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Supplementary material

Appendix 1

ENVIREM: An expanded set of bioclimatic and topographic variables increases flexibility and improves performance of ecological niche modeling

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Table A1. Specific bioclimatic variables that had the strongest correlation in the present with any of the ENVIREM variables (Table 2), within each biogeographic realm and globally. Descriptions of the WorldClim bioclimatic variables can be found in Table 4 or Table A2.

	neotropical	palaearctic	nearctic	indo-malay	afrotropic	oceania	australasia	global
annualPET	bio 1	bio 10	bio 1	bio 1	bio 5	bio 9	bio 10	bio 1
aridityIndexThornthwaite	bio 17	bio 12	bio 18	bio 15	bio 17	bio 18	bio 12	bio 17
climaticMoistureIndex	bio 12	bio 2	bio 2	bio 12	bio 12	bio 12	bio 12	bio 12
continentality	bio 4	bio 4	bio 4	bio 4	bio 4	bio 4	bio 4	bio 4
embergerQ	bio 12	bio 12	bio 12	bio 12	bio 12	bio 12	bio 12	bio 12
growingDegDays0	bio 1	bio 1	bio 1	bio 1	bio 1	bio 1	bio 1	bio 1
growingDegDays5	bio 1	bio 1	bio 1	bio 1	bio 1	bio 1	bio 1	bio 1
maxTempColdest	bio 11	bio 11	bio 11	bio 11	bio 11	bio 9	bio 11	bio 11
minTempWarmest	bio 10	bio 10	bio 10	bio 10	bio 10	bio 10	bio 10	bio 10
monthCountByTemp10	bio 10	bio 10	bio 1	bio 1	bio 11	bio 5	bio 1	bio 1
PETColdestQuarter	bio 11	bio 3	bio 3	bio 11	bio 11	bio 9	bio 11	bio 11
PETDriestQuarter	bio 9	bio 9	bio 9	bio 9	bio 9	bio 18	bio 9	bio 9
PETseasonality	bio 4	bio 5	bio 5	bio 7	bio 4	bio 3	bio 4	bio 7
PETWarmestQuarter	bio 5	bio 5	bio 5	bio 5	bio 5	bio 5	bio 2	bio 5
PETWettestQuarter	bio 8	bio 8	bio 8	bio 8	bio 8	bio 2	bio 8	bio 8
thermicityIndex	bio 1	bio 10	bio 10	bio 11	bio 1	bio 1	bio 11	bio 1

Table S2. Pearson correlation coefficients between each of the climatic ENVIREM variables and the WorldClim bioclimatic variable with which the ENVIREM variable is most strongly correlated (Table S1), globally and in separate biogeographic realms. For each variable and realm, the bottom-left triangle contains the correlation coefficient in the present, and the top-right triangle contains the correlation coefficient in the mid-Holocene (CCSM4) for the same bioclimatic variable. Grey shading indicates that the absolute value of the correlation is ≤ 0.85 .

	neotropical		paleartic		nearctic		indo-malay		afrotropic		oceania		australasia		global	
annualPET	0.88	0.88	0.94	0.93	0.96	0.96	0.8	0.79	0.9	0.86	0.83	0.87	0.94	0.93	0.91	0.91
aridityIndexThornthwaite	-0.84	-0.85	-0.78	-0.74	-0.73	-0.73	0.89	0.88	-0.83	-0.81	-0.8	-0.86	-0.91	-0.9	-0.81	-0.81
climaticMoistureIndex	0.93	0.93	-0.82	-0.8	-0.59	-0.59	0.91	0.9	0.98	0.98	0.89	0.9	0.95	0.95	0.81	0.81
continentality	1	1	1	1	0.99	0.99	0.99	0.99	0.99	0.99	1	0.99	1	1	1	1
embergerQ	0.95	0.95	0.91	0.92	0.94	0.94	0.88	0.88	0.94	0.93	0.92	0.92	0.97	0.97	0.93	0.92
growingDegDays0	1	1	0.93	0.92	0.89	0.88	1	1	1	1	1	1	1	1	0.97	0.97
growingDegDays5	1	1	0.91	0.9	0.85	0.84	1	0.99	1	1	1	1	1	1	0.96	0.96
maxTempColdest	0.98	0.98	1	1	1	1	0.97	0.97	0.92	0.92	0.98	0.98	0.97	0.96	1	1
minTempWarmest	0.98	0.98	0.99	0.99	0.98	0.97	0.96	0.93	0.96	0.94	1	1	0.96	0.96	0.98	0.97
monthCountByTemp10	0.87	0.87	0.95	0.94	0.93	0.92	0.74	0.79	0.49	0.58	0.62	0.73	0.7	0.74	0.95	0.95
PETColdestQuarter	0.93	0.93	0.87	0.87	0.87	0.88	0.91	0.92	0.82	0.79	0.58	0.43	0.93	0.92	0.9	0.89
PETDriestQuarter	0.83	0.84	0.92	0.92	0.87	0.86	0.89	0.85	0.84	0.8	-0.74	-0.8	0.74	0.71	0.87	0.87
PETseasonality	0.98	0.97	0.73	0.75	0.91	0.93	0.97	0.97	0.93	0.91	-0.76	-0.62	0.96	0.95	0.7	0.69
PETWarmestQuarter	0.74	0.75	0.98	0.97	0.99	0.99	0.94	0.93	0.84	0.8	0.84	0.82	0.94	0.94	0.91	0.9
PETWettestQuarter	0.79	0.8	0.89	0.89	0.95	0.95	0.68	0.66	0.62	0.45	-0.82	-0.82	0.91	0.89	0.83	0.81
thermicityIndex	1	1	0.98	0.98	0.98	0.98	0.96	0.97	0.99	0.98	1	1	0.97	0.97	0.98	0.98

