Supplementary data: Transitions in social complexity along elevational gradients reveal a combined impact of season length and development time on social evolution

Running title: Sociality, development time, and altitude

Sarah D. Kocher[§,1,*], Loïc Pellissier[2,3*], Carl Veller[4,5], Jessica Purcell[3], Martin A. Nowak[1,4,6], Michel Chapuisat[3,+], and Naomi E. Pierce[1,+]

[1]Department of Organismic and Evolutionary Biology, Museum of Comparative Zoology, Harvard University, Cambridge, MA 02138 USA

[2]Arctic Research Centre, Department of Bioscience, Aarhus University, DK-4000 Roskilde, Denmark

[3]Department of Ecology and Evolution, University of Lausanne, Lausanne, Switzerland

[4]Program for Evolutionary Dynamics, Harvard University, Cambridge, MA 02138 USA

[5]Department of Economics, Harvard University, Cambridge, MA 02138 USA

[6]Department of Mathematics, Harvard University, Cambridge, MA 02138 USA

*These authors contributed equally to this work

[+]Co-senior authors

[§]Correspondence should be addressed to skocher@fas.harvard.edu

Table S1. Experimental data used in this study. Egg-to-adult development time, foraging days, and social structure designations from the literature (with supplementary references at the end of this document).

Species name	Sociality	Foraging days	Mean development	References
Bombus_muscorum	high	147.94082		Michener, 1974
Bombus_pomorum	high	142.90494		Michener, 1974
Bombus_distinguendus	high	139.64638		Michener, 1974
Bombus_confusus	high	137.71312		Michener, 1974
Bombus_ruderatus	high	135.16582		Bourke, 1997; Sakagami & Katayama, 1977
Bombus_campestris	high	121.75652		Michener, 1974
Bombus_vestalis	high	116.45526		Michener, 1974
Bombus_veteranus	high	111.7013		Michener, 1974
Bombus_terrestris	high	111.37092	25.5	Bourke, 1997; Laverty & Plowright, 1985, Del Castillo & Fairbairn, 2012; Wenseleers & Al, 2006
Bombus_pascuorum	high	106.63812		Michener, 1974
Bombus_argillaceus	high	106.22276		Michener, 1974
Bombus_humilis	high	104.61458		Michener, 1974
Bombus_lapidarius	high	103.98566		Del Castillo & Fairbairn, 2012; Winston, 1991
Bombus_sylvarum	high	103.0321		Del Castillo & Fairbairn, 2012
Bombus_barbutellus	high	101.8957		Michener, 1974
Bombus_hypnorum	high	101.8128		Bourke, 1997; Michener, 1974
Bombus_hortorum	high	99.459176		Del Castillo & Fairbairn, 2012; Michener, 1974; Michener, 1974; Sakagami, 1976
Bombus_sylvestris	high	99.415638		Michener, 1974
Bombus_bohemicus	high	94.02081		Michener, 1974
Bombus_lucorum	high	89.39406		Bourke, 1997; Del Castillo & Fairbairn, 2012; Sakagami, 1976; 1976
Bombus_pratorum	high	85.068156		Free, 1955; Gonzalez & Mejia, 2004
Bombus_subterraneus	high	74.920438		Michener, 1974
Bombus_magnus	high	74.72998		Michener, 1974
Bombus_norvegicus	high	74.11919		Michener, 1974

