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Testing range-limit hypotheses using range-wide habitat suitability and occupancy for the scarlet monkeyflower (*Erythranthe cardinalis*)

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Calibration curves by region

As a complement to logistic regressions, which require a threshold for habitat suitability but allow continuous examination of occupancy across latitude and elevation, we examined calibration curves, which are threshold-independent but require subdivision of sampling locations into latitudinal or elevational groups. We reasoned that decreased occupancy at a range margin would result in a lower intercept of the calibration curve compared to the range center. Specifically, we predicted that intercepts of the calibration curves for the central latitude and mid elevation groups would not differ from 0, while calibration curves for the northern and southern latitudinal groups or the low and high elevation groups could have intercepts significantly less than 0 (i.e. negative bias, indicating lower-than-expected occupancy, consistent with dispersal limitation).

Calibration curves showed lower occupancy in the north compared to the south and center. Intercepts for all five model types were significantly less than zero in the north (Table S3). This negative bias suggests that predicted probabilities of occurrence were generally too high compared to actual occupancy, and this was particularly apparent in high suitable sites (Fig. S5, S6). Except for the BRT and RF models, intercepts were not significantly different from 0 at the range center or in the south (Table S3), such that actual occupancy in these regions was better reflected by predicted probabilities of occurrence (Fig. S5, S6). In most cases, slopes were not significantly different from the expected value of one (Table S3).

Calibration curves showed lower occupancy at low and high elevation compared to the mid elevation range center. For all model types except MAX, intercepts were significantly less than zero at low elevation (suggesting predicted probabilities of occurrence were too high compared to actual occupancy), while for all model types except GLM, intercepts were significantly less than zero at high elevation (Table S3). For RF and BRT models, intercepts were also significantly less than zero at mid elevation, but to a lesser degree than at range edges (Table S3). Slopes were much greater than 1 for the MAX model (Table S3); the combination of negative bias and positive spread indicates that actual occupancy tended to be lower than predicted probability of occurrence for all but the highest predicted probabilities in the MAX model (Fig. S5). Inspection of the calibration curves revealed that the mid elevation range center tended to have higher observed probabilities of occurrence in sites with low suitability scores, and regions converged on similar observed probabilities in sites with higher suitability scores (Fig. S5, S6). Sites of high suitability were just as likely to be occupied at the range edges as at the range center, which agrees with logistic regressions for most models showing no significant variation in occupancy among sites above the suitability threshold. Thus, in contrast with Hargreaves et al. (2014), who found that sink populations were more likely at and beyond elevational range edges than at the range center, we conclude that populations at the elevation range center are more likely to spill over into unsuitable habitat (e.g., sink populations).

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Table S1. One-way ANOVA testing for variation in suitability among latitudinal or elevational regions. For all tests, numerator degrees of freedom = 2 and denominator degrees of freedom = 237. Model abbreviations are as follows: generalized linear models (GLM), generalized additive models (GAM), random forests (RF), boosted regression trees (BRT), and MaxEnt (MAX).

		GLM	GAM	RF	BRT	MAX
Latitude	F	12.23	14.69	11.79	14.77	11.31
	P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Elevation	F	21.80	21.72	27.18	23.03	38.80
	P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

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Table S2. Coefficient estimates and adjusted R^2 for quadratic regressions of predicted suitability vs. latitude or elevation. Model abbreviations are as follows: generalized linear models (GLM), generalized additive models (GAM), random forests (RF), boosted regression trees (BRT), and MaxEnt (MAX).

		GLM	GAM	RF	BRT	MAX
Presence	Latitude	6.5e-01	5.7e-01*	5.1e-01	4.9e-01.	1.7e-01*
	Latitude^2	-8.7e-03***	-7.7e-03***	-6.7e-03***	-6.6e-03***	-2.4e-03***
	Adj. R^2	0.27	0.26	0.11	0.12	0.17
Absence	Latitude	4.7e-01$^+$	3.8e-01**	3.8e-01$^+$	3.9e-01**	2.1e-01**
	Latitude^2	-6.2e-03***	-5.1e-03**	-5e-03**	-5.3e-03**	-2.8e-03**
	Adj. R^2	0.10	0.10	0.07	0.10	0.10
Presence	Elevation	3.8e-04	3.6e-04	4.2e-04	3.9e-04	2.2e-04
	Elevation^2	-2.1e-07***	-1.9e-07***	-2.5e-07***	-2.2e-07***	-1.2e-07***
	Adj. R^2	0.14	0.12	0.16	0.11	0.35
Absence	Elevation	1.3e-04***	7e-05***	3.3e-05***	1e-06***	2.7e-05***
	Elevation^2	-1.2e-07**	-9.9e-08*	-8.7e-08*	-8.3e-08	-5.6e-08*
	Adj. R^2	0.20	0.22	0.21	0.18	0.28

$^+P<0.10$; $^*P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$

Table S3. Parameters of calibration curves for models applied to regional groups of testing data. Significant deviations from slopes of 1 and intercepts of 0 were tested via likelihood ratio tests of deviance from models with and without constrained parameters. Model abbreviations are as follows: generalized linear models (GLM), generalized additive models (GAM), random forests (RF), boosted regression trees (BRT), and MaxEnt (MAX).