Table A3. ENVIREM and WorldClim variables included in the *bioclim*, *bioclim + envirem-clim* and *bioclim + envirem-all* models, for 16 case study species not presented in the main text. Variables to include in each model were selected using a statistical variable selection approach (see Methods section for additional details).

	<i>Arborimus longicaudus</i> bioclim	<i>Arborimus longicaudus</i> bioclim + envirem-clim	<i>Arborimus longicaudus</i> bioclim + envirem-all	<i>Blarina brevicauda</i> bioclim	<i>Blarina brevicauda</i> bioclim + envirem-clim	<i>Blarina brevicauda</i> bioclim + envirem-all	<i>Chamaea fasciata</i> bioclim	<i>Chamaea fasciata</i> bioclim + envirem-clim	<i>Chamaea fasciata</i> bioclim + envirem-all	<i>Crotalus atrox</i> bioclim	<i>Crotalus atrox</i> bioclim + envirem-clim	<i>Crotalus atrox</i> bioclim + envirem-all	<i>Desmognathus wrighti</i> bioclim	<i>Desmognathus wrighti</i> bioclim + envirem-clim	<i>Desmognathus wrighti</i> bioclim + envirem-all	<i>Dicamptodon tenebrosus</i> bioclim	<i>Dicamptodon tenebrosus</i> bioclim + envirem-clim	<i>Dicamptodon tenebrosus</i> bioclim + envirem-all	<i>Dicrostonyx groenlandicus</i> bioclim	<i>Dicrostonyx groenlandicus</i> bioclim + envirem-clim	<i>Dicrostonyx groenlandicus</i> bioclim + envirem-all	<i>Elaphe obsoleta</i> bioclim	<i>Elaphe obsoleta</i> bioclim + envirem-clim	<i>Elaphe obsoleta</i> bioclim + envirem-all	
annual mean temp [bio1]																									
mean diurnal temp range [bio2]	+			+			+	+	+	+			+	+	+							+	+	+	
isothermality [bio3]	+	+	+	+	+	+	+	+	+																
temp seasonality [bio4]										+						+						+			
max temp warmest month [bio5]	+												+	+	+				+						
min temp coldest month [bio6]	+	+	+				+	+	+																
temp annual range [bio7]				+	+	+													+	+	+				
mean temp of wettest quarter [bio8]	+			+			+			+	+	+	+	+	+	+						+	+	+	
mean temp of driest quarter [bio9]	+	+	+							+	+	+										+	+	+	
mean temp of warmest quarter [bio10]				+						+	+	+										+	+	+	
mean temp of coldest quarter [bio11]				+	+	+																			
annual precip [bio12]																									
precip of wettest month [bio13]																						+			
precip of driest month [bio14]							+	+	+				+	+	+										
precip seasonality [bio15]	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+				
precip of wettest quarter [bio16]										+	+	+													
precip of driest quarter [bio17]		+	+													+						+	+	+	
precip of warmest quarter [bio18]	+	+	+				+	+	+				+	+	+	+	+	+	+	+	+				
precip of coldest quarter [bio19]	+	+	+				+	+	+	+						+	+	+	+	+	+				
annualPET																									
climaticMoistureIndex																									
continentality																									
embergerQ																									
growingDegDays0																									
growingDegDays5																									
maxTempColdest																									
minTempWarmest																									
PETColdestQuarter		+	+																						
PETDriestQuarter																									
PETseasonality																									
PETWarmestQuarter																									
PETWettestQuarter		+	+																						
thermicityIndex																									
topoRoughness																									
topoWetness			+			+																			+

Table A4. Optimized Maxent parameters for all 20 case study species, using AUC and AICc. The possible feature classes are linear (L), quadratic (Q), hinge (H), product (P) and threshold (T). The regularization multiplier (RM) controls the complexity of the model.

