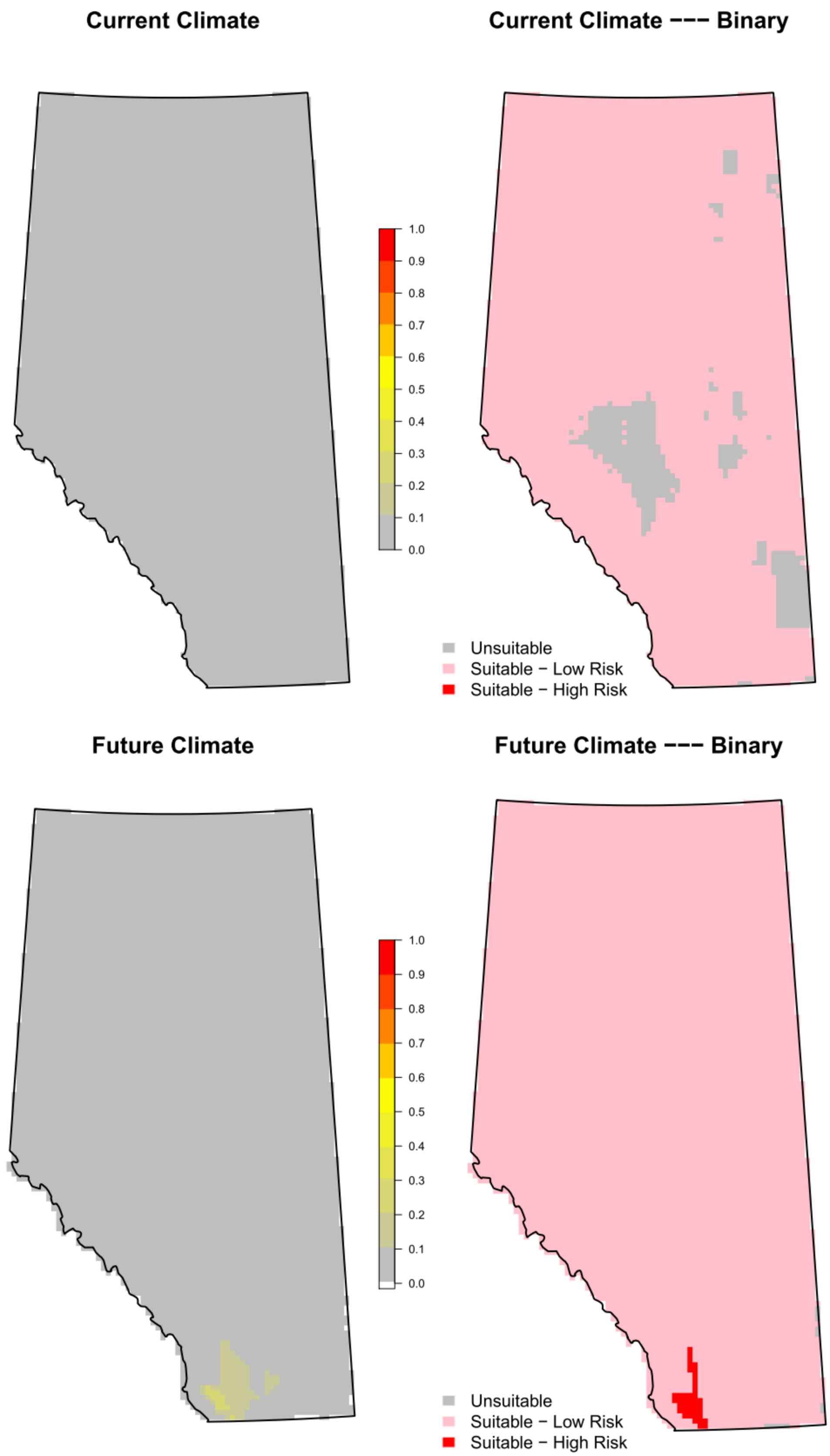
Centaurea jacea



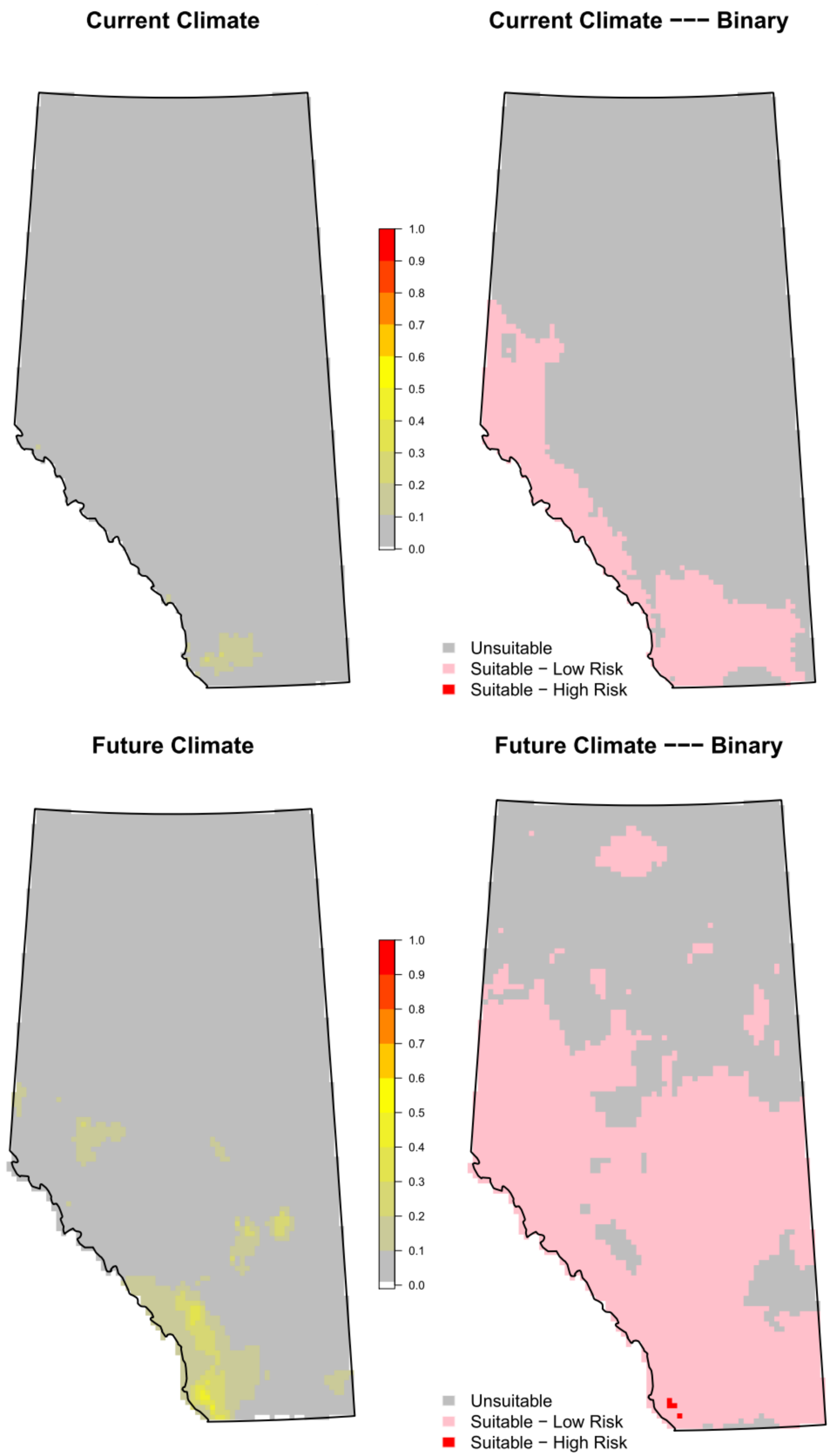
Cotoneaster integerrimus



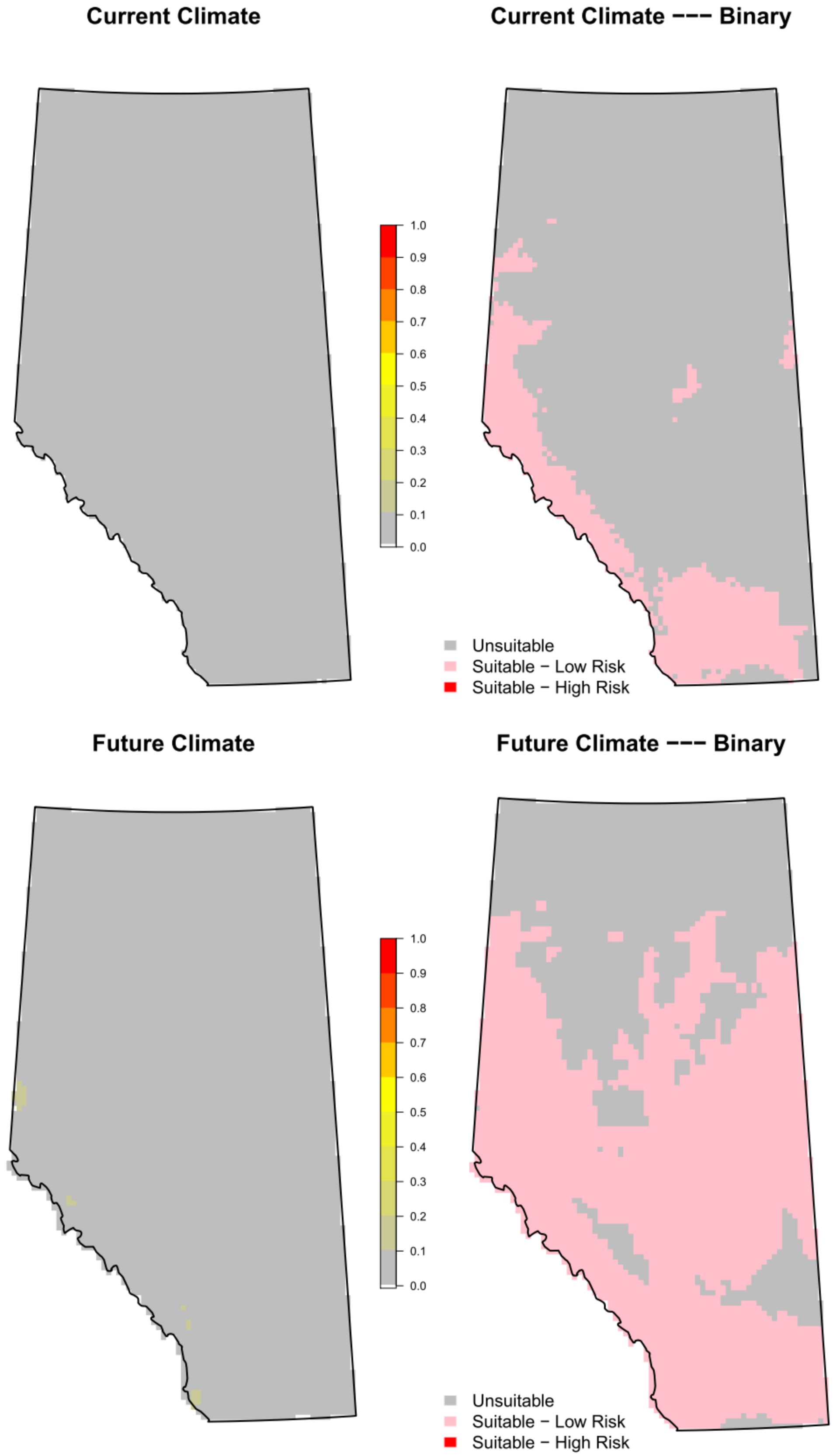
Vincetoxicum nigrum



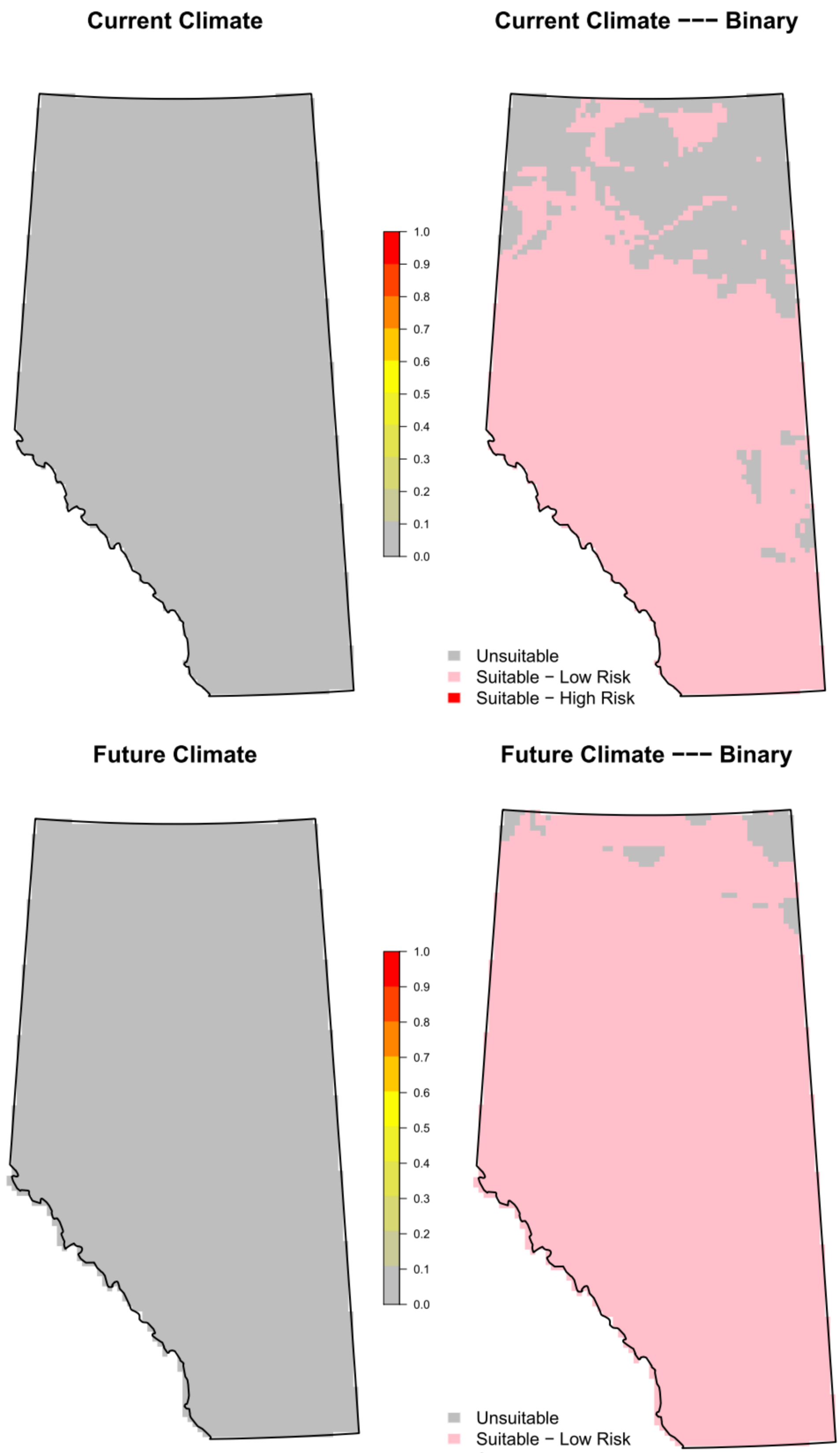