		GLM	GAM	RF	BRT	MAX
South	Slope	0.859	1.096	1.190	1.082	3.012*
	Intercept	0.263	0.042	-0.010	-0.730*	0.413
Center	Slope	1.363	1.382	0.863	0.579*	3.034**
	Intercept	-0.494	-0.515	-0.535**	-0.621***	0.157
North	Slope	0.569	0.775	1.01	0.663	1.988
	Intercept	-1.271***	-1.264***	-1.562***	-1.579***	-0.953***
Low	Slope	1.067	1.056	1.011	0.828	2.338^{+}
	Intercept	-0.623**	-0.687**	-0.944***	-1.243***	-0.251^{+}
Mid	Slope	0.773	1.069	0.782	0.539*	4.725***
	Intercept	-0.262	-0.408^{+}	-0.525**	-0.609***	-0.356
High	Slope	1.274	1.612	1.244	1.013	2.961**
	Intercept	-0.592^{+}	-0.732*	-0.689*	-1.091**	0.124

$^{+}$P<0.10; *P<0.05; **P<0.01; ***P<0.001; ****P<0.0001

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Table S4. Coefficient estimates and AIC values for logistic regressions of presence/absence vs. latitude or elevation across suitable sites. We compared models with and without quadratic terms, favoring the linear model unless ΔAIC > -2 (shown in bold). Model abbreviations are as follows: generalized linear models (GLM), generalized additive models (GAM), random forests (RF), boosted regression trees (BRT), and MaxEnt (MAX).

		Linear only		Linear + quadratic		
Factor	Model	Factor	AIC	Factor	$Factor^2$	AIC
Latitude	GLM	**-0.24*** **	**162.89**	3.19	-0.046^{+}	161.92
	GAM	-0.19**	186.70	**3.61***	**-0.050***	**183.93**
	RF	**-0.23** **	**145.18**	1.14	-0.018	146.60
	BRT	**-0.18** **	**194.62**	2.44^{+}	-0.035^{+}	193.24
	MAX	**-0.19** **	**183.57**	1.28	-0.020	184.89
Elevation	GLM	**0.00027**	**174.49**	0.0015	-6.84E-07	175.83
	GAM	**0.00063**$^{+}$	**192.82**	0.0032*	-1.52E-06^{+}	190.96
	RF	**0.00058**	**153.51**	0.0022	-1.05E-06	154.63
	BRT	0.00027	204.76	**0.0033***	**-1.80E-06***	**200.37**
	MAX	0.00062	190.04	**0.0035***	**-1.78E-06***	**187.88**

$^{+}P<0.10$; $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$

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Figure S1. Modeled suitability by latitudinal or elevational region. A) Generalized linear model (GLM) by latitudinal region. B) GLM by elevational region. C) Boosted regression tree model (BRT) by latitudinal region. D) BRT by elevational region. E) Maxent model (MAX) by latitudinal region. F) MAX by elevational region. Black bars show medians, grey bars show means, and notches approximate a 95% confidence interval around the median. Boxes give the interquartile range and whiskers give the most extreme value that is within 1.5x the interquartile. Regions with different lower-case letters are significantly different in post-hoc comparisons of means.