Species	Variable Set	AUC		AICc	
		Feature Class	RM	Feature Class	RM
<i>Ambystoma maculatum</i>	bioclim	LQH	2.5	LQHPT	3
	bioclim + envirem-clim	LQHP	2.5	LQHPT	3
	bioclim + envirem-all	LQHP	1	LQHP	3.5
<i>Dendragapus obscurus</i>	bioclim	H	2.5	LQHPT	2
	bioclim + envirem-clim	LQ	2.5	LQHP	4
	bioclim + envirem-all	LQHP	0.5	LQHP	4
<i>Poliophtila californica</i>	bioclim	L	4	LQ	2
	bioclim + envirem-clim	LQHP	4	LQHP	4
	bioclim + envirem-all	LQHP	4	LQHP	4
<i>Poecile gambeli</i>	bioclim	H	2	LQHPT	4
	bioclim + envirem-clim	LQ	3	LQ	2
	bioclim + envirem-all	LQ	1	LQ	2
<i>Arborimus longicaudus</i>	bioclim	LQH	0.5	LQ	0.5
	bioclim + envirem-clim	H	1	LQHP	2
	bioclim + envirem-all	H	1.5	LQHPT	2
<i>Blarina brevicauda</i>	bioclim	H	2	LQHPT	1
	bioclim + envirem-clim	H	2.5	LQHPT	1
	bioclim + envirem-all	H	2	LQHPT	1
<i>Chamaea fasciata</i>	bioclim	LQHPT	3.5	LQHP	3
	bioclim + envirem-clim	LQH	3	LQHP	4
	bioclim + envirem-all	LQHP	4	LQHPT	3.5
<i>Crotalus atrox</i>	bioclim	H	2.5	LQHP	4
	bioclim + envirem-clim	LQH	4	LQ	2
	bioclim + envirem-all	LQHPT	3.5	LQ	2.5
<i>Desmognathus wrighti</i>	bioclim	LQH	1	LQH	2
	bioclim + envirem-clim	LQ	0.5	LQ	1.5
	bioclim + envirem-all	LQH	2	LQ	2
<i>Dicamptodon tenebrosus</i>	bioclim	H	4	LQ	1
	bioclim + envirem-clim	LQH	3	LQ	1
	bioclim + envirem-all	LQH	3	LQ	1
<i>Dicrostonyx groenlandicus</i>	bioclim	H	1	LQ	0.5
	bioclim + envirem-clim	H	1	LQ	0.5
	bioclim + envirem-all	H	1.5	LQ	1
<i>Elaphe obsoleta</i>	bioclim	H	4	LQHPT	1.5
	bioclim + envirem-clim	H	4	LQHPT	2.5
	bioclim + envirem-all	LQHP	4	LQHPT	1.5
<i>Eumeces fasciatus</i>	bioclim	LQ	3	LQHPT	2
	bioclim + envirem-clim	L	4	LQH	3.5
	bioclim + envirem-all	L	4	LQ	2.5
<i>Glaucmys sabrinus</i>	bioclim	LQH	4	LQHP	3
	bioclim + envirem-clim	LQHPT	1	LQHPT	2.5
	bioclim + envirem-all	LQHPT	1	LQHPT	3
<i>Glaucmys volans</i>	bioclim	H	4	LQHPT	2
	bioclim + envirem-clim	LQHP	0.5	LQHPT	1
	bioclim + envirem-all	LQHP	1	LQHP	4
<i>Lampropeltis zonata</i>	bioclim	LQHP	3.5	LQ	2.5
	bioclim + envirem-clim	LQHP	4	LQHPT	3.5
	bioclim + envirem-all	LQHP	4	LQ	3.5
<i>Lepus arcticus</i>	bioclim	LQHP	4	LQ	1
	bioclim + envirem-clim	H	4	LQ	2
	bioclim + envirem-all	H	0.5	LQ	4
<i>Martes americana</i>	bioclim	LQHP	3.5	LQHPT	2.5
	bioclim + envirem-clim	LQ	1	LQHPT	4
	bioclim + envirem-all	LQHPT	3	LQHPT	4
<i>Myodes gapperi</i>	bioclim	LQHP	1.5	LQHPT	1
	bioclim + envirem-clim	LQHPT	1	LQHPT	1.5
	bioclim + envirem-all	LQHPT	1	LQHPT	1
<i>Plethodon idahoensis</i>	bioclim	H	3	LQ	0.5
	bioclim + envirem-clim	H	4	LQ	1
	bioclim + envirem-all	H	4	LQ	1

Table A5. Schoener's *D* niche overlap for all case study species, between the *bioclim* and *bioclim + envirement-clim* models, in both the present and during the LGM with three GCMs.