Cytisus scoparus



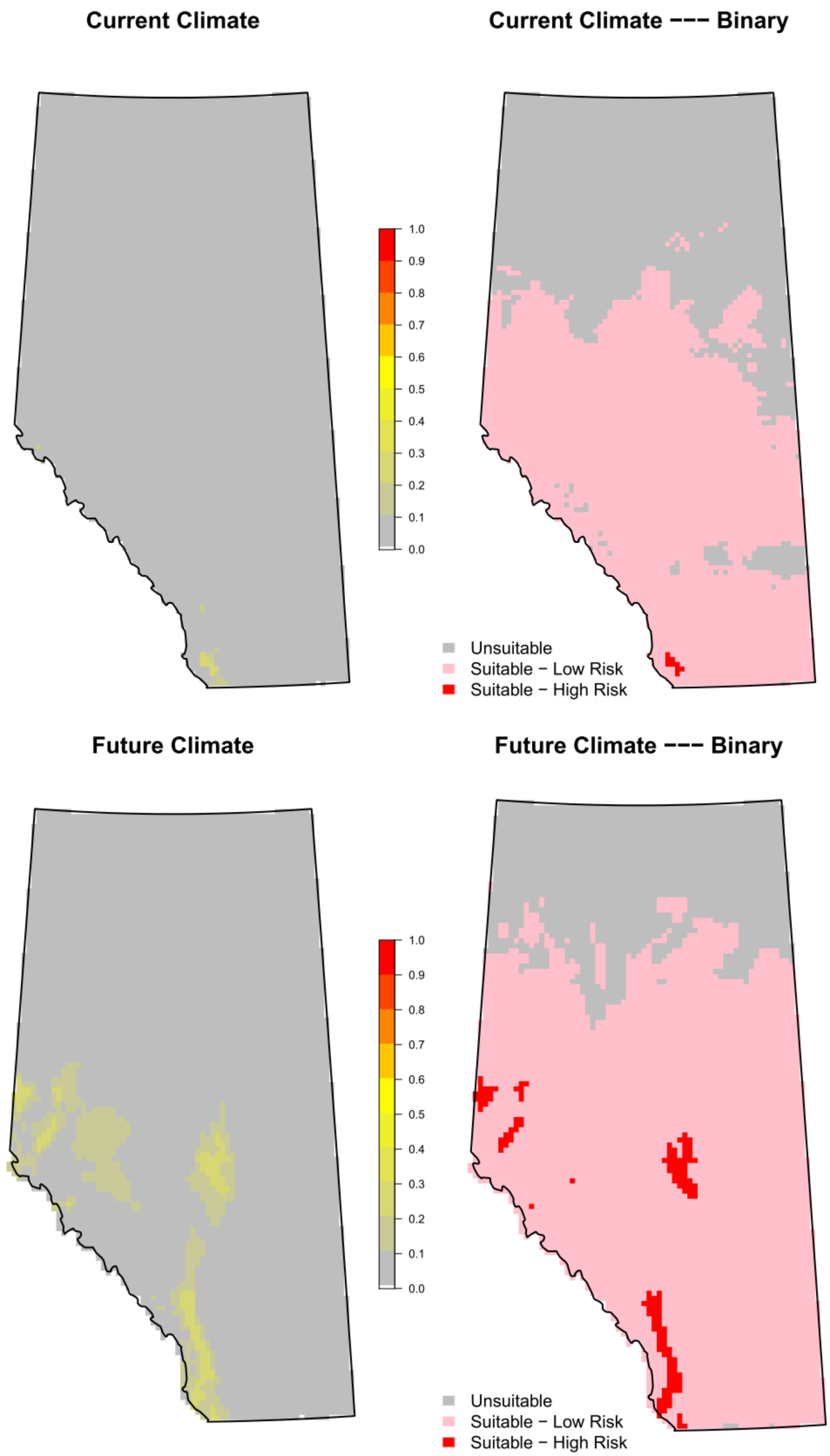
Echinops sphaerocephalus



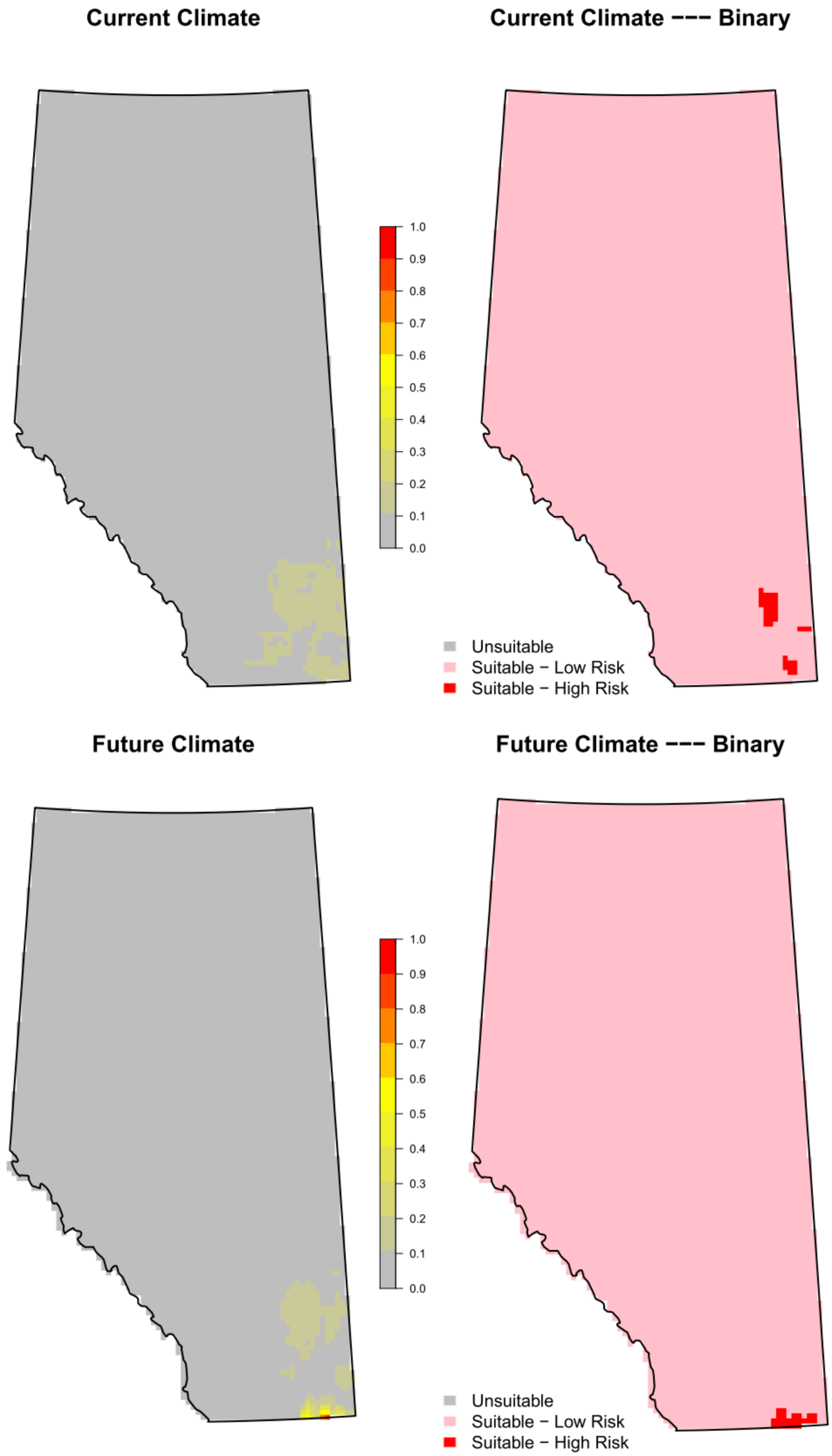
Elaeagnus umbellata



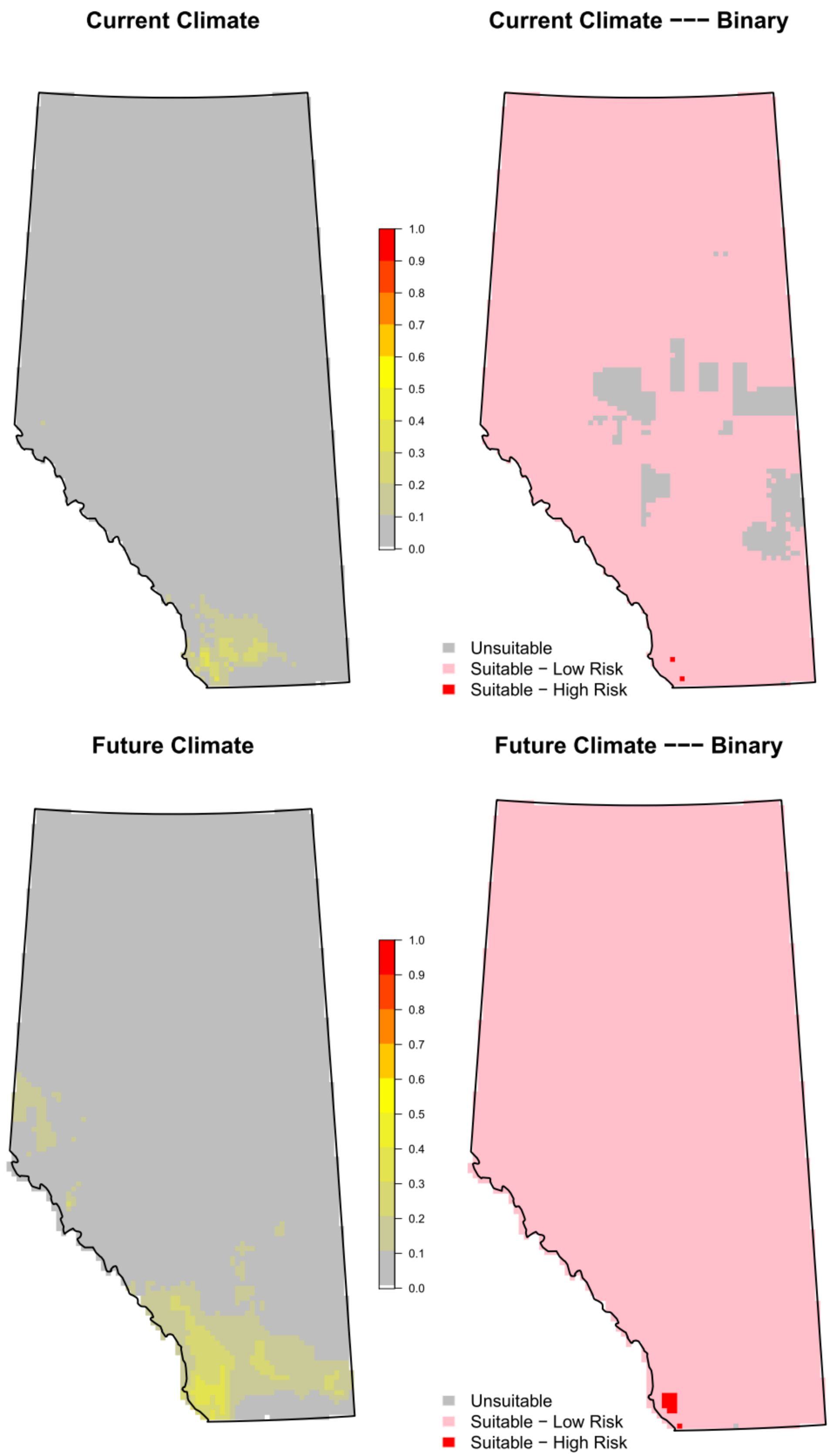
Fallopia sachalinensis



