Hemlock woolly adelgid niche models from the invasive eastern North American range with projections to native ranges and future climates

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Supplementary Material

GIS data sources

Hemlock range GIS data sources

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Tables

Tab. S1 - One hundred nineteen environmental predictor indices (1 km resolution) used in developing 12 selected MaxEnt hemlock woolly adelgid niche models with six of 119 variables.[a]

Variable Index (Source)	Grid Name Abbreviation	Variable Frequency in 12 Selected Models (% of 72)[b]
79 Climatic Indices (for 1960–1990 derived from WorldClim [2017] of Hijmans et al. [2005])		
19 Bioclim Indices (WorldClim 2017)		
Annual mean temperature	*bio_1*	0 (0.0)
Mean diurnal range (mean of monthly TMAX – TMIN)	*bio_2*	0 (0.0)
Isothermality (*bio_2*/*bio_7*) ($\times$ 100)	*bio_3*	0 (0.0)
Temperature seasonality (standard deviation $\times$ 100)	*bio_4*	1 (1.4)
Maximum temperature of warmest month	*bio_5*	0 (0.0)
Minimum temperature of coldest month	*bio_6*	0 (0.0)
Temperature annual range (*bio_5* – *bio_6*)	*bio_7*	0 (0.0)
Mean temperature of wettest quarter	*bio_8*	2 (2.8)
Mean temperature of driest quarter	*bio_9*	0 (0.0)
Mean temperature of warmest quarter	*bio_10*	0 (0.0)
Mean temperature of coldest quarter	*bio_11*	0 (0.0)
Annual precipitation	*bio_12*	0 (0.0)
Precipitation of wettest month	*bio_13*	0 (0.0)
Precipitation of driest month	*bio_14*	0 (0.0)
Precipitation seasonality (coefficient of variation)	*bio_15*	1 (1.4)
Precipitation of wettest quarter	*bio_16*	0 (0.0)
Precipitation of driest quarter	*bio_17*	0 (0.0)
Precipitation of warmest quarter	*bio_18*	1 (1.4)
Precipitation of coldest quarter	*bio_19*	1 (1.4)
Subtotal		6 (8.3)
36 Monthly Temperature/Precipitation Indices (WorldClim 2017)		
Mean monthly minimum temperature (12)	*tmin_1-tmin_12*	*tmin_10* - 1 (1.4); 11 $\times$ 0 (0.0)

Tab. S1 (Cont.)- One hundred nineteen environmental predictor indices (1 km resolution) used in developing 12 selected MaxEnt hemlock woolly adelgid niche models with six of 119 variables.[a]

Variable Index (Source)	Variable Index (Source)	Variable Index (Source)
Mean monthly maximum temperature (12)	*tmax_1-* *tmax_12*	*tmax_1* - 1 (1.4); *tmax_2* - 2 (2.8); *tmax_3* - 1 (1.4); 9 × 0 (0.0)
Mean monthly rainfall (50%) (12)	*prec_1-* *prec_12*	*prec_1* – 3 (4.2); *prec_2* – 2 (2.8); 10 × 0 (0.0)
Subtotal		10 (13.8)
24 Monthly Actual and Potential Evapotranspiration (AET-PET) Indices (PET; Zomer et al. 2007; 2008; AET; Trabucco and Zomer 2010)		
Mean monthly AET (12)	*aet_1-* *aet_12*	*aet_2* - 1 (1.4); *aet_6* - 1 (1.4); *aet_7* - 1 (2.8); 9 × 0 (0.0)
Mean monthly PET (12)	*pet_1-* *pet_12*	*pet_1* - 1 (1.4); *pet_3* - 2 (2.8); *pet_7* - 1 (1.4); *pet_11* – 4 (5.6); 8 × 0 (0.0)
Subtotal		11 (15.2)
16 Topographic Indices		
Twelve Geomorphologic Indices (derived from 15 arc second resolution HydroSHEDs grids of Lehner et al. 2008; last 10 indices calculated using Geomorphometry and Gradient Metrics Toolbox for ArcGIS [Evans et al. 2014])[c]		
Elevation	*elev*	3 (4.2)
Slope	*slope*	4 (5.5)
Martonne's Modified Dissection Coefficient (Dissection, DISS), 3 km circular radius	*diss3kr*	0 (0.0)
Topographic Position Index (TPI), 3 km circular radius	*tpi3kr*	0 (0.0)
TPI, 9 km circular radius	*tpi9kr*	1 (1.4)
TPI, 19 km circular radius	*tpi19kr*	1 (1.4)
Elevation Relief Ratio (ERR, = Surface Relief Ratio, SRR), 3 km circular radius	*err3kr*	0 (0.0)

Tab. S1 (Cont.)- One hundred nineteen environmental predictor indices (1 km resolution) used in developing 12 selected MaxEnt hemlock woolly adelgid niche models with six of 119 variables.[a]