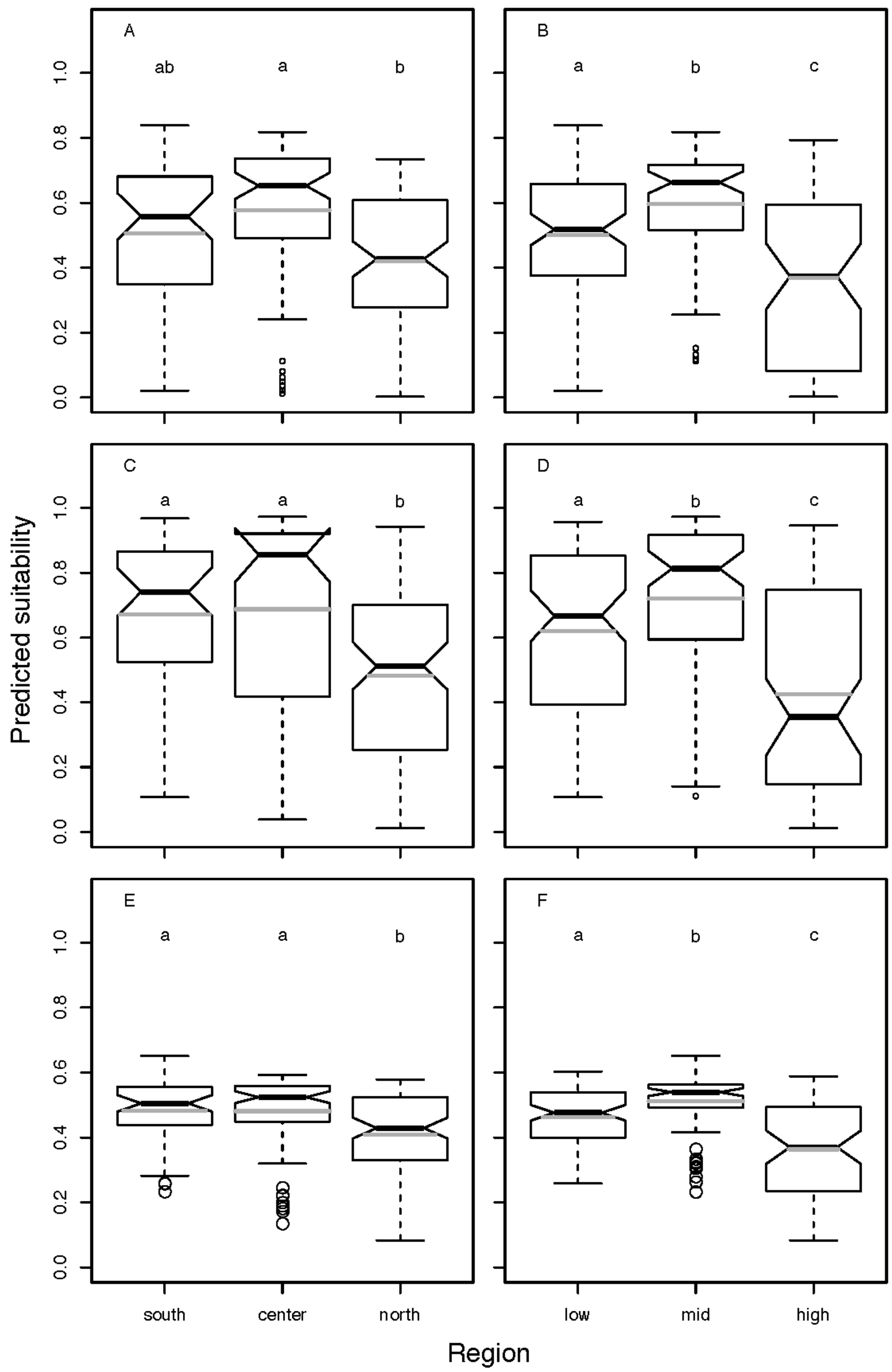

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Figure S2. Quadratic regressions of modeled suitability versus latitude (°N) and elevation (m). Panels display average scores across 10 replicate training models and best-fit lines for presences (filled symbols and solid lines) and absences (open symbols and dashed lines) from A) generalized linear models (GLM) versus latitude (°N), B) GLM versus elevation (m), C) boosted regression trees (BRT) versus latitude, D) BRT versus elevation, E) Maxent (MAX) versus latitude, and F) MAX versus elevation.