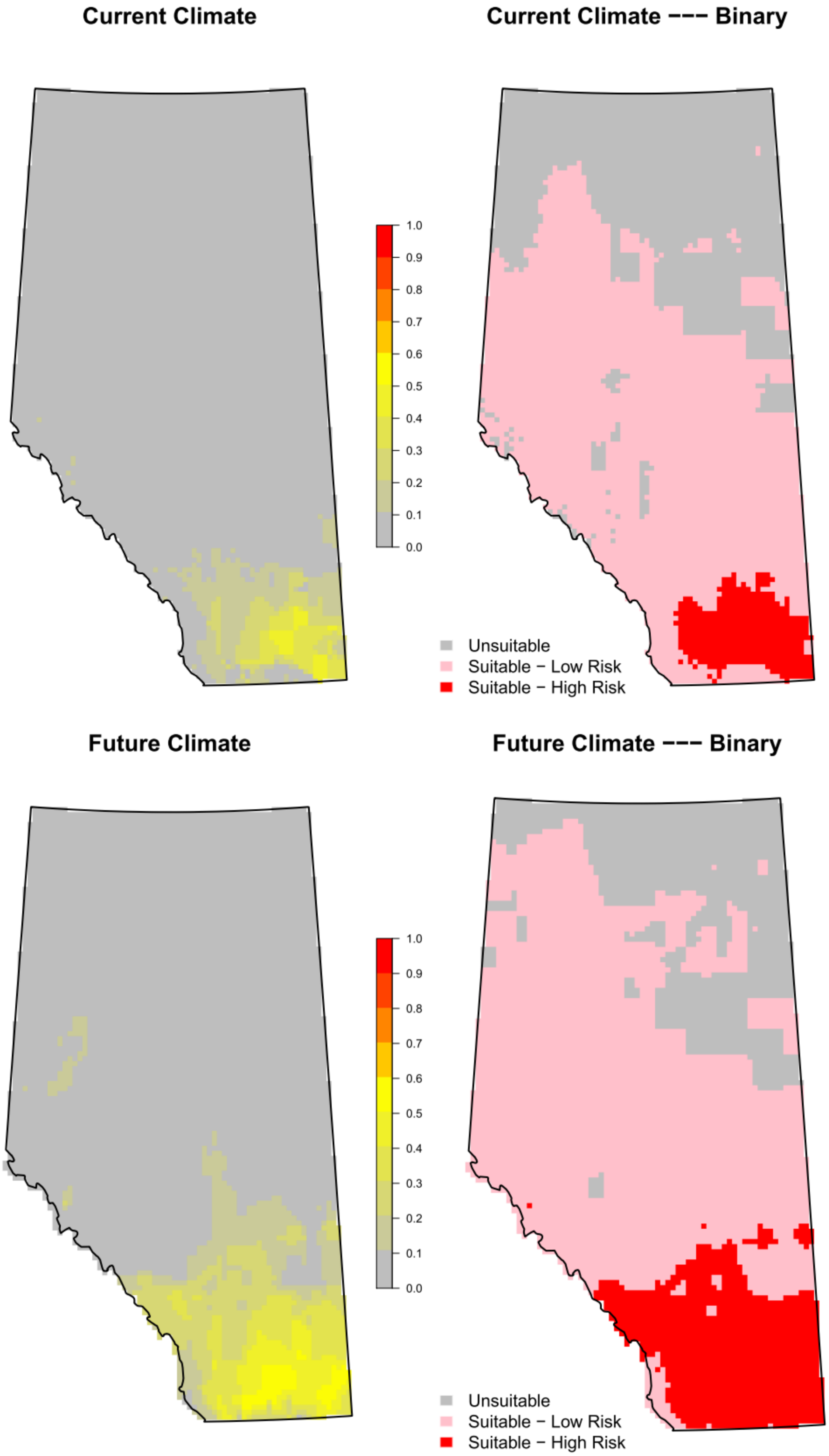
Halogeton glomeratus



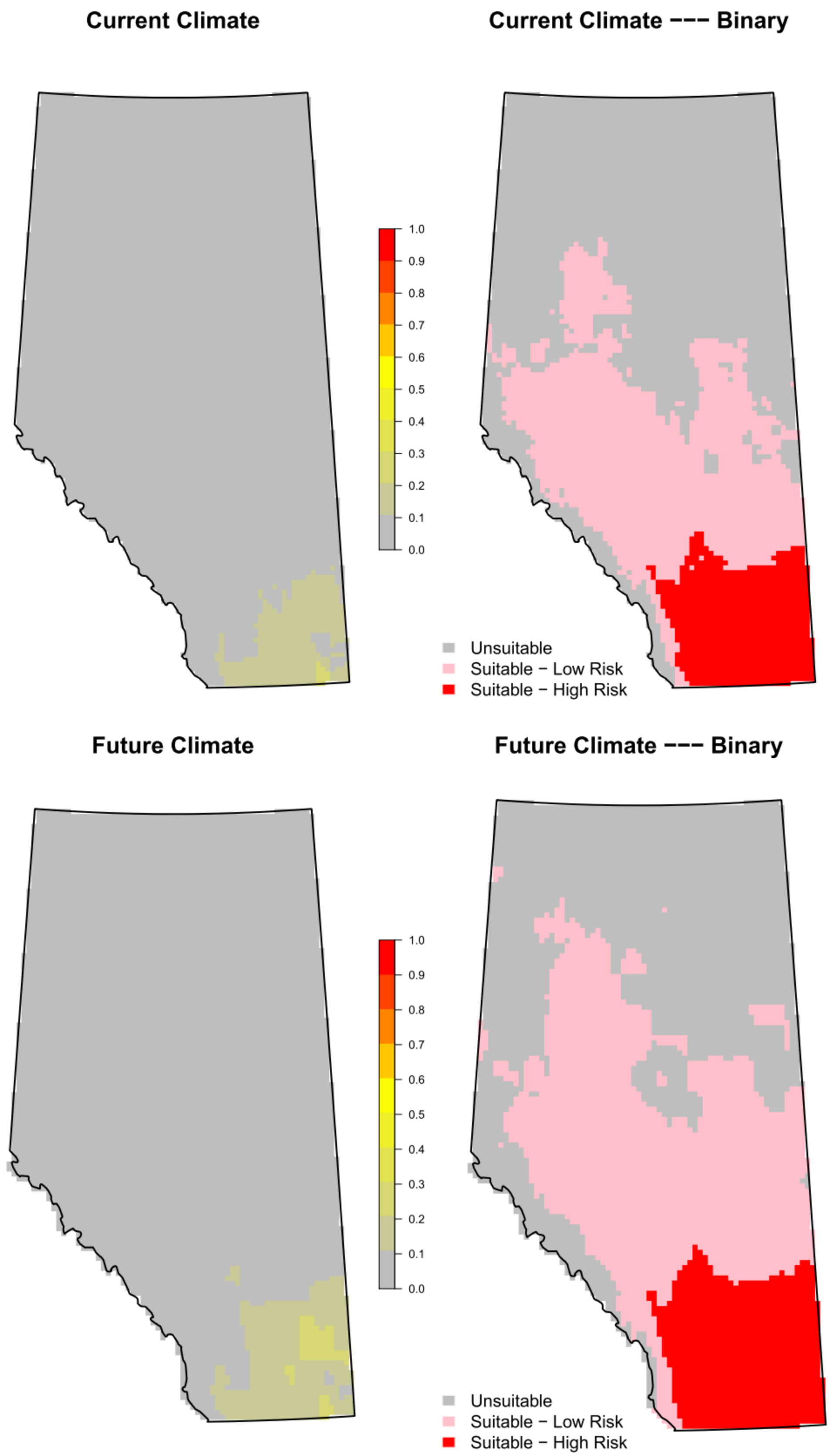
Onopordum acanthum



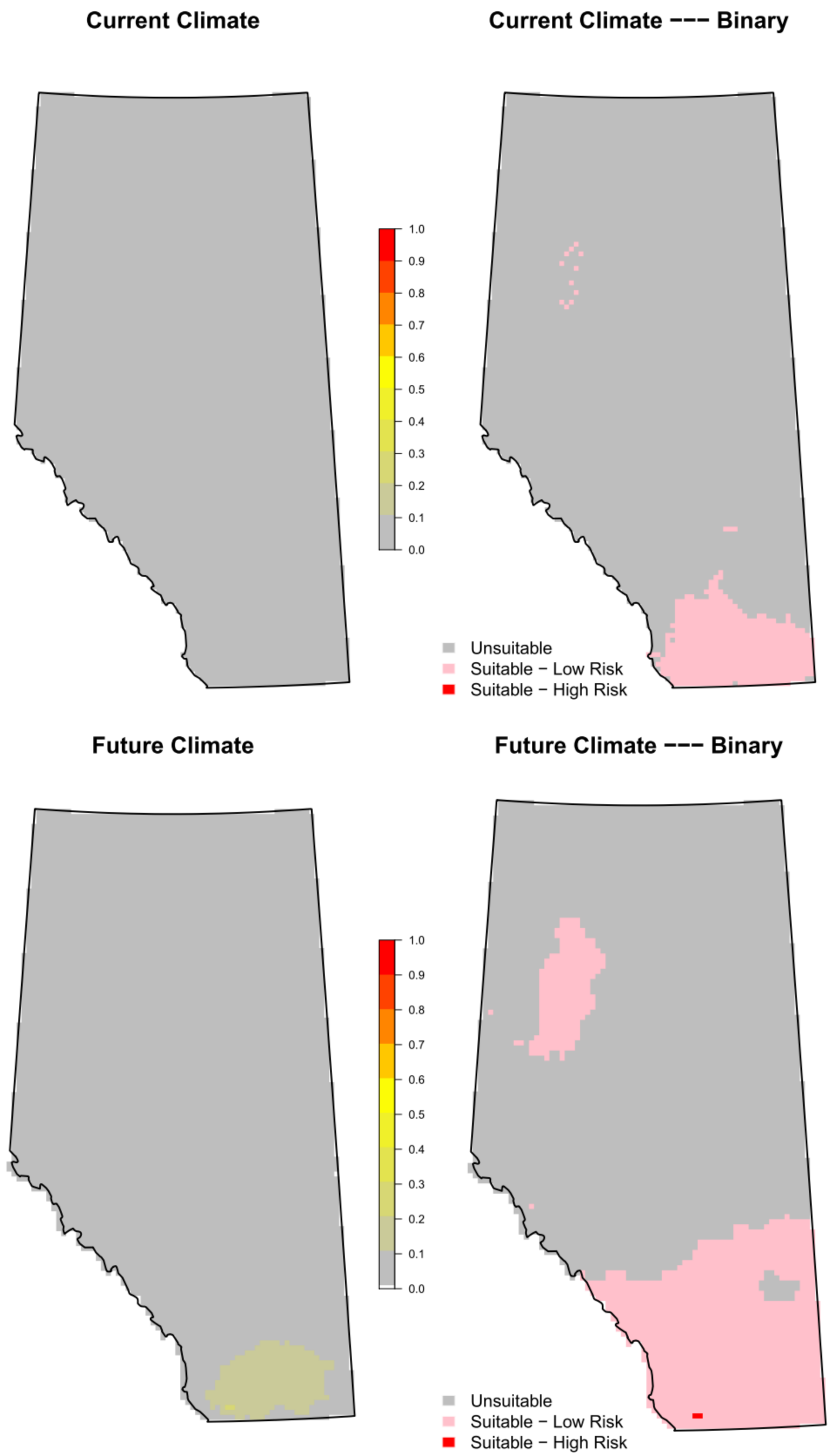
Peganum harmala



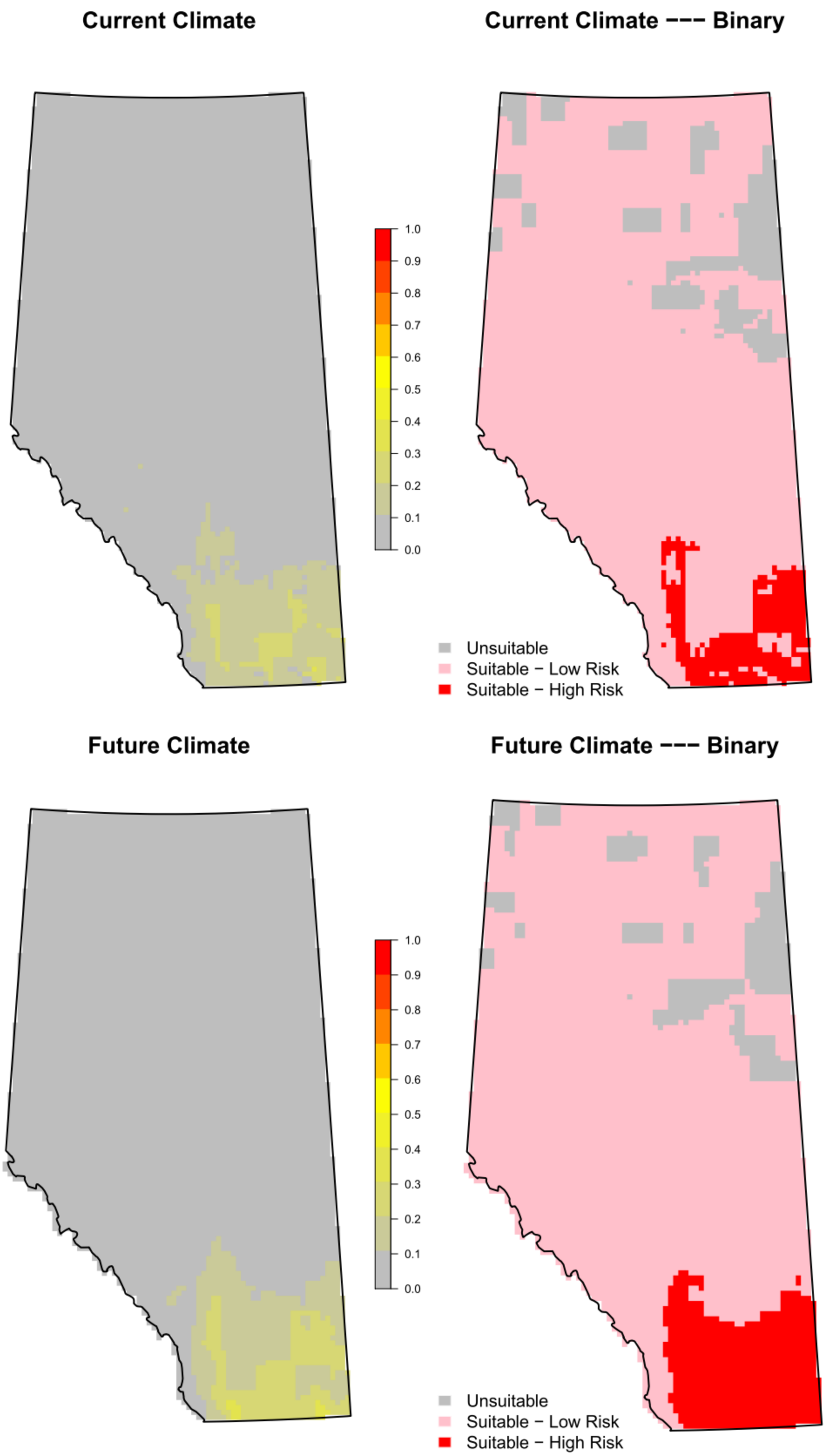