Variable Index (Source)	Variable Index (Source)	Variable Index (Source)
Compound Topographic Index (CTI)	*cti*	0 (0.0)
Heat Load Index (HLI)	*hli*	0 (0.0)
Integrated Moisture Index (IMI)	*imi*	0 (0.0)
Site Exposure Index (SEI)	*sei*	2 (2.8)
Slope Cosine Aspect Index (SCAI)	*scai*	0 (0.0)
Four Hydrogeomorphologic Indices (derived from 15 arc second resolution HydroSHEDs polyline river network shapefile of Lehner et al. 2008)		
Distance to Streams (STRMDIST)	*strmdist*	1 (1.4)
Distance to Low Flow Accumulation Areas (< 5,000 cells; STRMLOFLODIST)	*strmloflodist*	2 (2.8)
Distance to Medium Flow Accumulation Areas (5,000–60,000 cells; STRMMDFLODIST)	*strmmdflodist*	1 (1.4)
Distance to High Flow Accumulation Areas (>60,000 cells; STRMHIFLODIST)	*strmhiflodist*	0 (0.0)
Subtotal		15 (20.8)
24 Edaphic Indices (derived from 250 m resolution global SoilGrids250m of Hengl et al. [2017])		
12 Soil Property Indices		
Top Soil: 0–5 cm		
% Sand	*sand5cm*	1 (1.4)
% Clay	*clay5cm*	0 (0.0)
% Silt	*silt5cm*	5 (6.9)
Bulk Density	*blkden5cm*	2 (2.8)
Coarse Fragments	*frags5cm*	2 (2.8)
Soil pH in H_2O	*pH5cm*	2 (2.8)
Subtotal		0 (0.0)
Deep Soil: 0–30 cm		
% Sand	*sand30cm*	2 (2.8)
% Clay	*clay30cm*	0 (0.0)

Tab. S1 (Cont.)- One hundred nineteen environmental predictor indices (1 km resolution) used in developing 12 selected MaxEnt hemlock woolly adelgid niche models with six of 119 variables.[a]

Variable Index (Source)	Variable Index (Source)	Variable Index (Source)
% Silt	*silt30cm*	2 (2.8)
Bulk Density	*blkden30cm*	1 (1.4)
Coarse Fragments	*frags30cm*	0 (0.0)
Soil pH in H_2O	*silt30cm*	1 (1.4)
Subtotal		18 (25.0)
12 USDA Soil Classification Suborder Indices (six orders; percent probability per grid cell)[d]		
Spodosols Order		
Aquods	*aquods*	0 (0.0)
Orthods	*orthods*	1 (1.4)
Alfisols Order		
Aqualfs	*aqualfs*	0 (0.0)
Udalfs	*udalfs*	1 (1.4)
Entisols Order		
Orthents	*orthents*	2 (2.8)
Psamments	*psamments*	1 (1.4)
Inceptisols Order		
Aquepts	*aquepts*	1 (1.4)
Ochrepts	*ochrepts*	4 (5.5)
Udepts	*udepts*	2 (2.8)
Ultisols Order		
Aqults	*aqults*	0 (0.0)
Udults	*udults*	0 (0.0)
Andisols Order		
Cryands	*cryands*	0 (0.0)
Subtotal		12 (16.7)

[a]See Table S3 for six variables used in each of 12 feature-selected MaxEnt models and Table S2 for ranking of all variables.
[b]Frequency out of six variables times 12 models = 72 instances.
[c]For additional sources of indices and details see Tracy et al. (2018).
[d]Common soil suborders over the range of *Tsuga* spp. in North America and Asia.

Tab. S2 - MaxEnt model variable permutation importance for 42 of 119 variables used in top 12 six-variable hemlock woolly adelgid models selected by random subset feature selection algorithm.