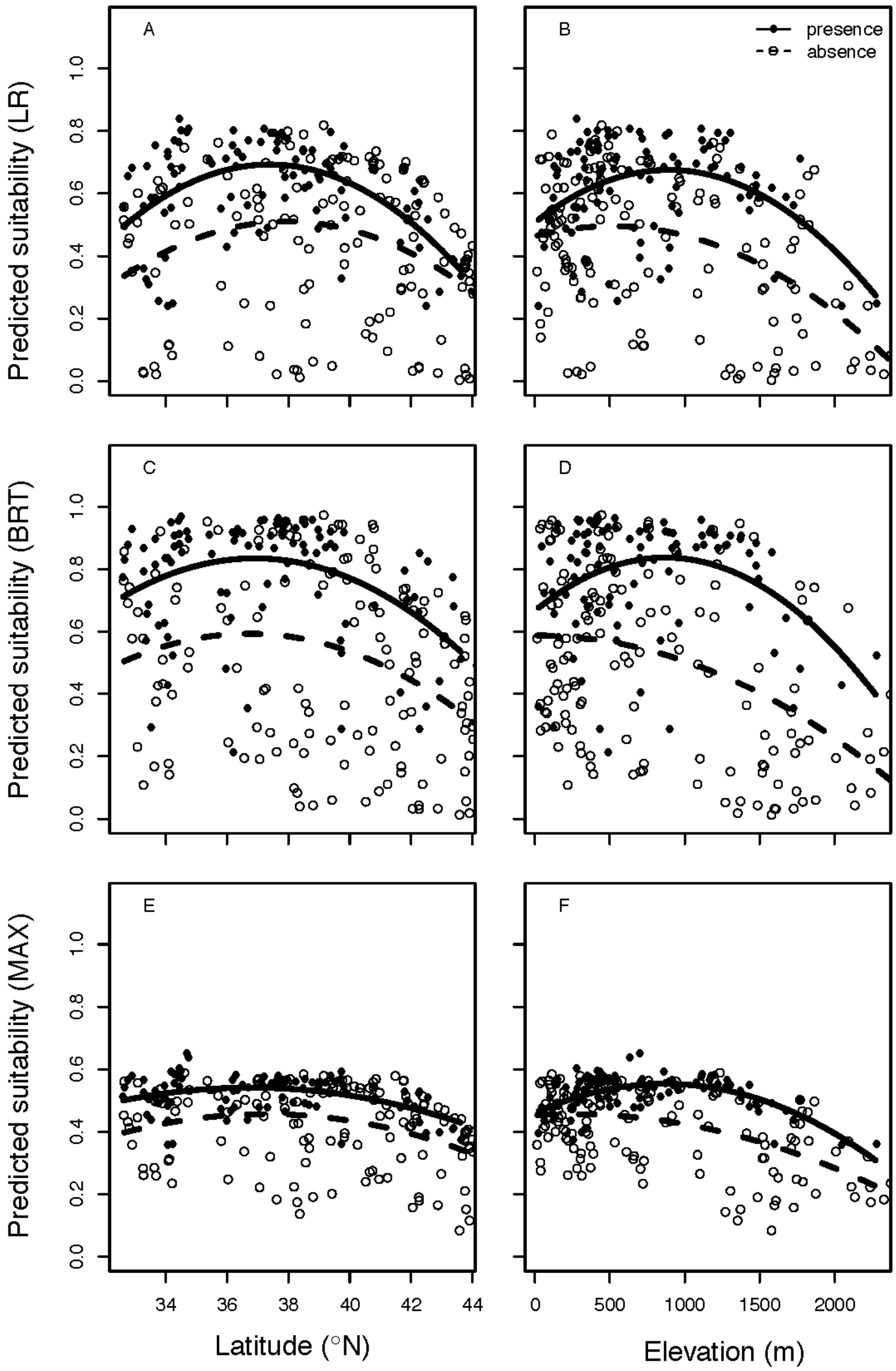

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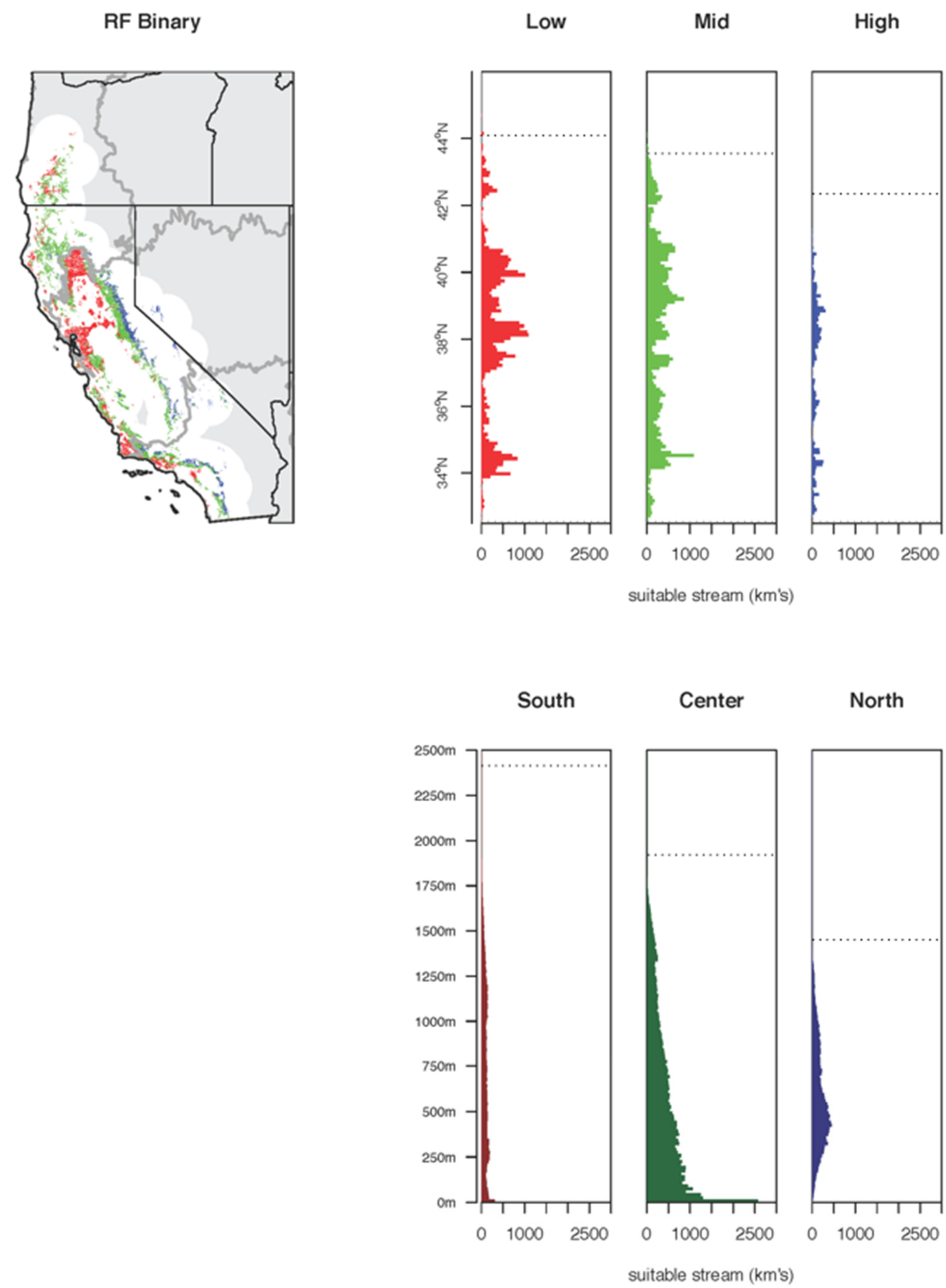
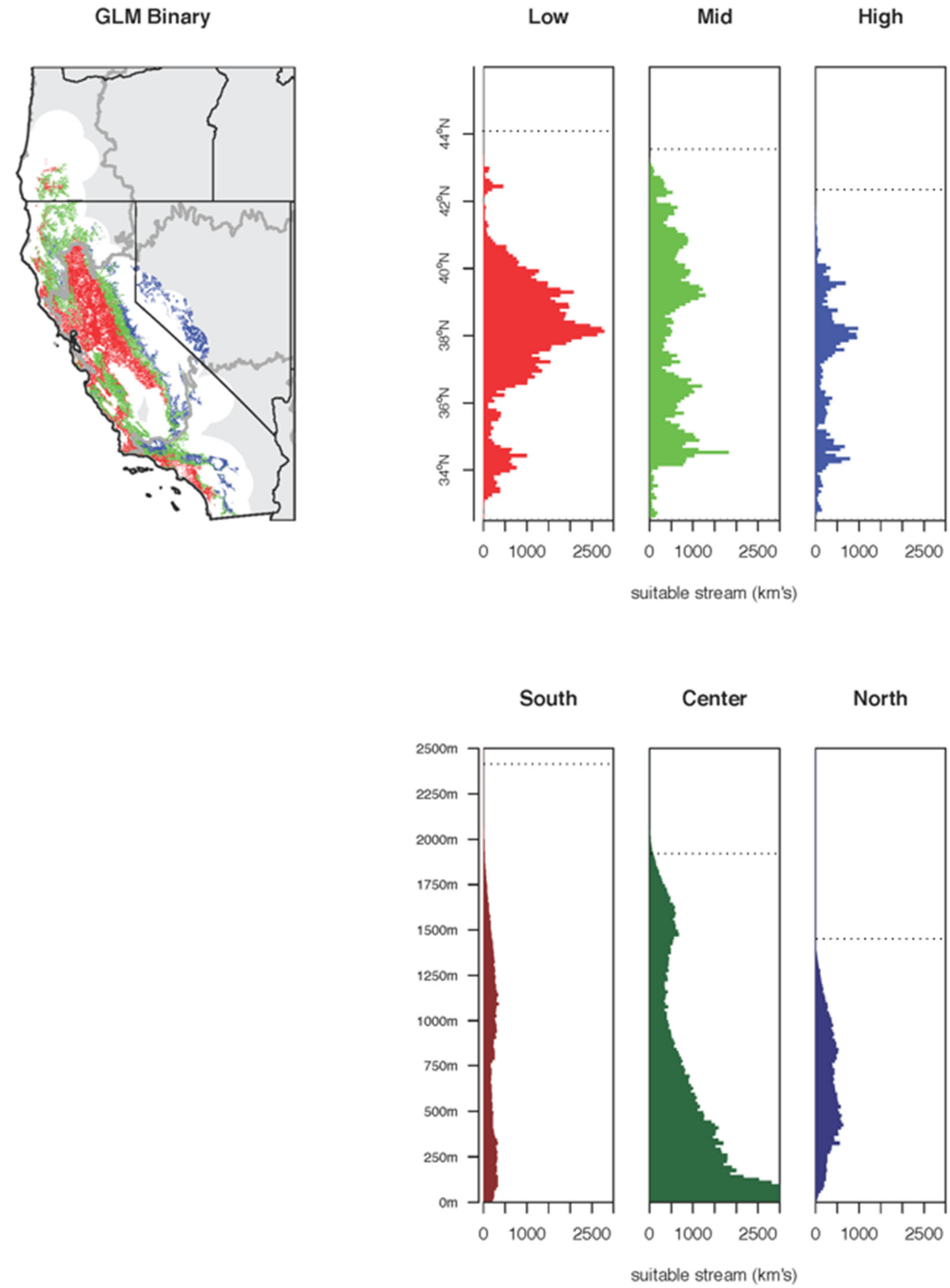
Figure S3. Histograms of climatically suitable stream habitat versus latitude (within each elevational group; top panels) or versus elevation (within each latitudinal group; bottom panels) for all models except GAM (which is shown in Fig. 4). Maps depict climatically suitable habitat within low (red), mid (green), and high (blue) elevation categories. Mapped projections and sums of suitable habitat are limited to a spatial extent of 80km from presence records (shown as white polygon).