Sphaerophysa salsula



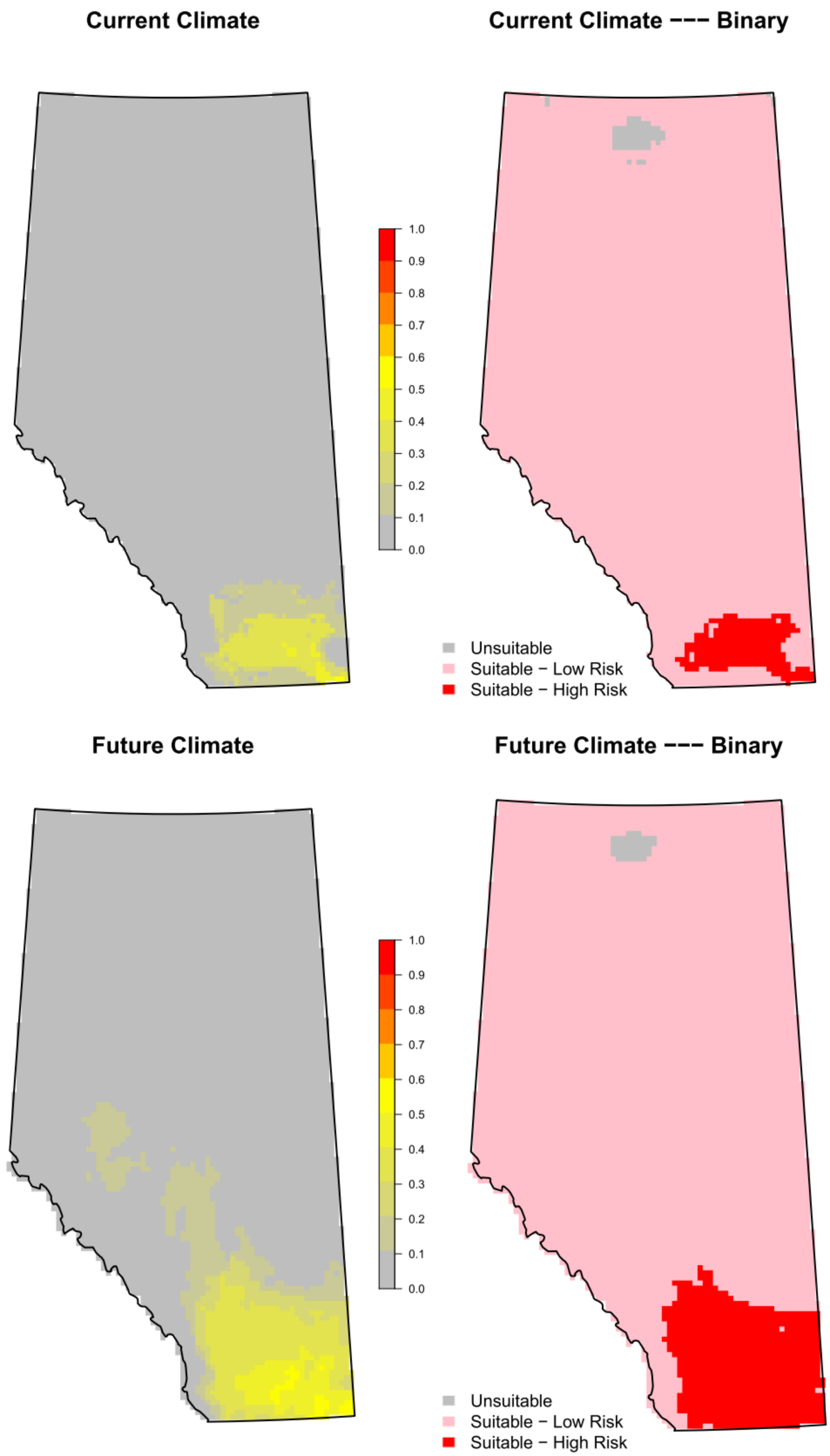
Taeniatherum caput-medusae



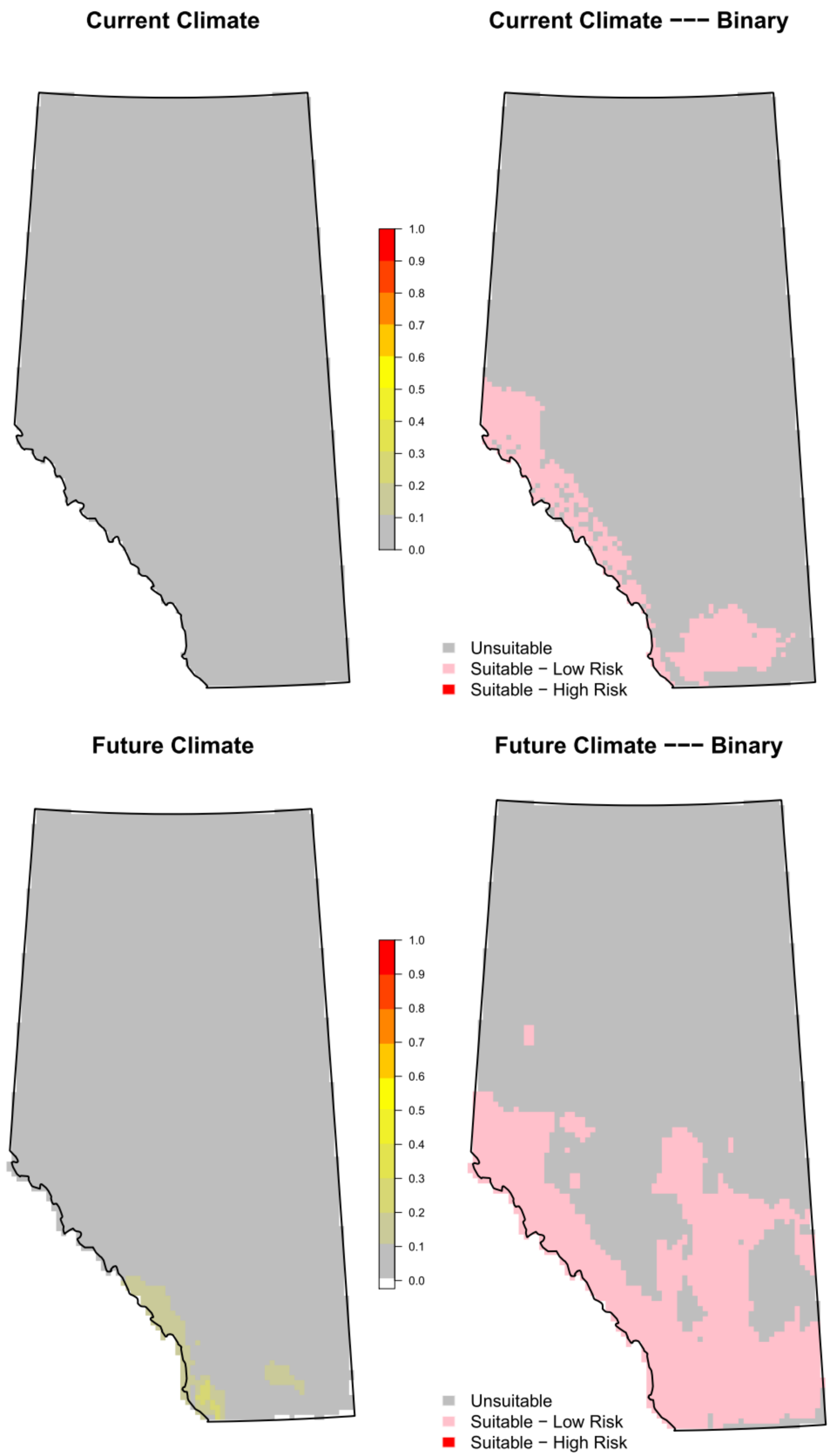
Tamarix chinensis



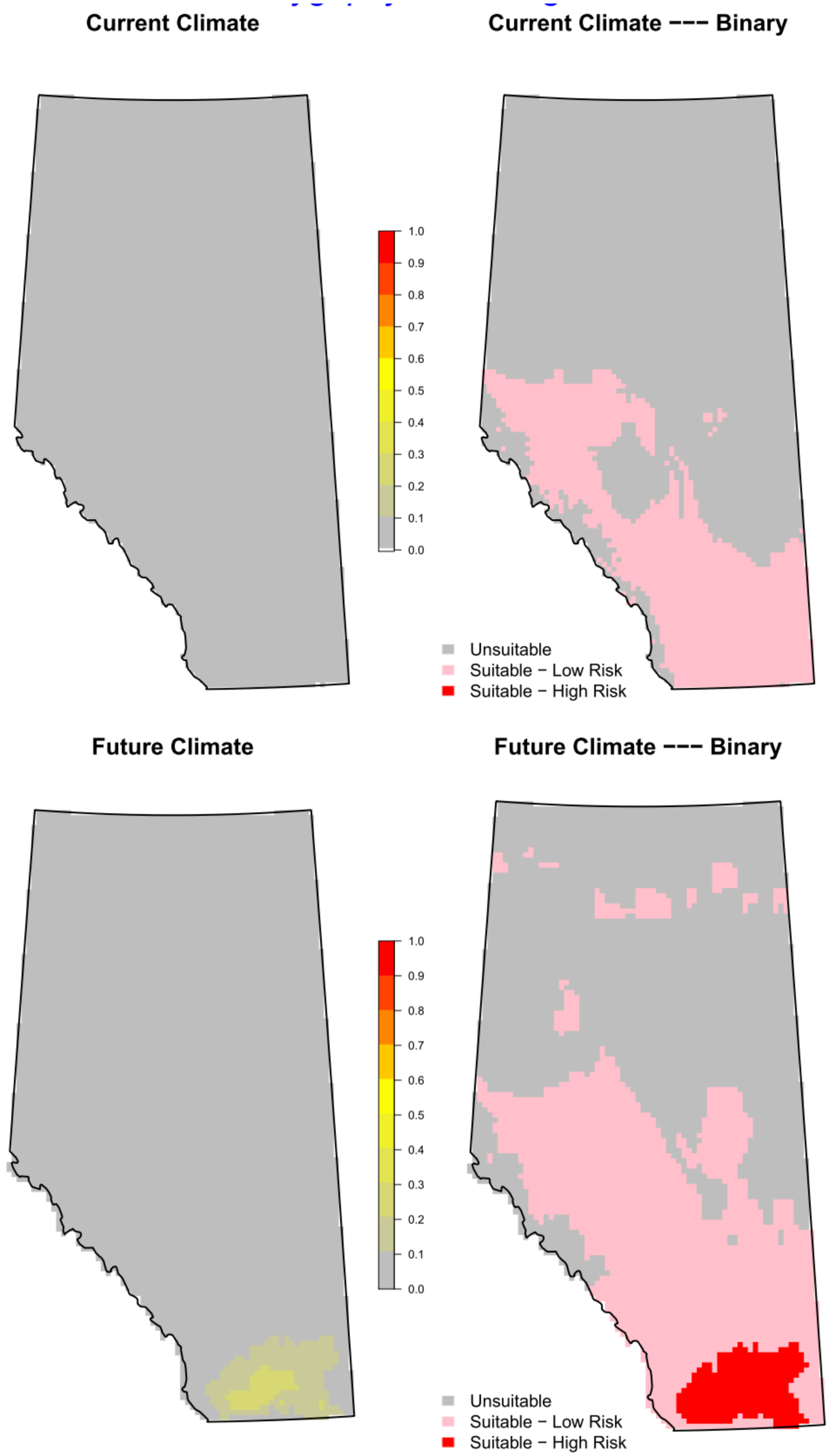
Tribulus terrestris