Species	Schoener's <i>D</i>			
	Current	LGM CCSM4	LGM MPI-ESM-P	LGM MIROC-ESM
<i>Ambystoma maculatum</i>	0.914	0.841	0.755	0.892
<i>Arborimus longicaudus</i>	0.879	0.612	0.475	0.550
<i>Blarina brevicauda</i>	0.940	0.782	0.795	0.771
<i>Chamaea fasciata</i>	0.974	0.964	0.970	0.973
<i>Crotalus atrox</i>	0.929	0.755	0.886	0.746
<i>Dendragapus obscurus</i>	0.927	0.786	0.790	0.829
<i>Desmognathus wrighti</i>	0.824	0.257	0.178	0.415
<i>Dicamptodon tenebrosus</i>	0.962	0.926	0.846	0.859
<i>Dicrostonyx groenlandicus</i>	0.923	0.771	0.794	0.720
<i>Elaphe obsoleta</i>	0.926	0.860	0.833	0.842
<i>Eumeces fasciatus</i>	0.933	0.812	0.774	0.804
<i>Glaucomys sabrinus</i>	0.882	0.684	0.765	0.661
<i>Glaucomys volans</i>	0.883	0.600	0.645	0.621
<i>Lampropeltis zonata</i>	0.882	0.774	0.862	0.858
<i>Lepus arcticus</i>	0.955	0.885	0.899	0.897
<i>Martes americana</i>	0.899	0.777	0.756	0.732
<i>Myodes gapperi</i>	0.901	0.621	0.674	0.530
<i>Plethodon idahoensis</i>	0.909	0.008	0.015	0.018
<i>Poecile gambeli</i>	0.871	0.733	0.542	0.793
<i>Polioptila californica</i>	0.868	0.849	0.890	0.843

Figure A1. Occurrence records and training regions for the 20 case study species (occurrence records from Waltari *et al.* 2007).