Variable[a]	MaxEnt Model Permutation Importance, Mean ± SD (number of top 12 models)	Multi Multi-Objective Optimization Ranking by Mean Permutation Importance (0.6 weight) and Number Appearances in Top 12 Models (0.4 weight)[b]
pet_11	43.4 ± 4.8 (4)	1
slope	33.4 ± 6.4 (4)	2
ochrepts	19.4 ± 7.1 (4)	3
silt5cm	12.7 ± 3.3 (5)	4
udepts	44.3 ± 8.9 (2)	5
tmax_2	40.2 ± 5.4 (2)	6
frags5cm	35.5 ± 5.2 (2)	7
ph5cm	19.5 ± 7.4 (2)	8
blkden5cm	18.7 ± 4.7 (2)	9
prec_1	9.1 ± 9.1 (3)	10
elev	8.7 ± 7.1 (3)	11
sand30cm	11.8 ± 3.5 (2)	12
silt30cm	7 ± 0.9 (2)	13
orthents	5.3 ± 1.1 (2)	14
prec_2	4.5 ± 2.2 (2)	15
bio_8	3.5 ± 1.2 (2)	16
strmloflodist	2.5 ± 0.1 (2)	17
aet_7	1.9 ± 0.8 (2)	18
sei	0.4 ± 0.5 (2)	19
pet_1	39.5 ± 0 (1)	20
bio_4	38.3 ± 0 (1)	21
pet_3	36.5 ± 0 (1)	22
aet_2	35.6 ± 0 (1)	23
tmax_1	33.2 ± 0 (1)	24
tmax_3	33 ± 0 (1)	25
blkden30cm	16.2 ± 0 (1)	26
ph30cm	14.6 ± 0 (1)	27
orthods	13 ± 0 (1)	28
aquepts	12.2 ± 0 (1)	29
pet_7	7.7 ± 0 (1)	30
tmin_10	7.6 ± 0 (1)	31
udalfs	5.3 ± 0 (1)	32
sand5cm	4.8 ± 0 (1)	33
strmdist	2.3 ± 0 (1)	34
tpi9kr	1.6 ± 0 (1)	35
bio_19	1.6 ± 0 (1)	36
tpi3kr	1.4 ± 0 (1)	37

Tab. S2 (Cont.) - MaxEnt model variable permutation importance for 42 of 119 variables used in top 12 six-variable hemlock woolly adelgid models selected by random subset feature selection algorithm.

Variable[a]	Variable[a]	Variable[a]
strmmdflodist	1.2 ± 0 (1)	38
aet_6	1.1 ± 0 (1)	39
bio_18	0.5 ± 0 (1)	40
psamments	0.5 ± 0 (1)	41
bio_15	0.1 ± 0 (1)	42

[a]See Table S1 for variable abbreviations and sources of variables and Table S3 for variables used in each of top 12 models.
[b]Variables ranked using weighted joint criteria with MCDM R package.

Tab. S3 - Hemlock woolly adelgid feature-selected MaxEnt model environmental variables.

Model Number					
Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
elev	*bio_19*	*aquepts*	*blkden5cm*	*bio_8*	*bio_4*
prec_2	*ochrepts*	*bio_8*	*ochrepts*	*orthents*	*orthods*
sei	*pet_3*	*bio_15*	*orthents*	*prec_1*	*pet_7*
silt5cm	*ph5cm*	*frags5cm*	*pet_11*	*silt5cm*	*psamments*
tmax_3	*silt30cm*	*pet_11*	*sand30cm*	*slope*	*strmfloflodist*
udepts	*tmin_10*	*strmdist*	*tpi3kr*	*tmax_1*	*udepts*
Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
aet_7	*aet_2*	*elev*	*aet_7*	*aet_6*	*elev*
ph5cm	*bio_18*	*frags5cm*	*blkden5cm*	*blkden30cm*	*prec_1*
silt5cm	*ph30cm*	*pet_11*	*ochrepts*	*ochrepts*	*silt5cm*
slope	*prec_2*	*prec_1*	*pet_1*	*pet_11*	*strmloflodist*
tmax_2	*sand5cm*	*sand30cm*	*silt5cm*	*silt30cm*	*strmmdflodist*
tpi9kr	*slope*	*sei*	*udalfs*	*slope*	*tmax_2*