Ulex europaeus



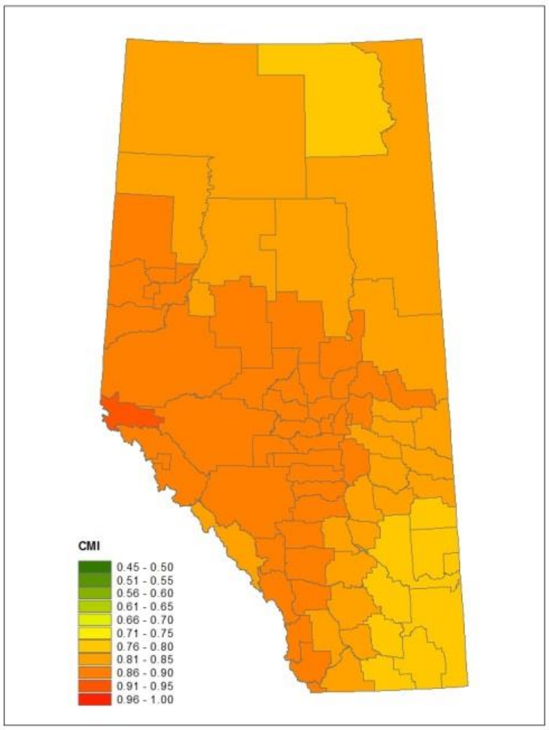
Zygophyllum fabago

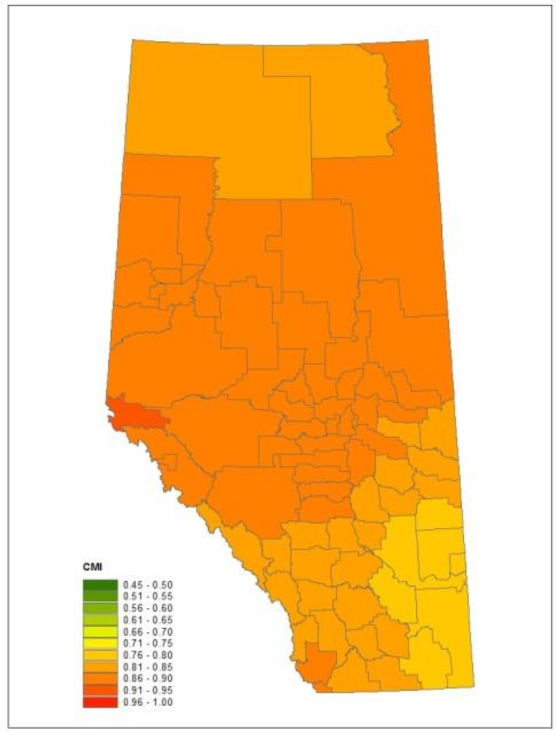


Appendix 4. CLIMEX climate matching by municipality for 16 potentially new invasive species in Alberta