GLM Binary
Low
Mid
High
44°N
42°N
40°N
38°N
36°N
34°N
0
1000
2500
suitable stream (km's)
South
Center
North
2500m
2250m
2000m
1750m
1500m
1250m
1000m
750m
500m
250m
0m
0
1000
2500
suitable stream (km's)

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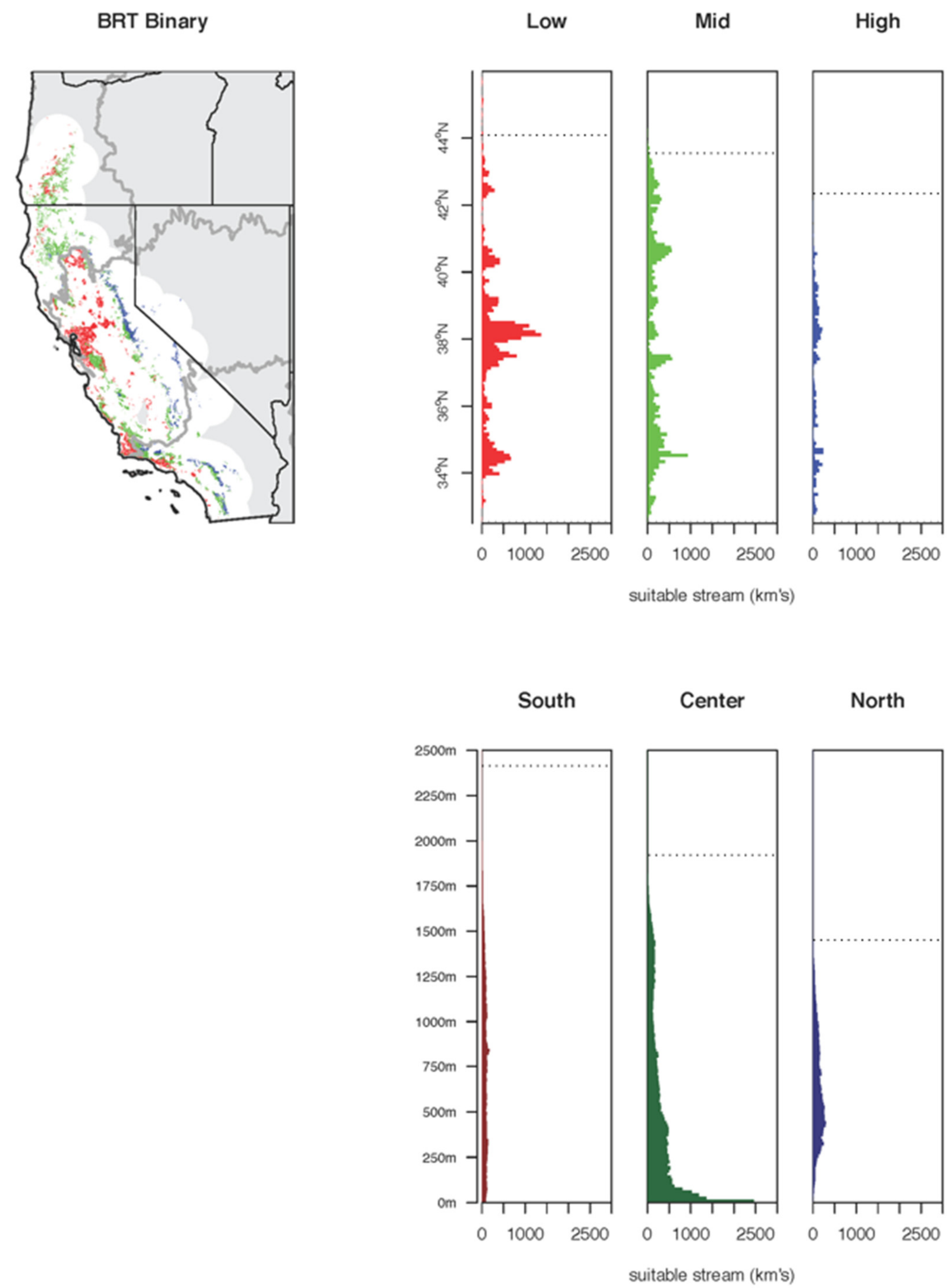