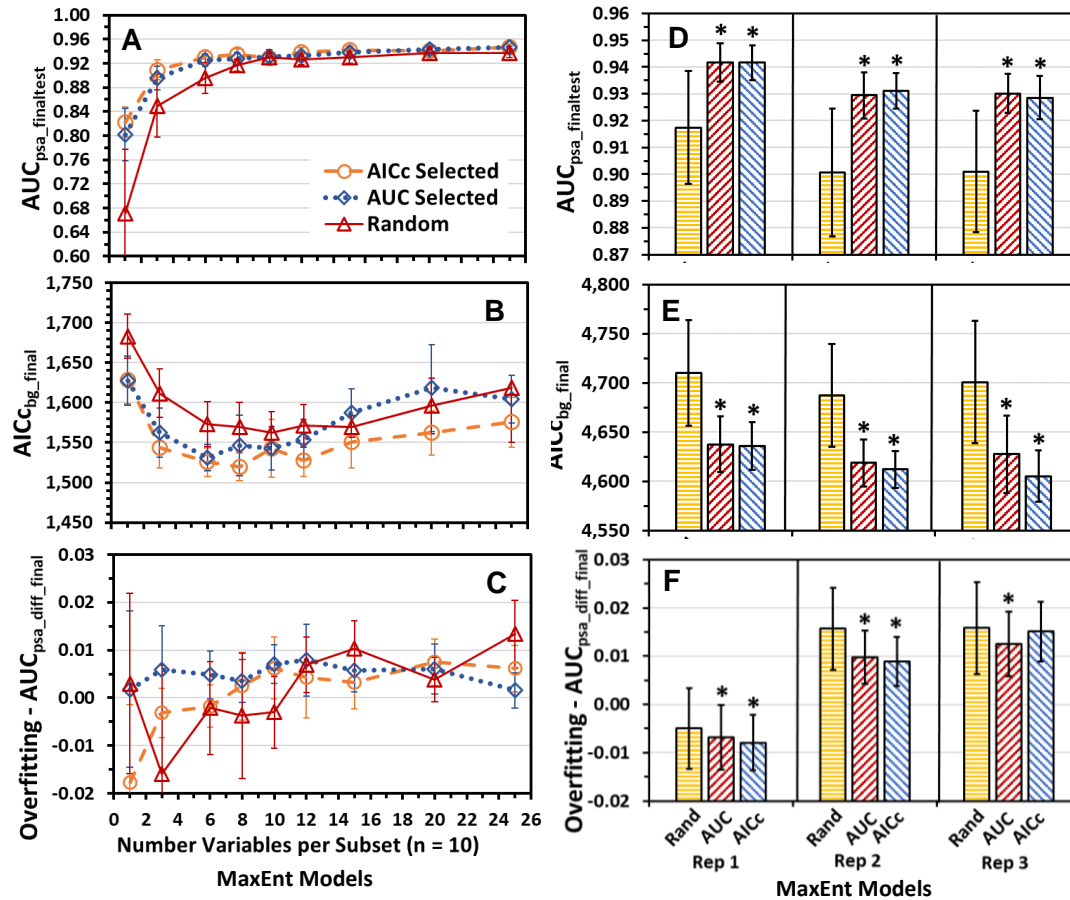[a]For variable abbreviations, see Table S1.