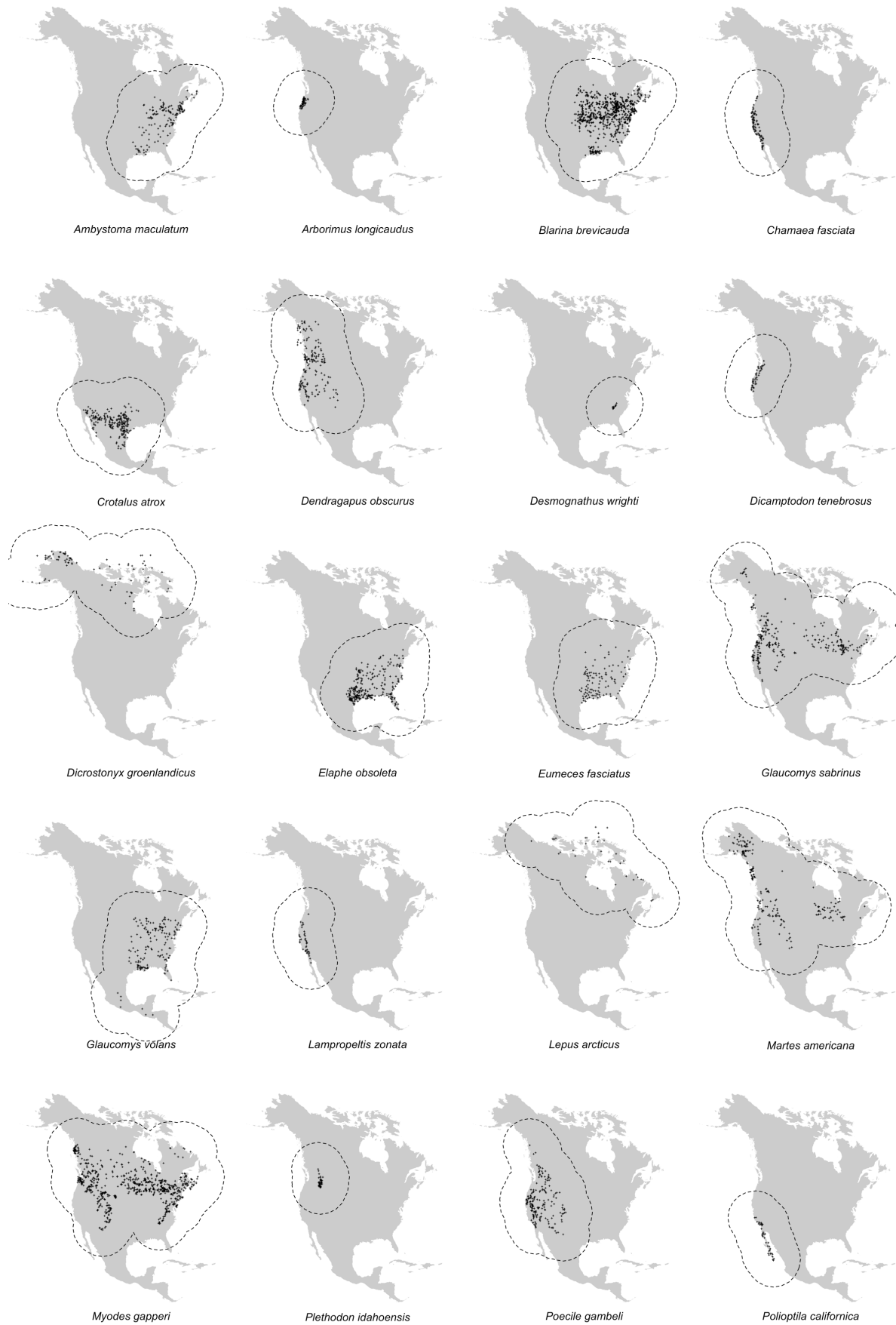


Figure A2. Model performance with and without the ENVIREM variables for 16 case study species not highlighted in the main text. Each line represents the set of feature classes that led to the best performance according to either AUC_{TEST} (top and middle panels) or AIC_c (bottom panel), with performance evaluated across a range of regularization multiplier values. AUC_{DIFF} is a measure of model overfitting for the model selected by maximizing AUC_{TEST} . In the AUC plots, the dotted line represents the value for the best-performing model. In the AIC_c plots, the grey shading represents a ΔAIC_c of 4 from the best (lowest) AIC_c score. Performance of models within the grey polygon is not considered to be substantially different (Burnham and Anderson 2004).