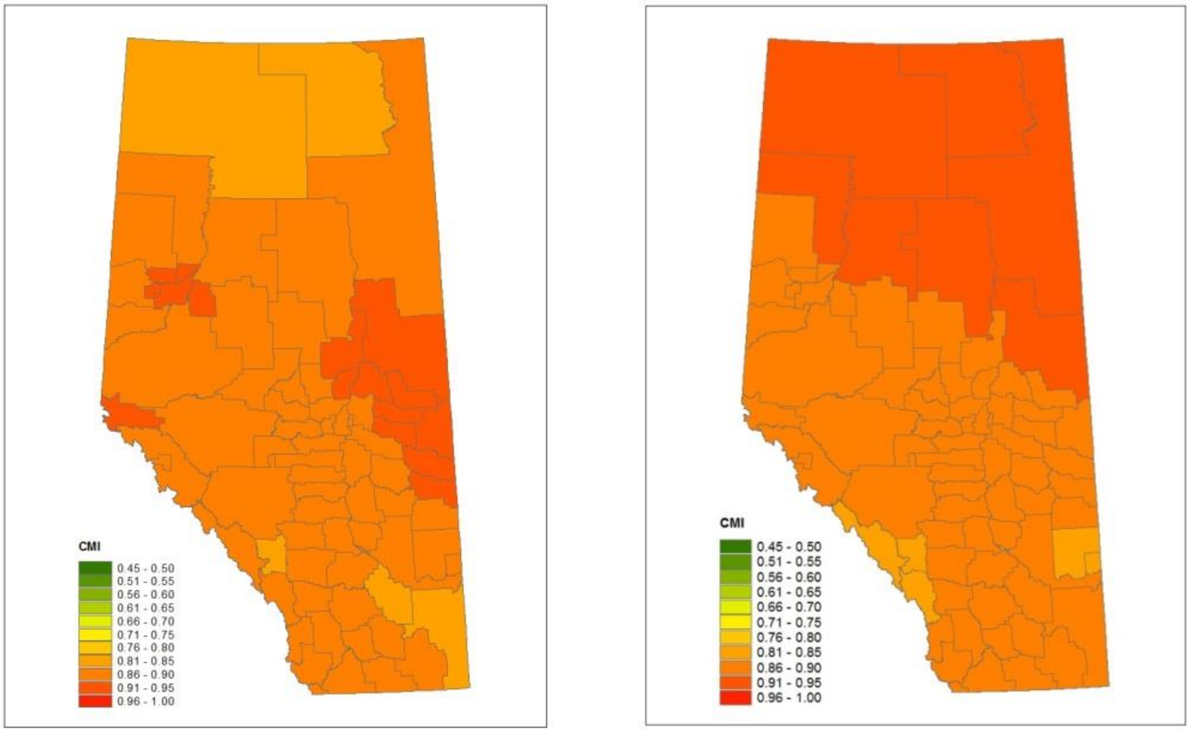
Figures on the left show climate match under current climate. Figures on the right show climate match in the 2050s under climate change. Climate Match Index (CMI) ≥ 0.7 indicates a suitable climate for the species.