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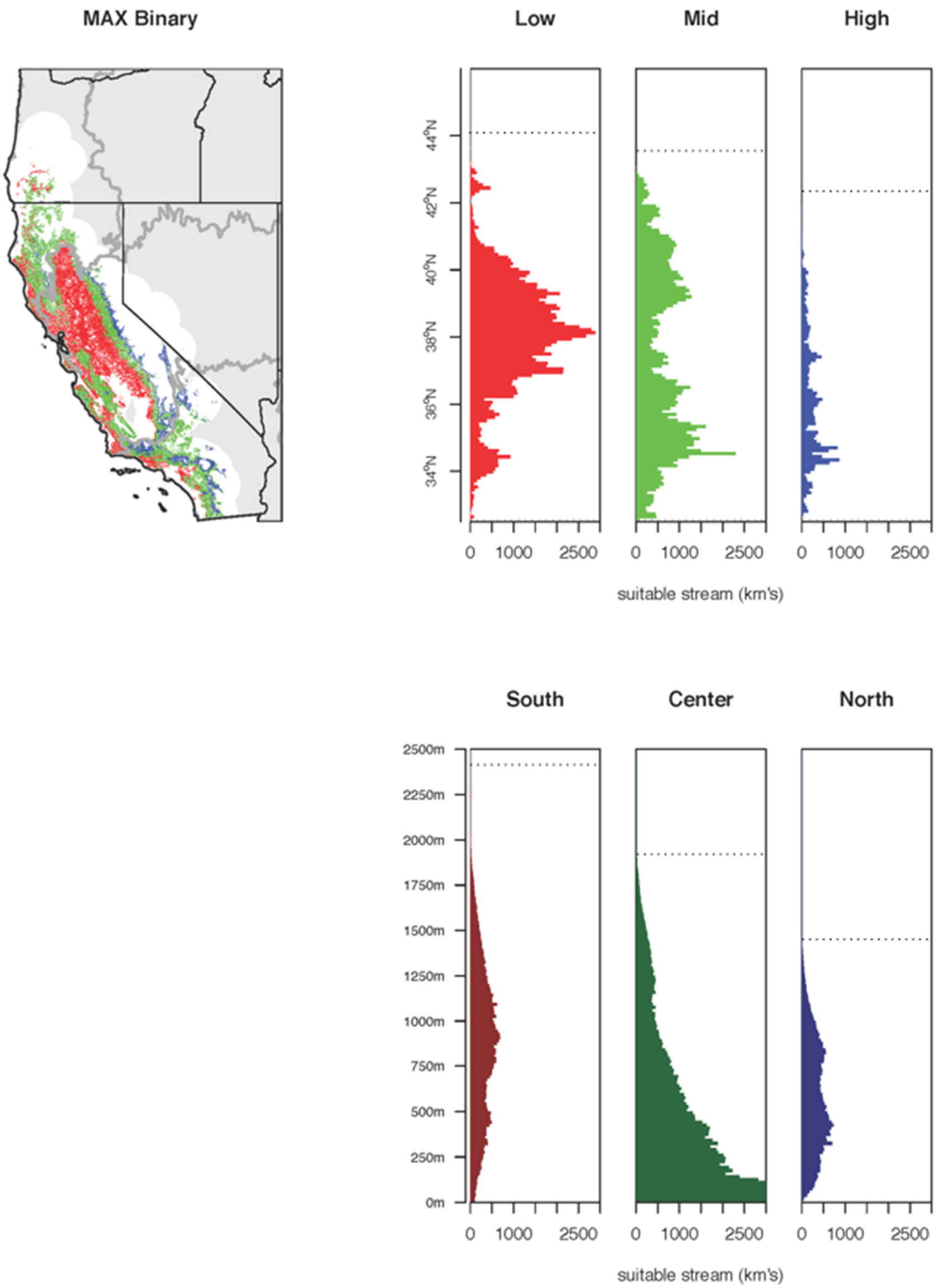

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Figure S4. Relative degree of environmental novelty in both (a) univariate and (b) multivariate environmental space. For each grid cell, environmental novelty was calculated following methods outlined in Mesgaran et al. (2014). Univariate novelty is 0 when values of all predictor variables for a given grid cell are within the univariate ranges of all predictor variables across the training data. Negative values indicate that values of at least some predictor variables fall outside the univariate range of the training data; increasingly negative values arise when this happens for many variables &/or to a greater degree per variable. Multivariate environmental novelty is based on Mahalanobis distance to the edge of the multivariate distribution of the training data. Multivariate novelty is 0 when the values of all predictor variables for a given grid cell fall within the correlation structure of the training data. Positive values indicate that values of the predictor variables exhibit different correlation structure, with values greater than one considered to be significantly novel in multivariate space. Thus, in each panel red indicates greater environmental novelty from the training data.