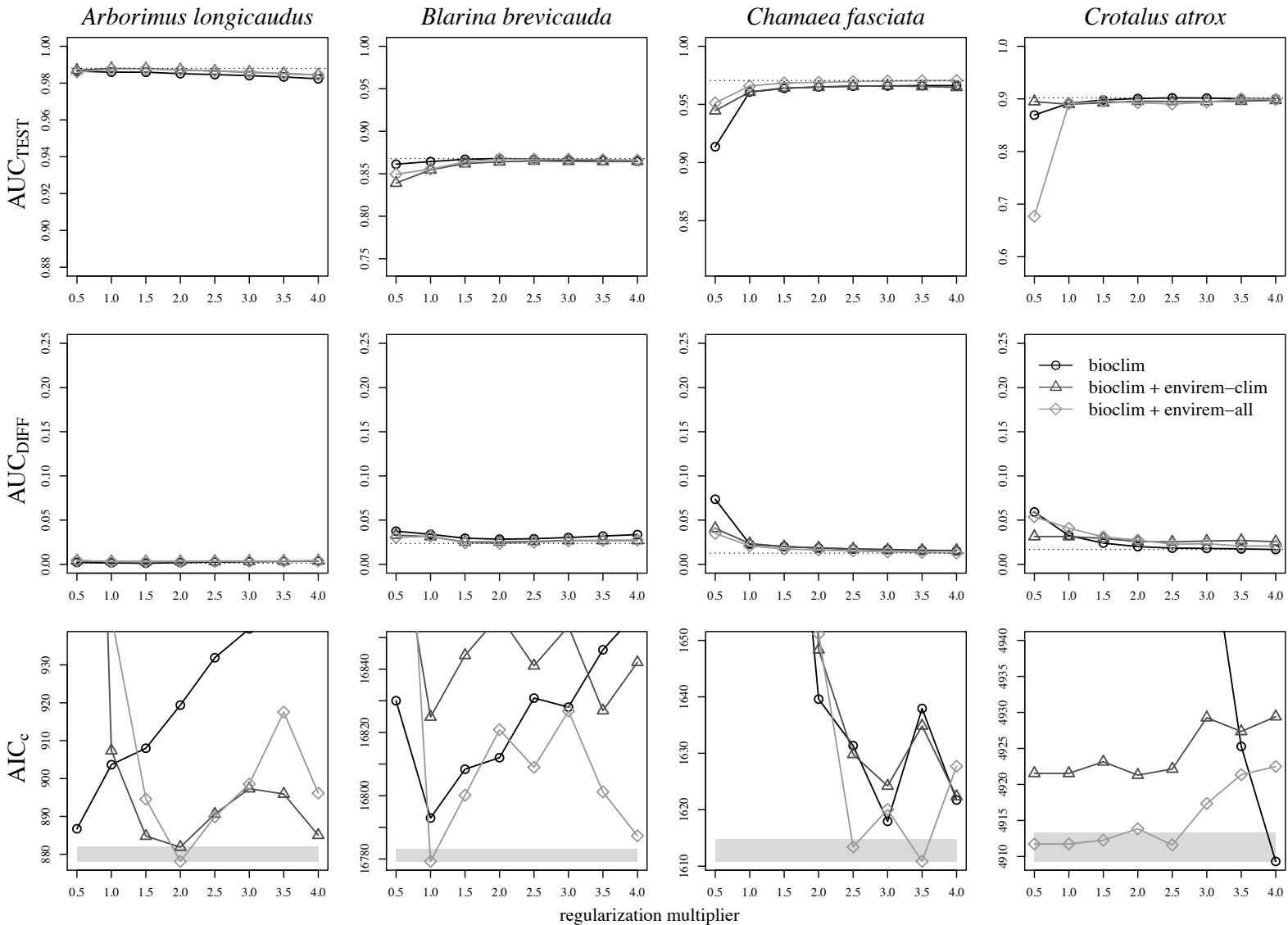


Figure A2. Continued.