Centaurea jacea

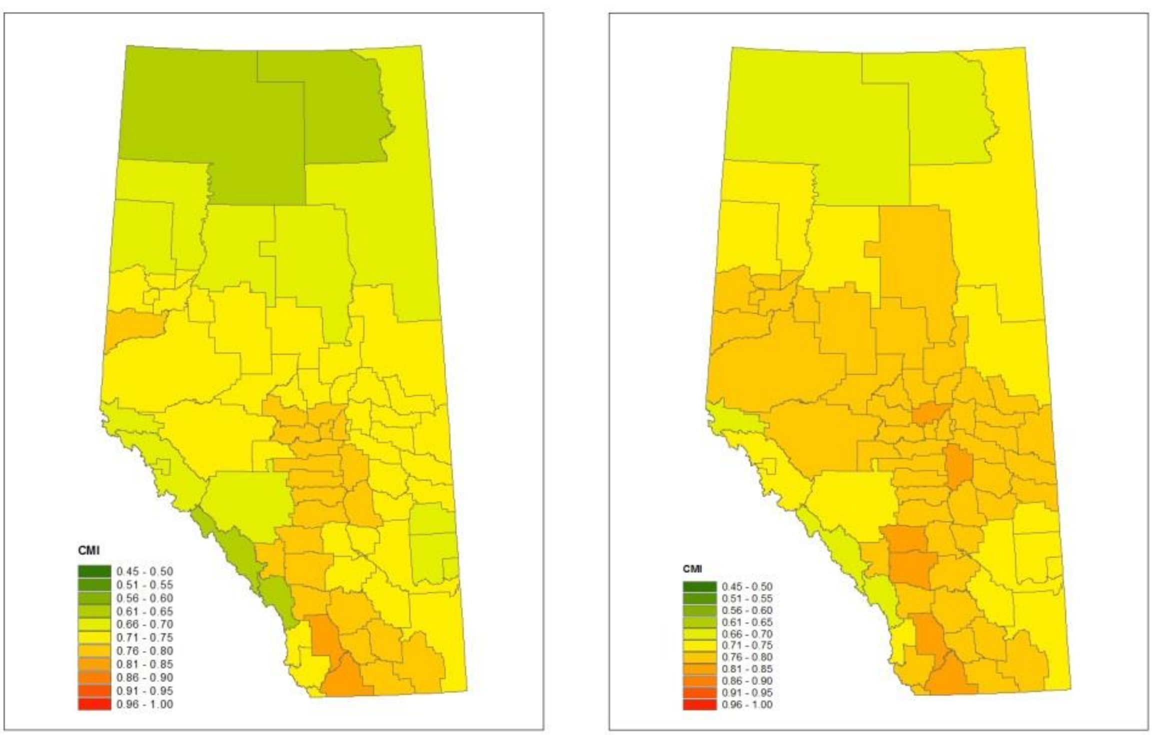




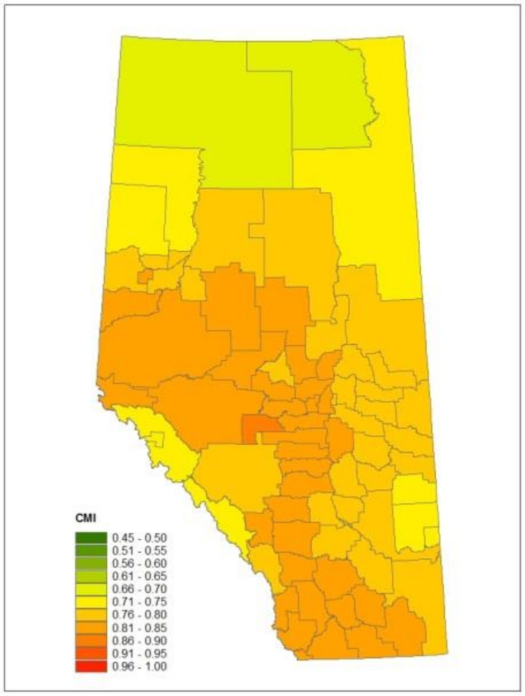
Cotoneaster integerrimus

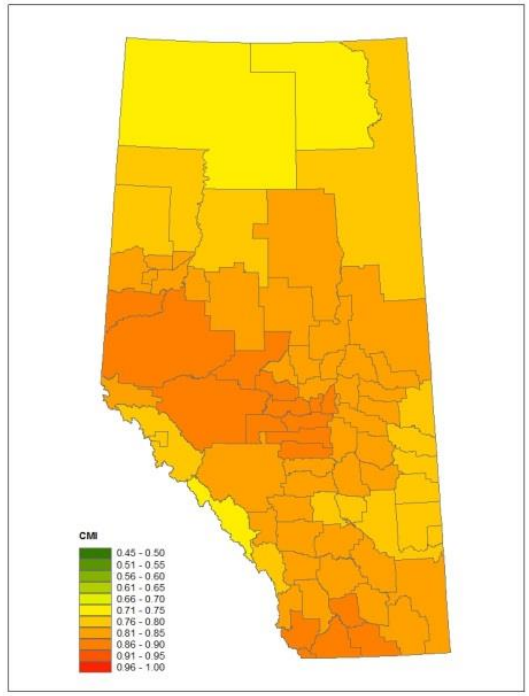


Vincetoxicum nigrum

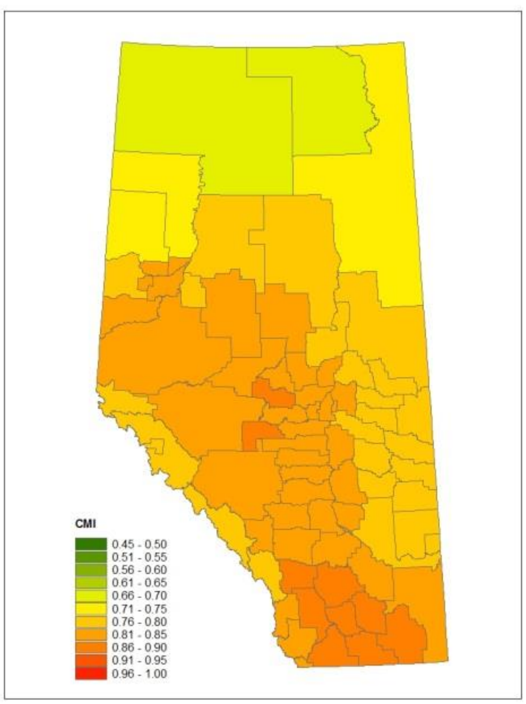


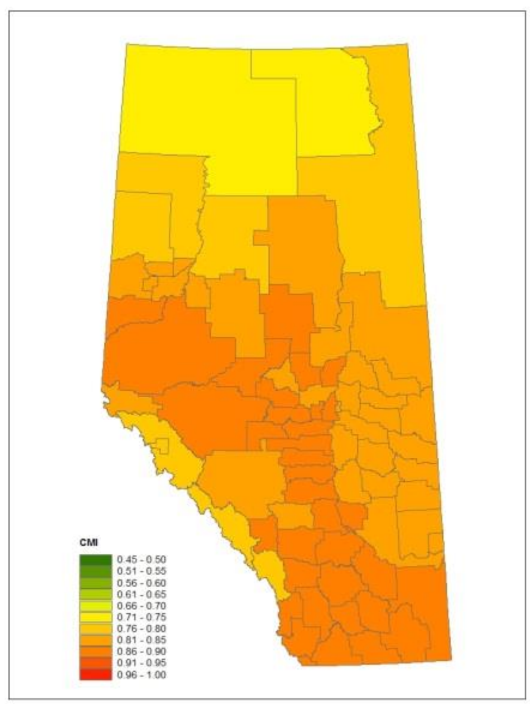
Cytisus scoparius



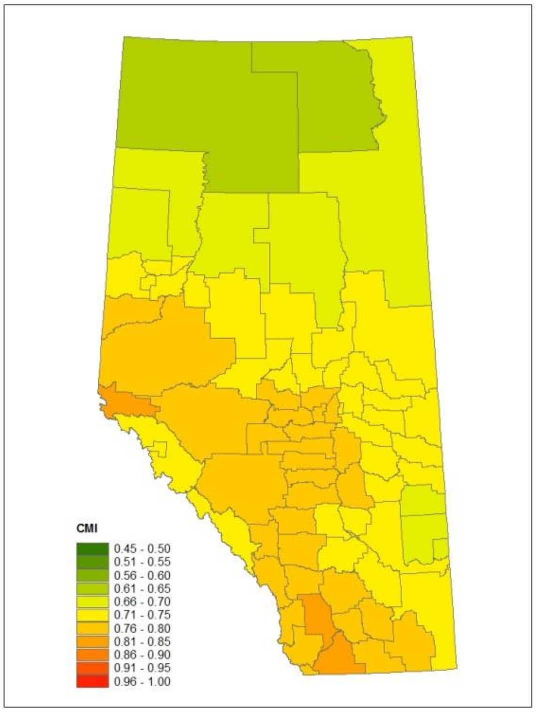


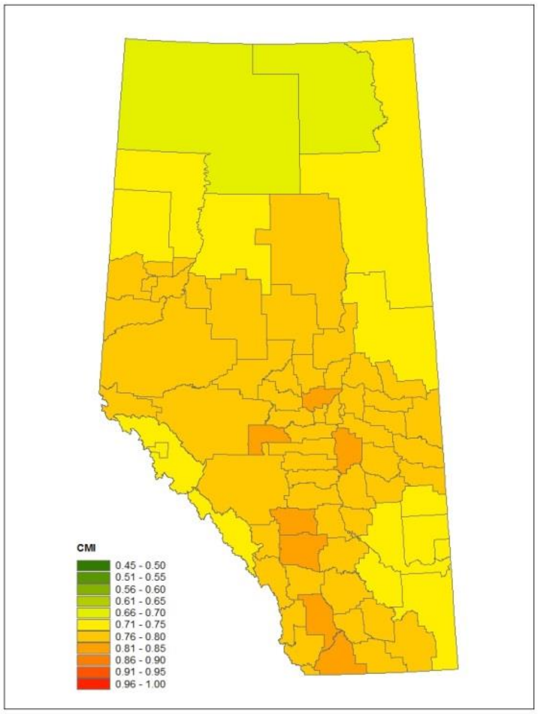
Echinops sphaerocephalus



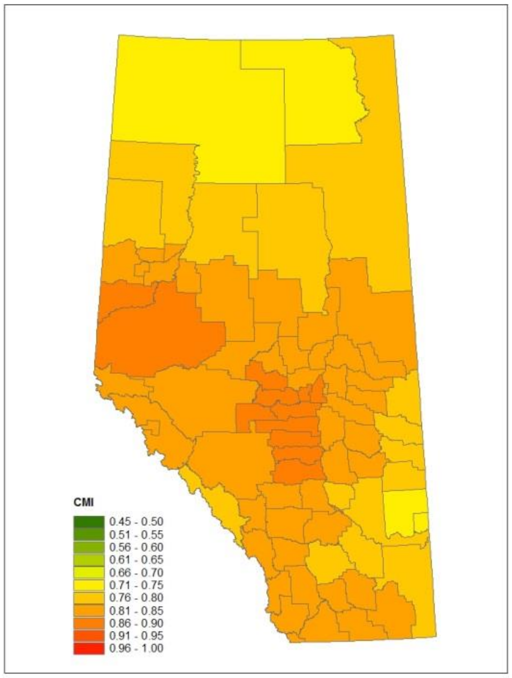


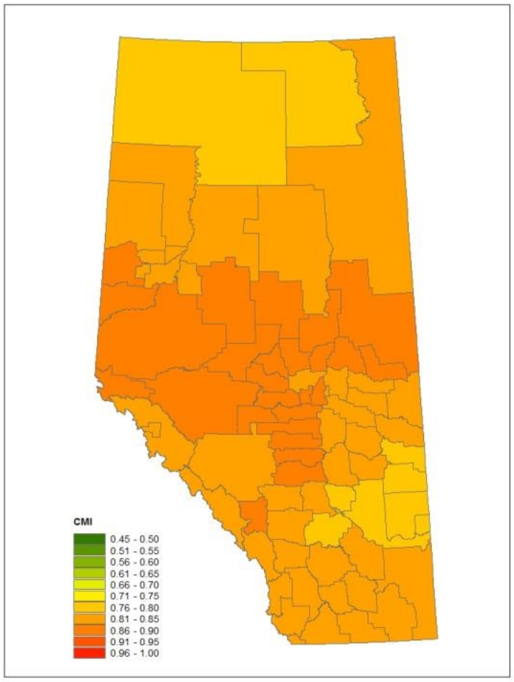
Elaeagnus umbellata



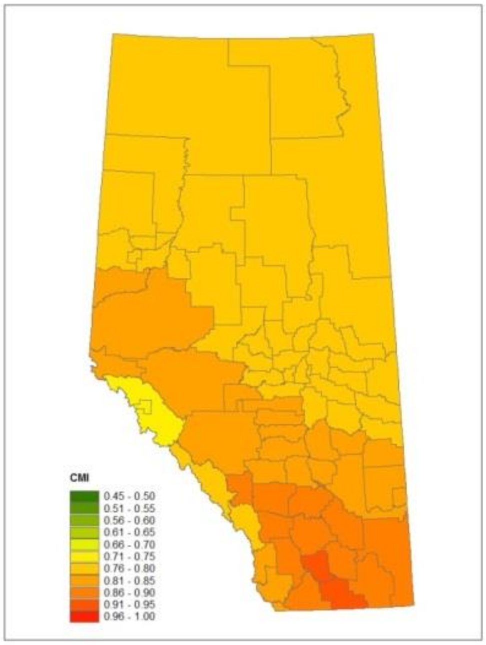


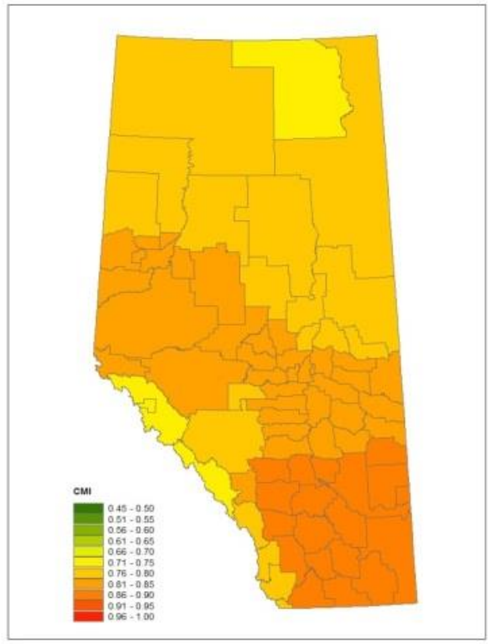
Fallopia sachalinensis



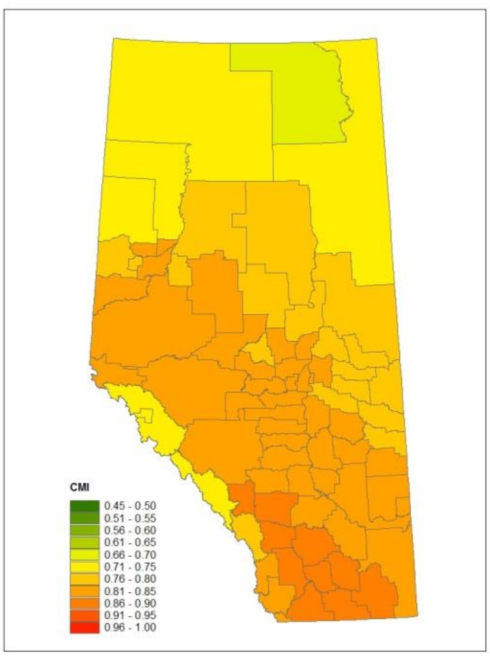