Figures

Fig. S1 - Hemlock woolly adelgid MaxEnt model evaluation statistics (mean ± SD) of $AUC_{psa\_finaltest}$ (A,D), $AICc_{bg\_final}$ (B,E), and $AUC_{psa\_diff\_final}$ (overfitting; C,F) for models developed from (A-C) top ten variable subsets selected by AUC_{psa} or AICc using random subset feature selection (RSFSA) and ten random subsets out of 250 randomly generated six-variable subsets of various sizes derived from 119 variables; and (D-F) top 250 variable subsets out of 3,000 subsets per three training set replicates selected by AUC_{psa} or AICc using RSFSA and top 300 random generated six-variable subsets out of 3,000 subsets derived from 119 variables. Means for AUC_{psa} selected or AICc selected model statistics within a replicate with an asterisk are significantly more optimal (higher for $AUC_{psa\_finaltest}$ and lower for $AICc_{bg\_final}$ and $AUC_{psa\_diff\_final}$) from that of random selected models ($P < 0.05$; Welch t test with Holm correction, preceded by significant Welch ANOVA test, $P < 0.05$)
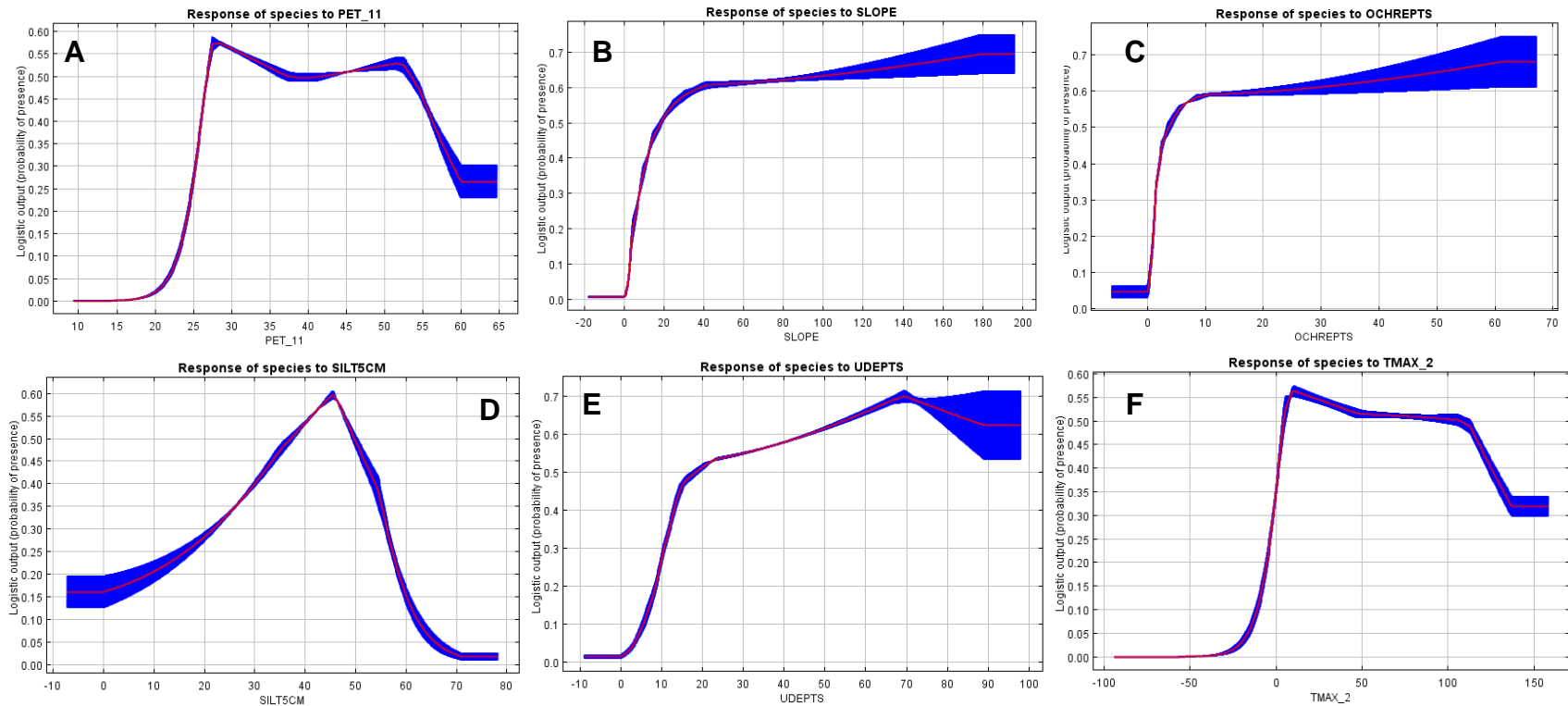
Fig. S2 - Hemlock woolly adelgid single-variable MaxEnt model variable response curves (logistic output probability of presence vs. variable) for the six top ranked variables (Table S2) from feature-selected models (Table S3): (A) *pet_11*, (B) s*lope*, (C) *ochrepts*, (D) *silt5cm*, (E) *udepts*, and (F) *tmax_2* (see Table S1 for abbreviations and Table S2 for variable ranking and permutation importance).
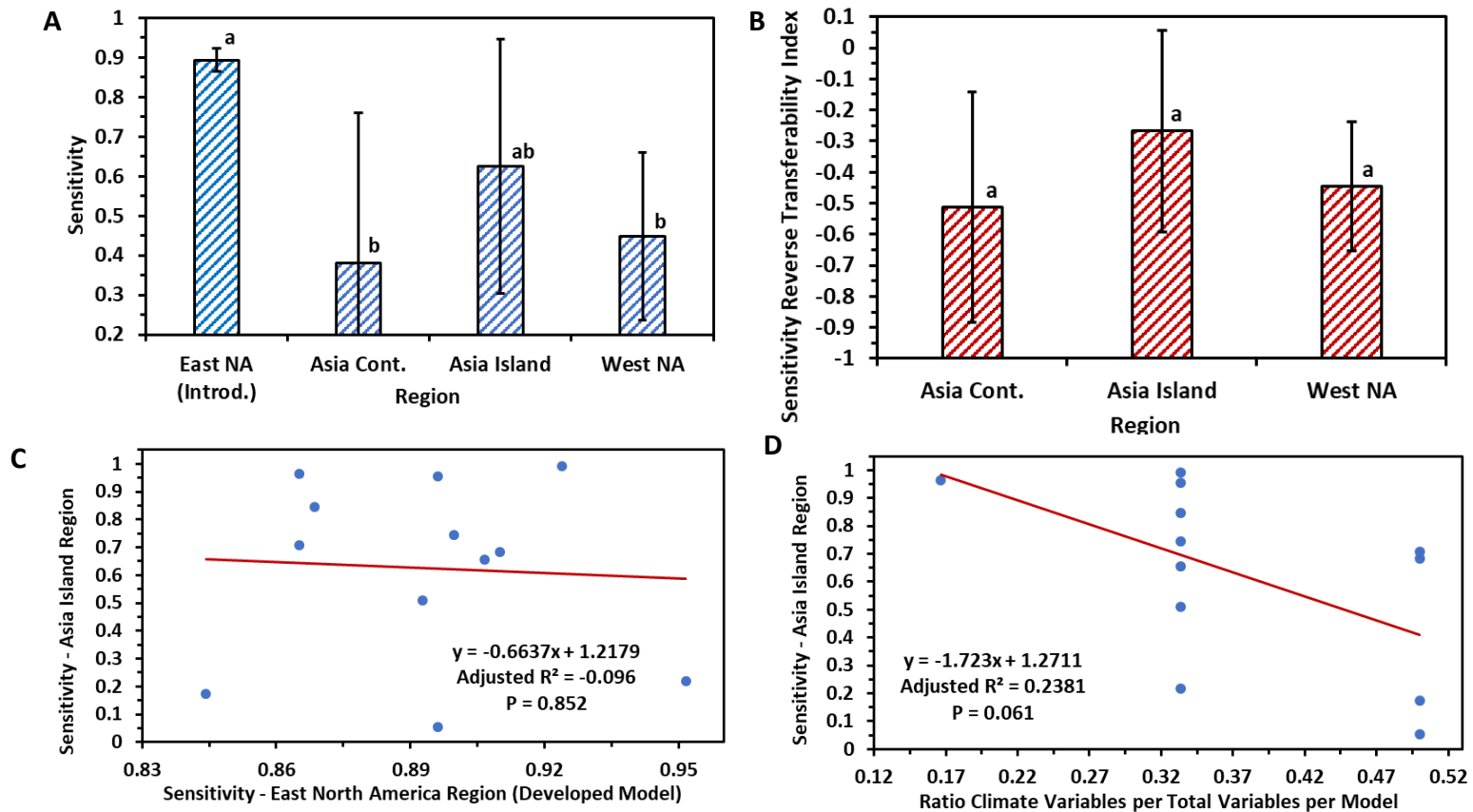
Fig. S3 - (A) Sensitivity of introduced hemlock woolly adelgid mean Maxent model projections ($\overline{X} \pm SD$; n = 12) for introduced (East North America) range and native ranges of Asia continental, Asia island, and West North America; (B) Sensitivity reverse transferability index from introduced range to native ranges ($\overline{X} \pm SD$; n = 12) (means with same letters are not significantly different, P < 0.05, Games Howell multiple comparison test with Holm correction following significant Welch ANOVA test, P < 0.05); (C) relationship between sensitivity of introduced model for Asia island region and sensitivity of introduced model in introduced region (East North America); (D) relationship between sensitivity of introduced model for Asia island region and percent of climate variables used in model (n = 12; P values from F-test of linear regression).
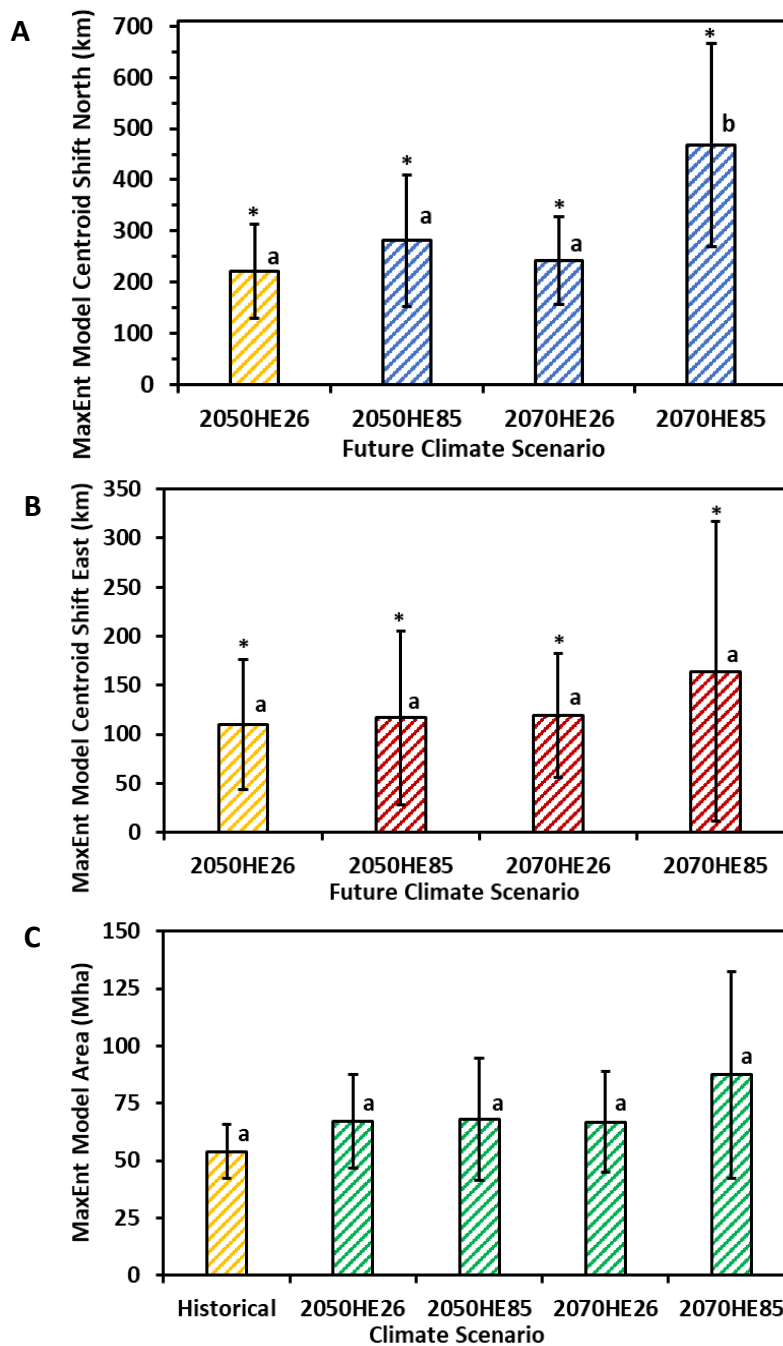
Fig. S4 - Characteristics of introduced hemlock woolly adelgid mean Maxent model projections ($\overline{X} \pm SD$; n = 12) under historical and future climate scenarios in eastern North America: (A) northward and (B) eastward shifts of future model centroids from historical model centroids (at zero shift); (C) areas of historical and future models. (* = mean significantly different from zero; $P < 0.02$; Welch t-test with Holm correction) (means with same letter are not significantly different from mean at far left, $P < 0.05$, paired Welch t-test with Holm correction).