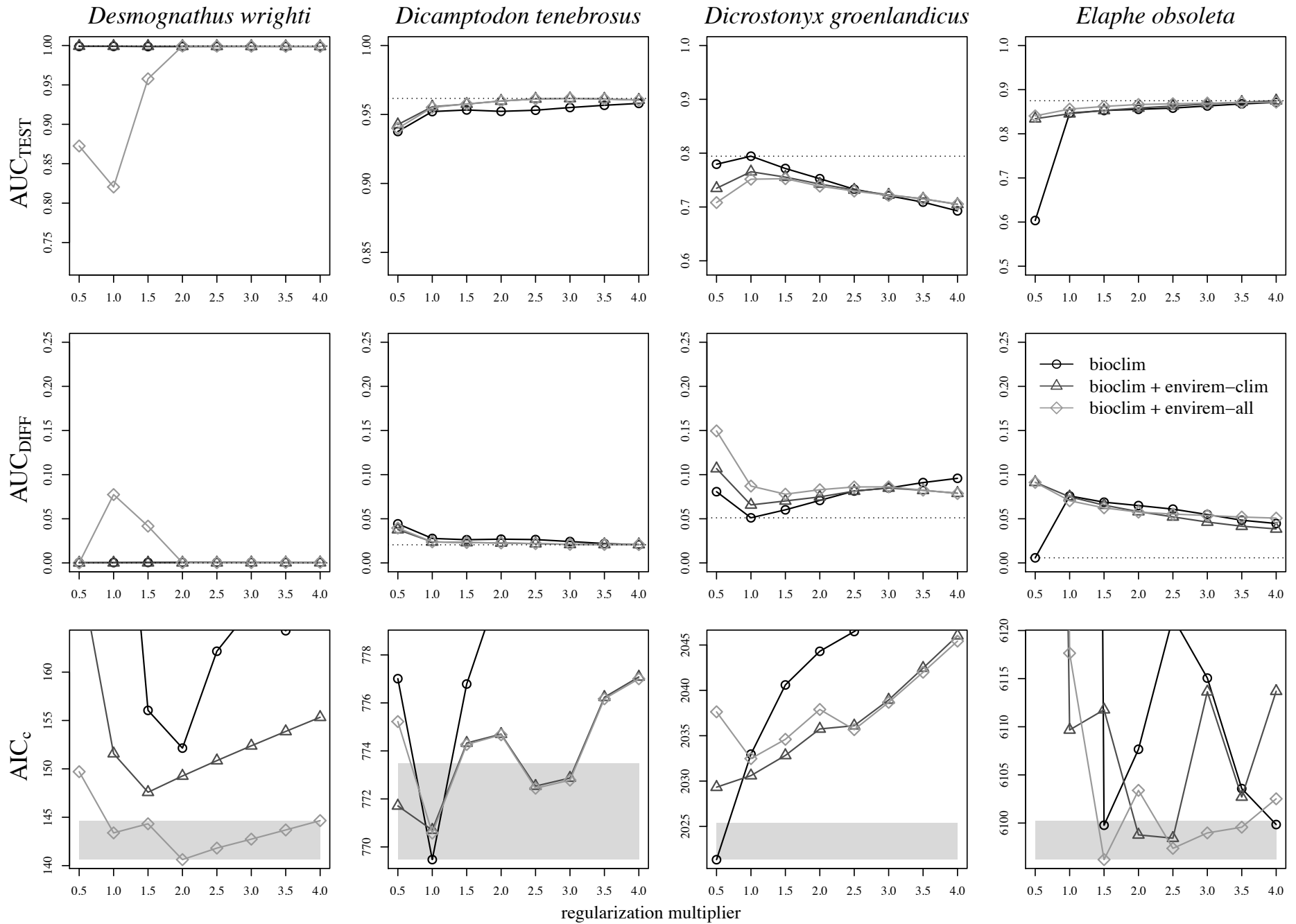


Figure A2. Continued.

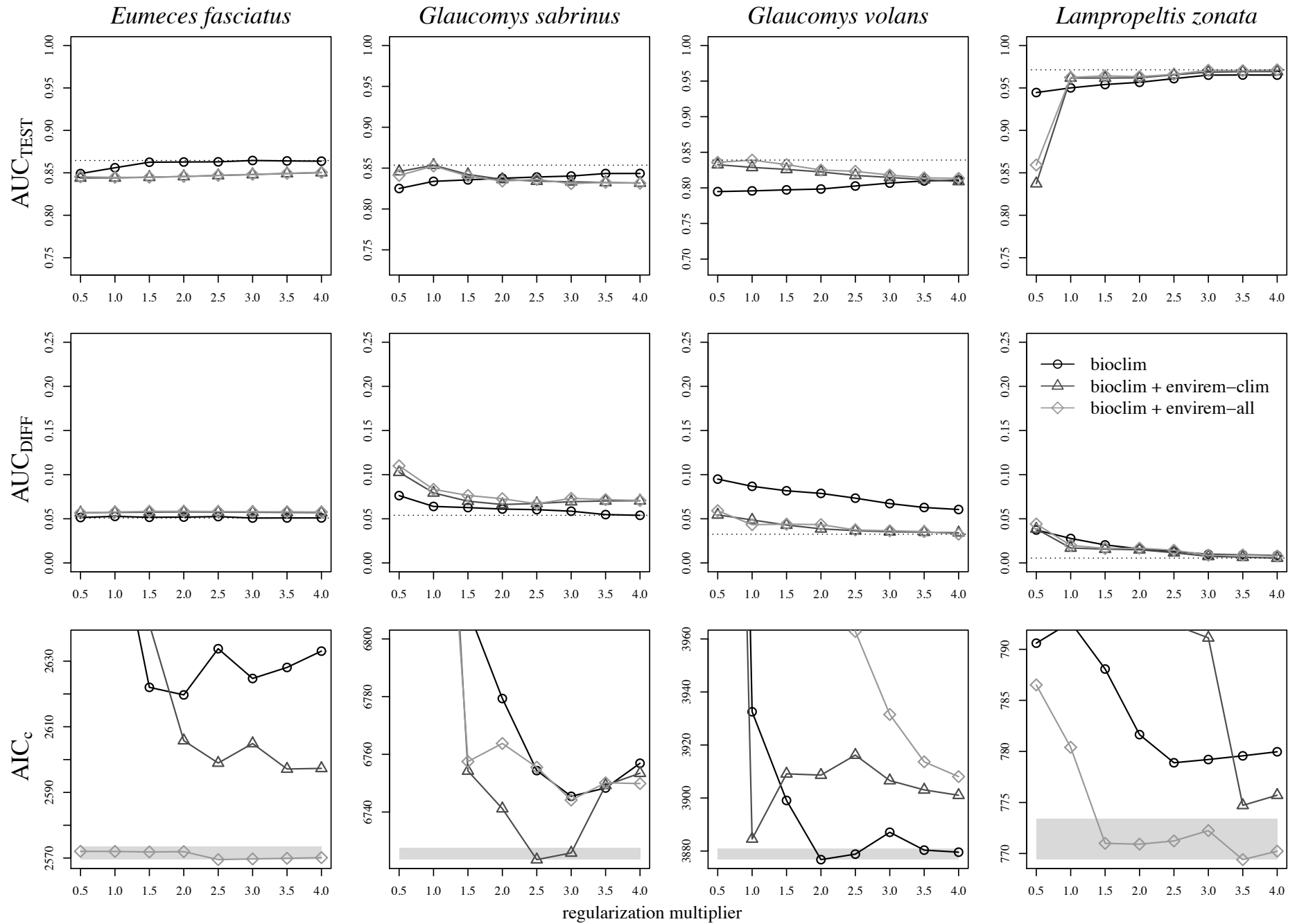


Figure A2. Continued.