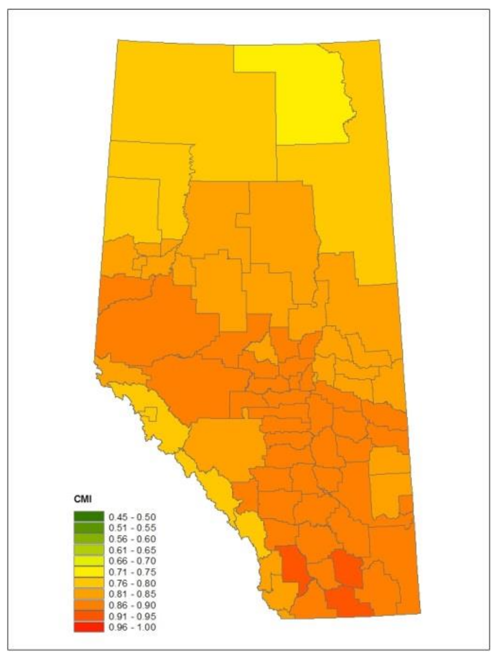
Halogeton glomeratus



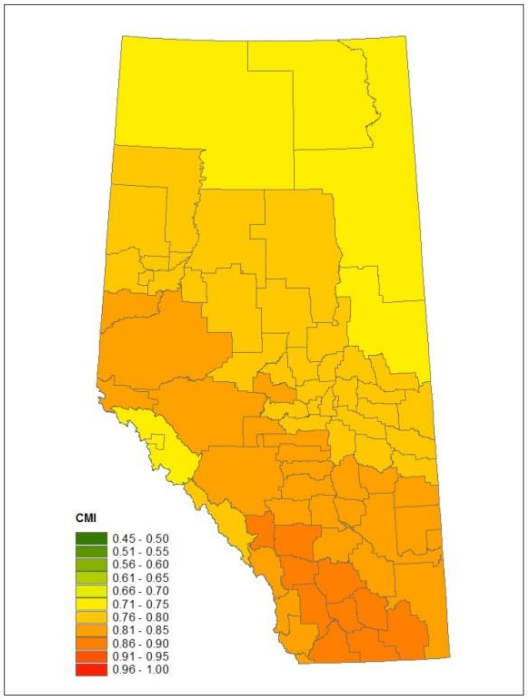


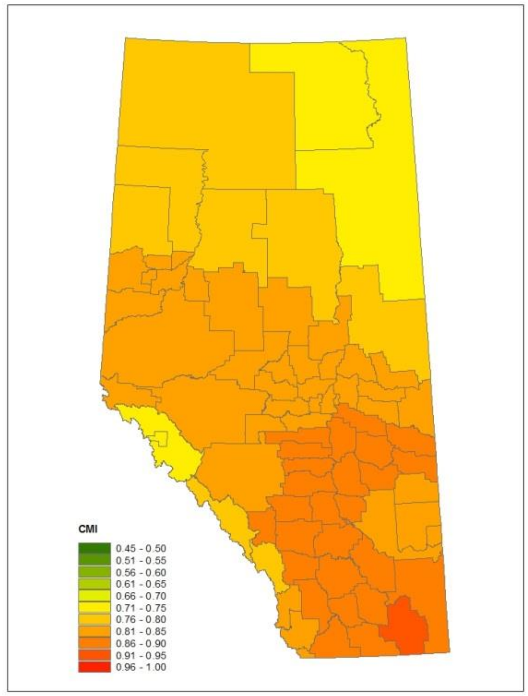
Onopordum acanthium



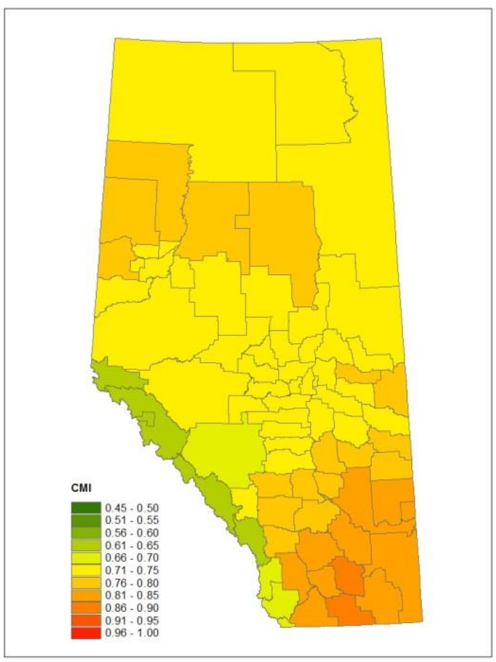


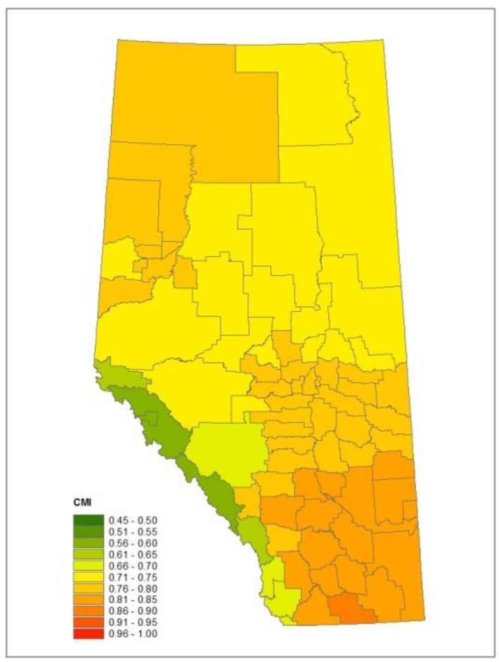
Peganum harmala



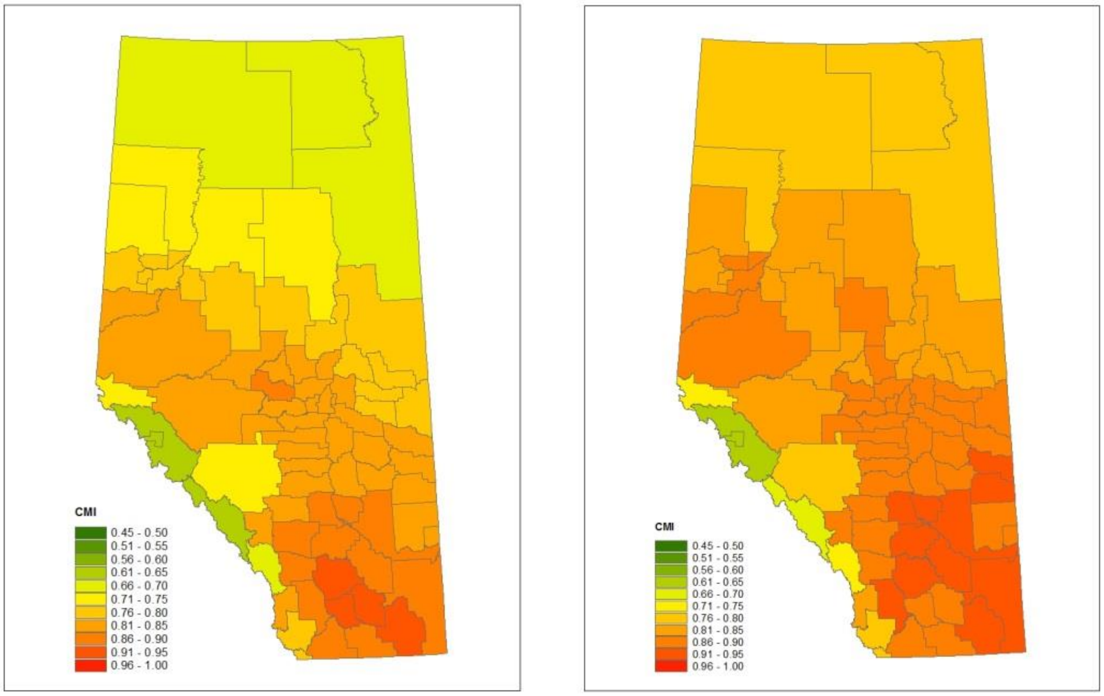


Sphaerophysa salsula

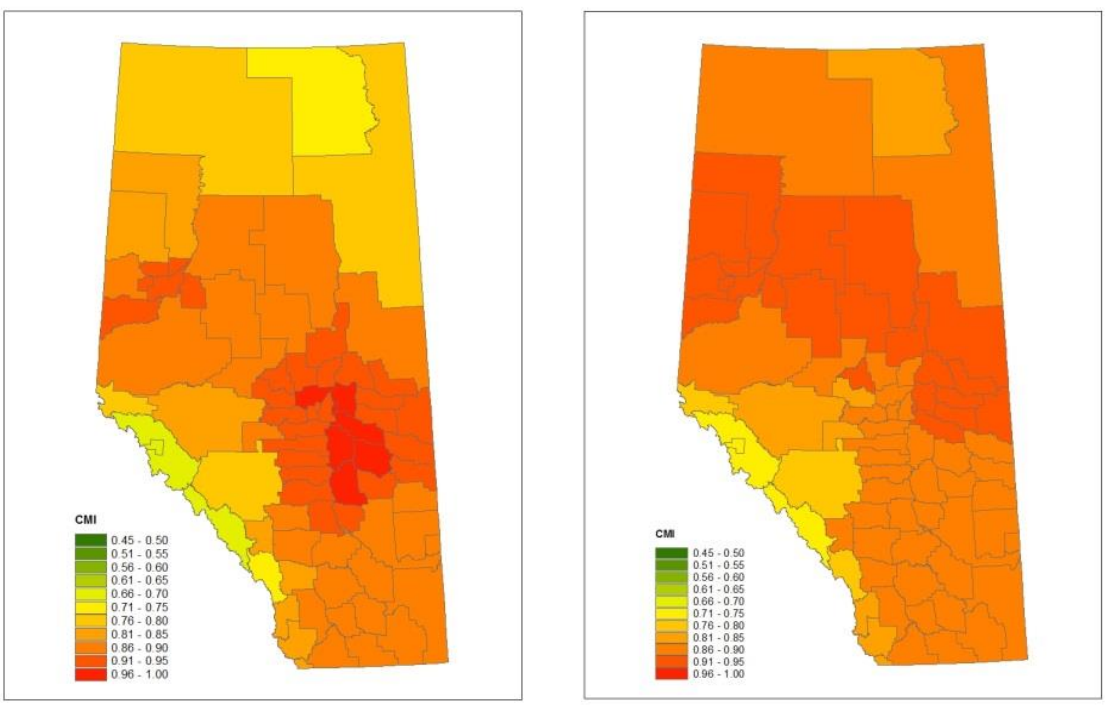




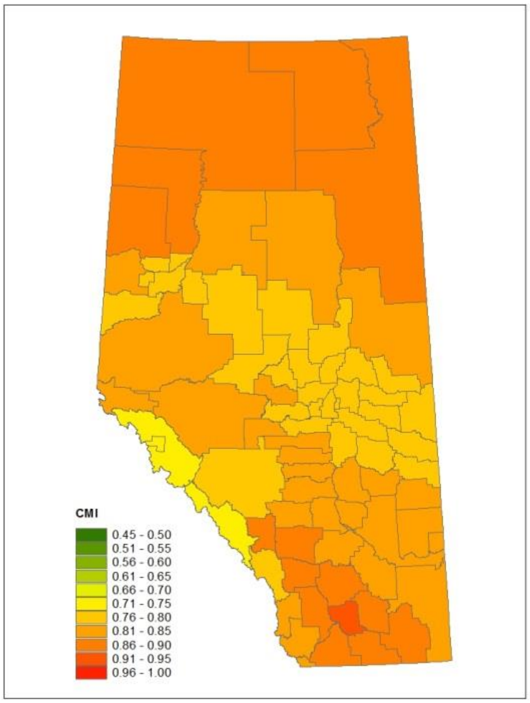
Taeniatherum caput-medusae

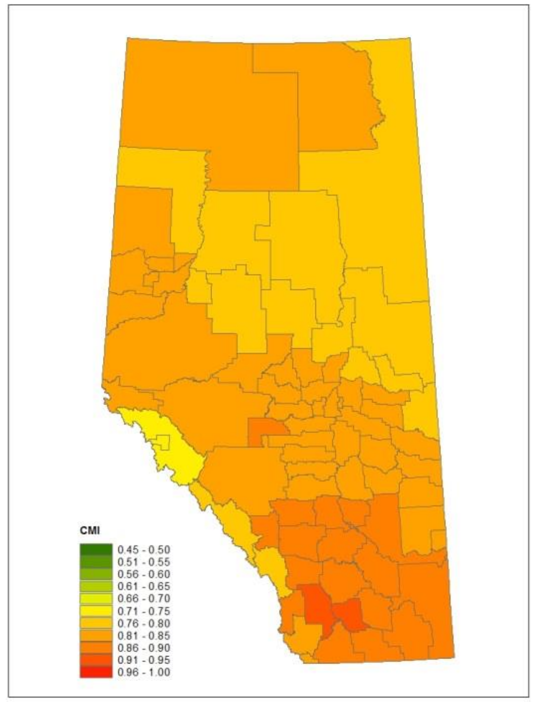


Tamarix chinensis

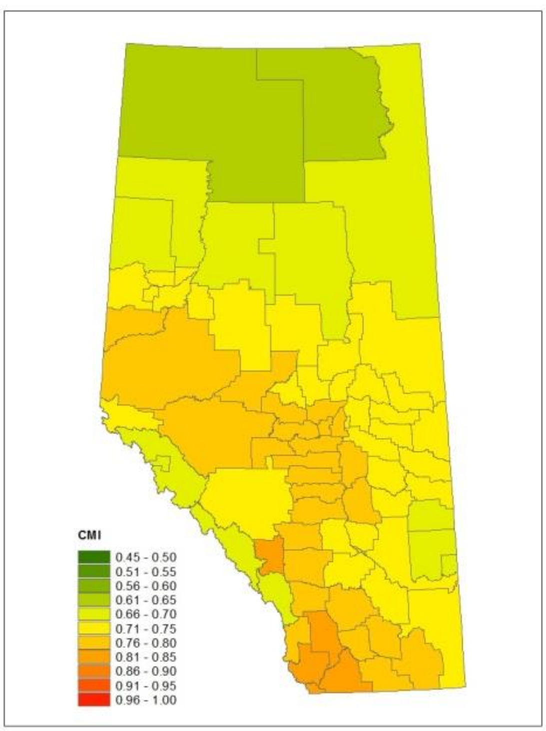


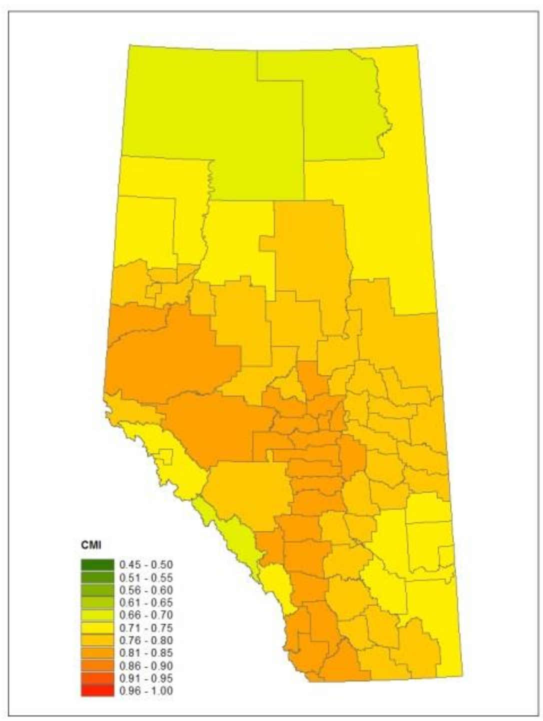
Tribulus terrestris





Ulex europaeus





Zygophyllum fabago