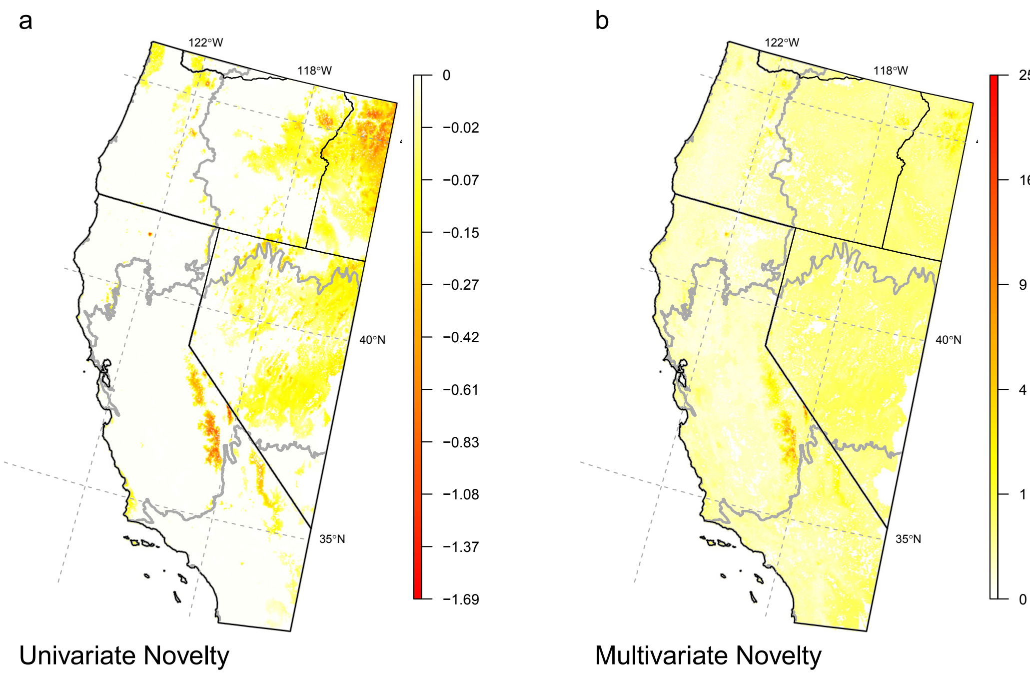

Figure S5. Calibration curves for A) generalized additive model (GAM) by latitudinal region, B) GAM by elevational region, C) random forests model (RF) by latitudinal region, and D) RF by elevational region. Blue = northern and high elevation groups, green = central and mid elevation groups, red = southern and low elevation groups. Dashed line shows expected curve for a perfectly calibrated model.