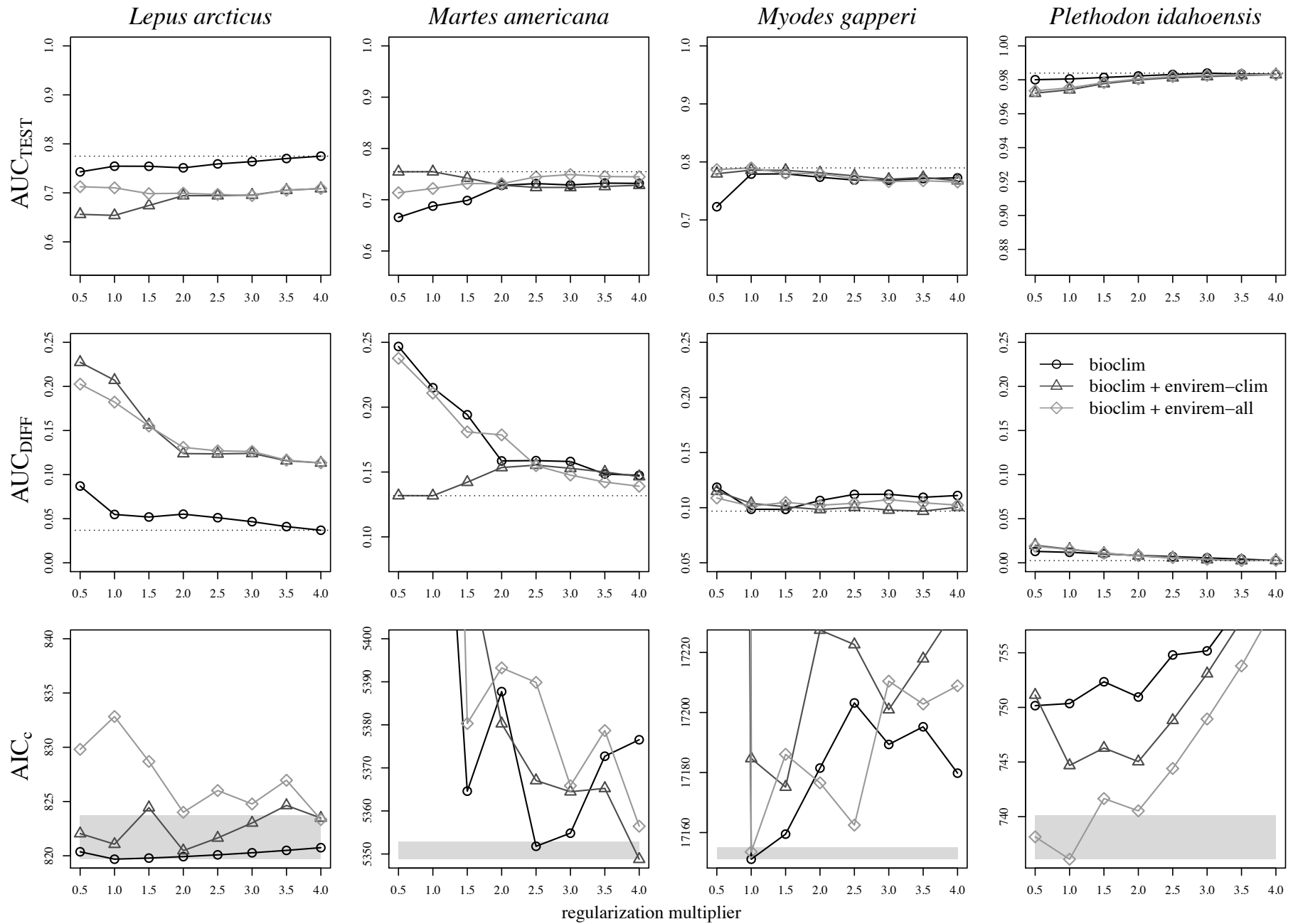


Figure A3. Predicted habitat suitability in the present for 16 case study species not highlighted in the main text, from Maxent models optimized in terms of feature class and regularization parameter according to the AICc metric, for models constructed with and without the ENVIREM variables. Suitability scores range from 0 (blue) to 1 (red). Habitat suitability is shown within the training region only, with predicted habitat suitability below a 95% training presence threshold considered to be unsuitable (grey).