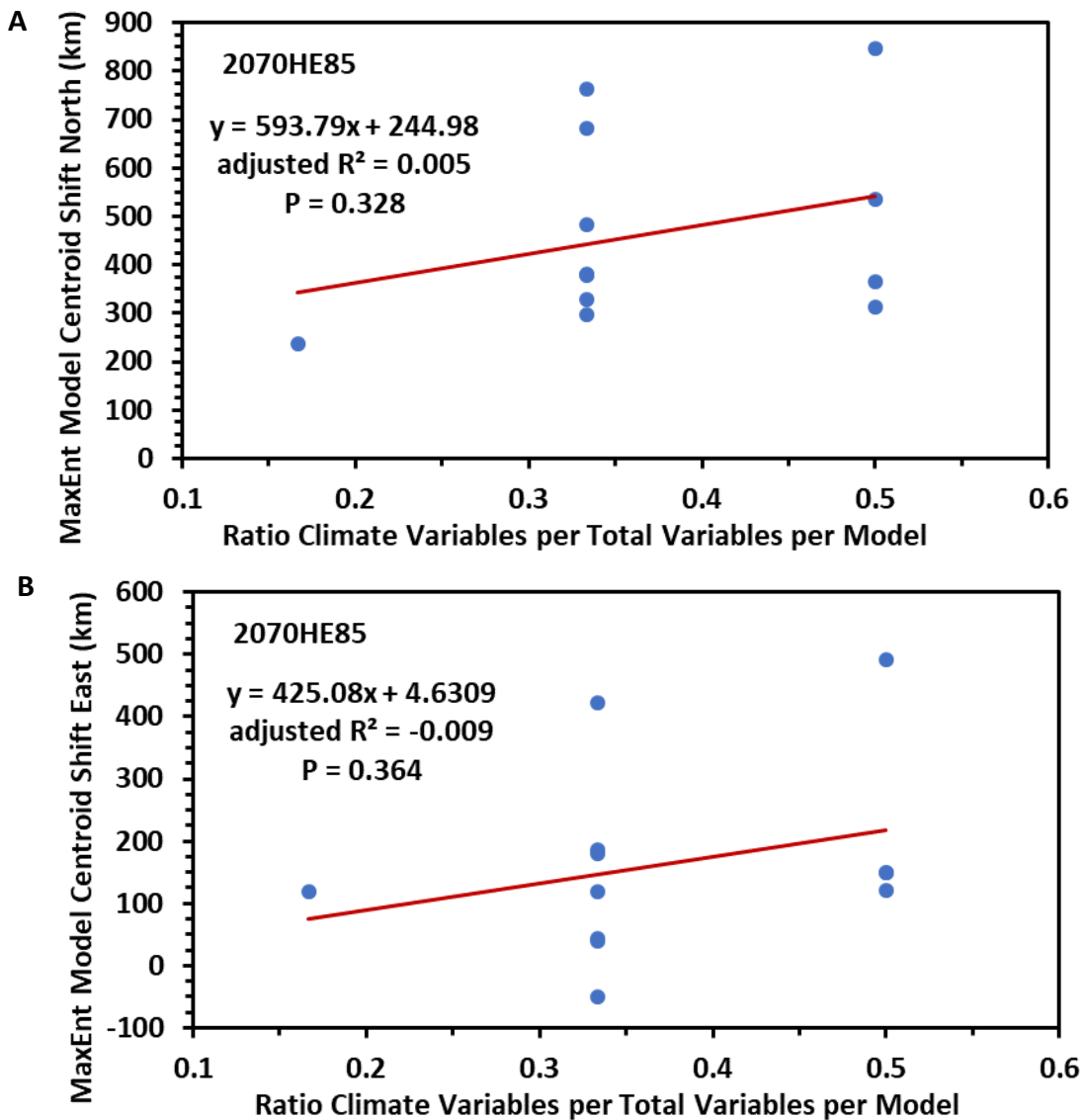
Fig. S5 - Relationship between northward (A) and eastward (B) shifts of centroids of introduced hemlock woolly adelgid MaxEnt model projections from historical to future 2070HE85 climates and the ratio of climate variables (1-3) to the number of total variables (6) per model (n = 12; P values from F-test of linear regression).
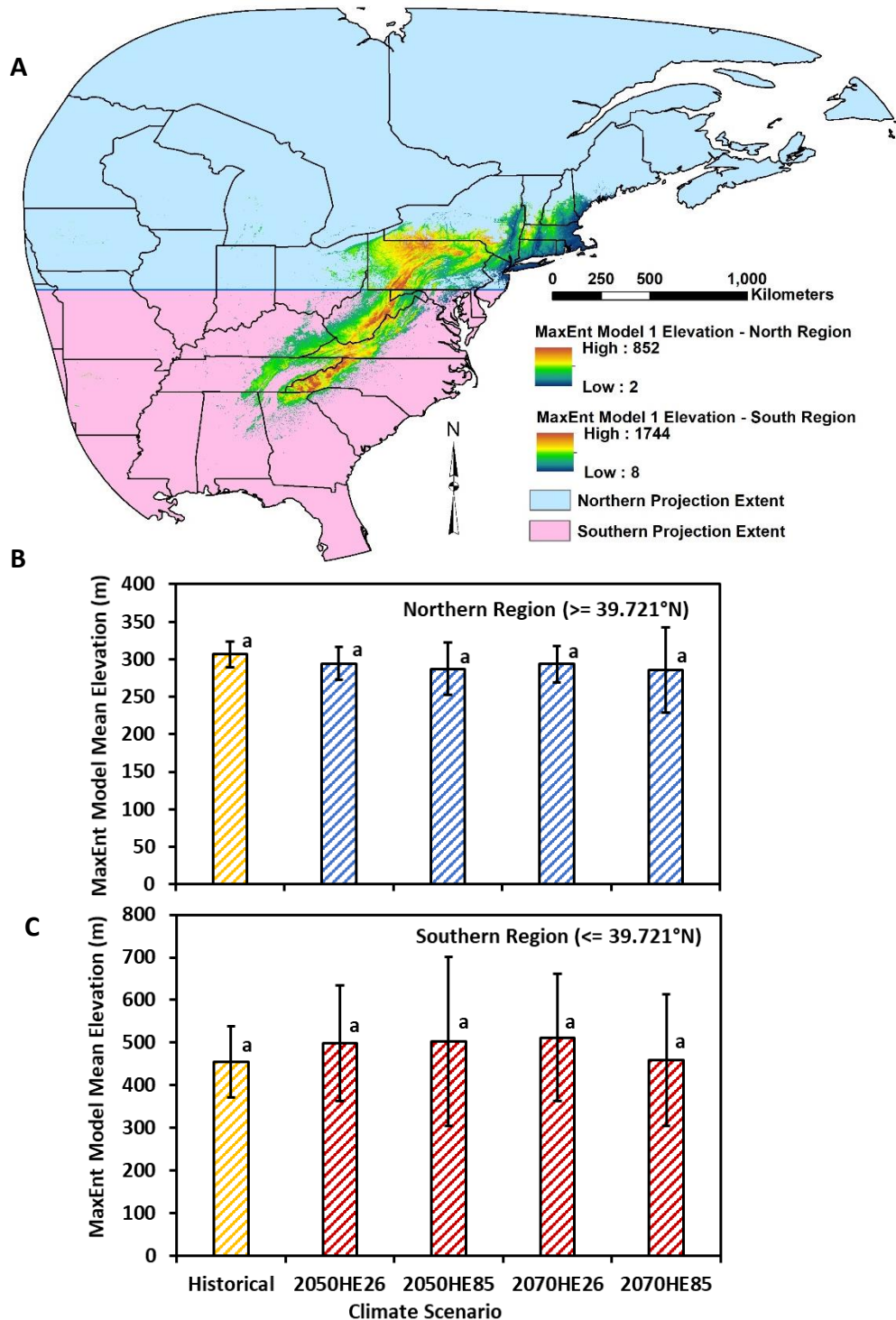
Fig. S6 - (A) North and South regions (divided at 39.721°N) for introduced hemlock woolly adelgid MaxEnt model projections with elevation for MaxEnt historical climate model 1 in two regions. Mean elevation ($\overline{X} \pm SD$; n = 11-12) within historical and future MaxEnt model projections for North (B) and South (C) regions (means with same letter are not significantly different from mean at far left, $P < 0.05$, paired Welch t-test with Holm correction).