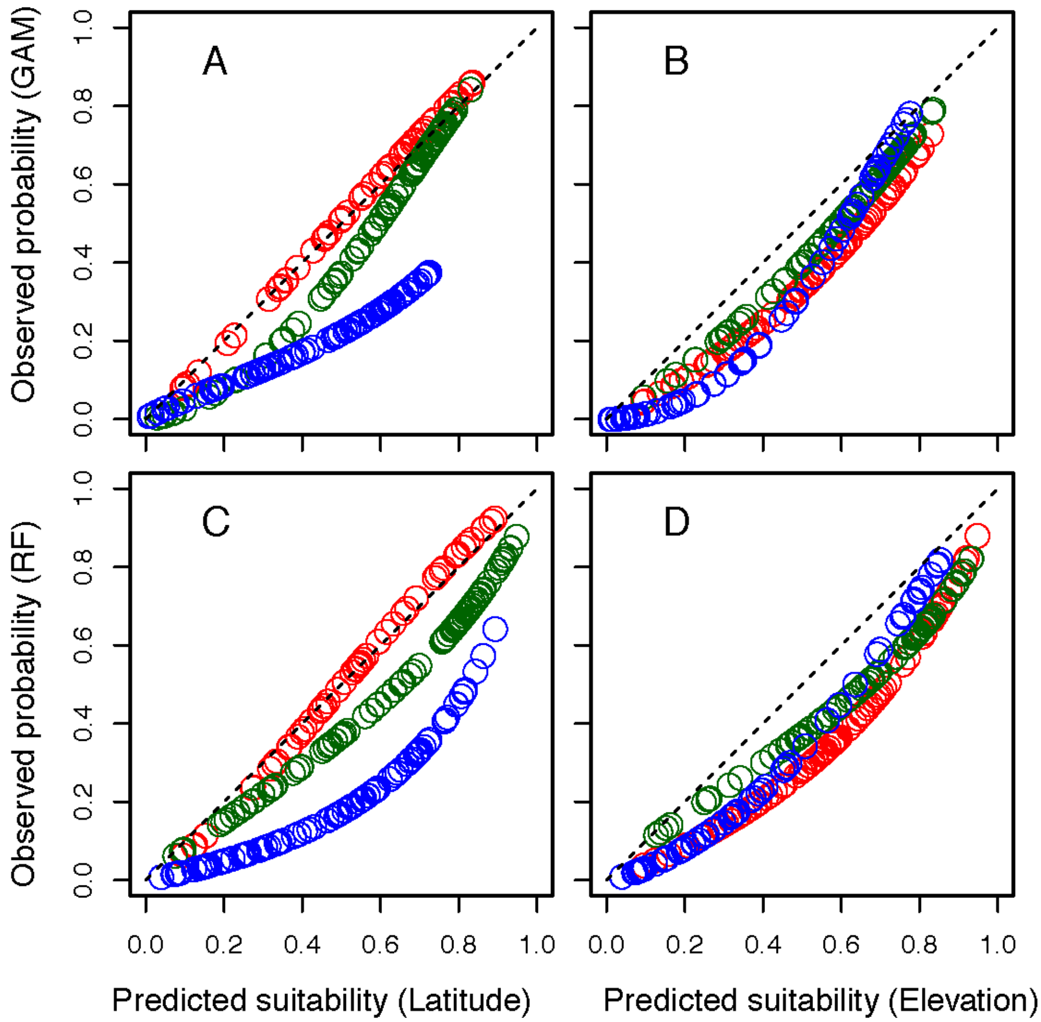

Figure S6. Calibration curves for A) generalized linear model (GLM) by latitudinal region, B) GLM by elevational region, C) boosted regression tree (BRT) by latitudinal region, D) BRT by elevational region, E) Maxent (MAX) by latitudinal region, and F) MAX by elevational region. Blue = northern and high elevation groups, green = central and mid elevation groups, red = southern and low elevation groups. Dashed line shows expected curve for a perfectly calibrated model.

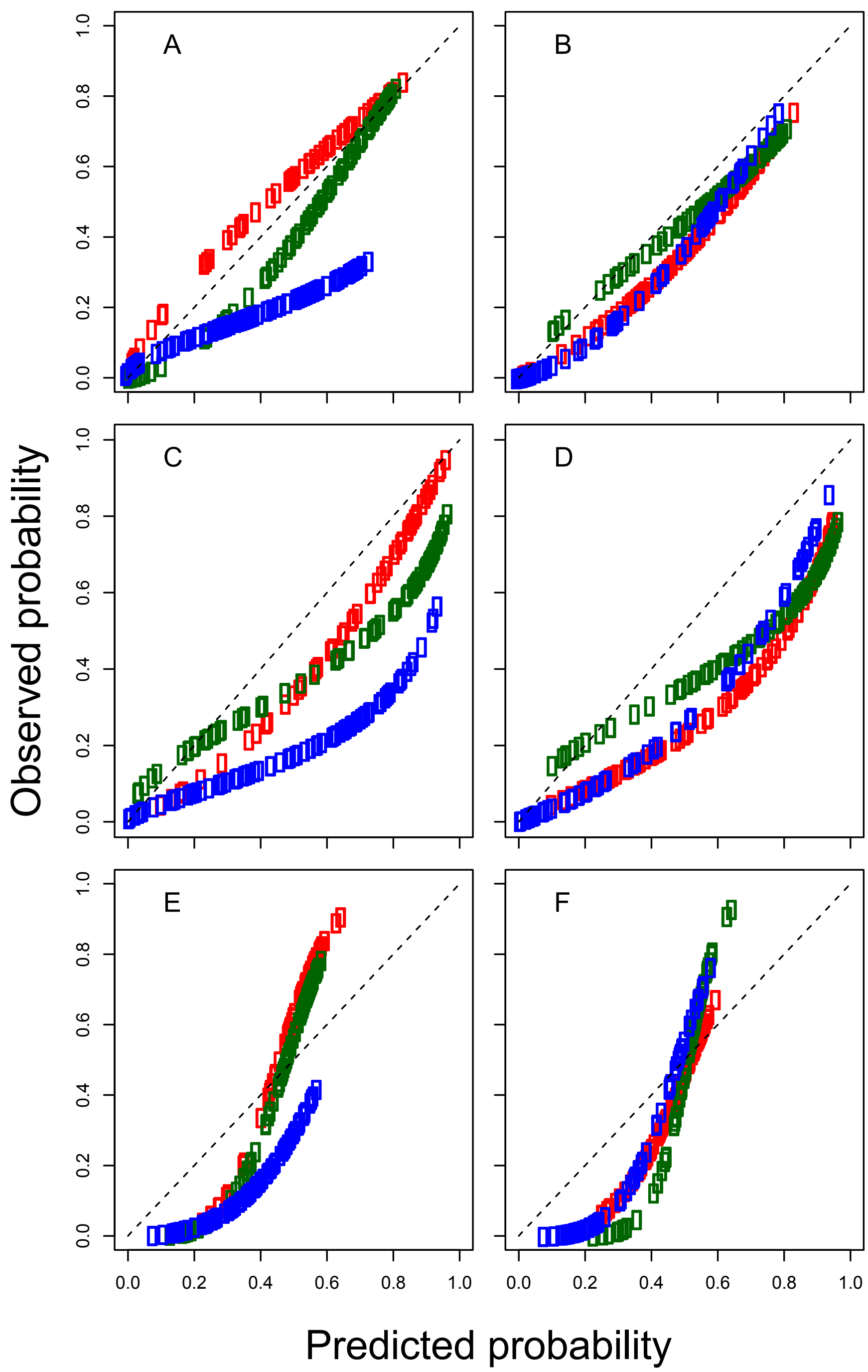

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Figure S7. Logistic regressions of occurrence in suitable sites versus range position for A) generalized linear model (GLM) across latitude, B) GLM across elevation, C) boosted regression tree (BRT) across latitude, D) BRT across elevation, E) Maxent (MAX) across latitude, and F) MAX across elevation. Dots depict testing data points above the suitability threshold in each model. Fitted lines show predicted probability of occurrence from best-fit models (black lines for models where linear or quadratic terms had $P<0.05$; grey lines for models with non-significant terms).