Bombus_rupestris	high	68.44023		Michener, 1974
Bombus_quadricolor	high	61.57486		Michener, 1974
Bombus_cryptarum	high	58.985388		Michener, 1974
Bombus_jonellus	high	56.074472		Michener, 1974
Bombus_wurflenii	high	55.012192		Michener, 1974
Bombus_ruderarius	high	54.361174		Michener, 1974
Bombus_inexspectatus	high	54.262844		Michener, 1974
Bombus_soroeensis	high	53.751726		Michener, 1974
Bombus_mesomelas	high	53.470338		Michener, 1974
Bombus_flavidus	high	47.348408		Michener, 1974
Bombus_sichelii	high	43.9006		Michener, 1974
Bombus_monticola	high	43.476364		Michener, 1974
Bombus_gerstaeckeri	high	43.06264		Michener, 1974
Bombus_mucidus	high	42.665376		Michener, 1974
Bombus_pyrenaeus	high	40.616888		Michener, 1974
Bombus_mendax	high	40.426764		Michener, 1974
Bombus_alpinus	high	20.32066		Laverty & Plowright, 1985
Bombus_atratus	high		29	Laverty & Plowright, 1985;Gonzalez & Mejia, 2004
Bombus_impatiens	high		26	Bourke, 1997; Michener, 1974; Cnaani, Schmid-Hempel, & Schmidt, 2002; Michener, 1974
Bombus_ephippiatus	high		24	Del Castillo & Fairbairn, 2012; Michener, 1974
Bombus_perplexus	high		22.5	Del Castillo & Fairbairn, 2012; Laverty & Plowright, 1985; Michener, 1974
Bombus_bimaculatus	high		22	Del Castillo & Fairbairn, 2012; Sakagami, 1976
Bombus_hypocrita	high		22	Del Castillo & Fairbairn, 2012; Michener, 1974; Laverty & Plowright, 1985; Michener, 1974
Bombus_ignitus	high		22	Del Castillo & Fairbairn, 2012; Mason, 1988; Michener, 1974; Yoon, Kim, & Kim, 2002
Bombus_ternarius	high		22	Del Castillo & Fairbairn, 2012
Apis_mellifera	high		21	Winston, 1991
Bombus_fervidus	high		20.5	Sakagami And Katayama 1980
Bombus_polaris	high		20	Del Castillo & Fairbairn, 2012; Laverty & Plowright, 1985
Bombus_vagans	high		19	Del Castillo & Fairbairn, 2012
Bombus_affinis	high			Bourke, 1997; Sakagami, 1976
Bombus_agrorum	high			Cumber, 1949

Bombus_appositus	high			Sakagami And Katayama 1981
Bombus_ardens	high			Del Castillo & Fairbairn, 2012
Bombus_balteaus	high			Sakagami & Katayama, 1977
Bombus_bifarius	high			Laverty & Plowright, 1985
Bombus_borealis	high			Michener, 1974
Bombus_californicus	high			Michener, 1974; Sakagami & Katayama, 1977
Bombus_centralis	high			{Delcastillo:2012kq}
Bombus_flavifrons	high			Michener, 1974
Bombus_frigidus	high			Michener, 1974
Bombus_melanopygus	high			Bourke, 1997; Cumber, 1949; Laverty & Plowright, 1985
Bombus_nevadensis	high			Michener, 1974
Bombus_occidentalis	high			Laverty & Plowright, 1985; Sakagami & Katayama, 1977
Bombus_pennsylvanicus	high			Michener, 1974
Bombus_rufocinctus	high			Michener, 1974
Bombus_sassaricus	high			Bourke, 1997; Michener, 1974
Bombus_terricola	high			Bourke, 1997; Sakagami, 1976
Bombus_wilmattae	high			Huth-Schwarz et al. 2011
Lasioglossum_politum	intermediate	154.4317		Danforth et al., 2003
Lasioglossum_malachurum	intermediate	146.6934		Knerer, 1992; Richards, 2000; Wyman & Richards, 2003; Packer & Knerer, 1985
Lasioglossum_lineare	intermediate	144.55384		Knerer, 1983; Packer & Knerer, 1985
Lasioglossum_marginatum	intermediate	139.37964		Michener, 1974
Halictus_scabiosae	intermediate	138.4544		Plateaux-Quenu, 1972
Lasioglossum_pauxillum	intermediate	137.3926		Packer & Knerer, 1985
Halictus_subauratus	intermediate	131.71848		Westrich, 1990
Lasioglossum_interruptum	intermediate	130.4472		Danforth et al., 2003
Lasioglossum_morio	intermediate	130.1395		Danforth et al., 2003
Lasioglossum_nigripes	intermediate	126.5545		Packer & Knerer, 1985
Halictus_tumulorum	intermediate	121.421		Westrich, 1990
Halictus_sexcinctus	intermediate	110.54328	33	Richards, 2001
Halictus_maculatus	intermediate	108.8383		Knerer, 1980
Halictus_smaragdulus	intermediate	93.30192		Westrich, 1990
Allodape_ceratinoides	intermediate			Michener, 1974
Allodape_friesei	intermediate			Michener, 1974

Allodape_mucronata	intermediate		Michener, 1974
Allodape_panurgoides	intermediate		Michener, 1974
Allodape_rufogastra	intermediate		Michener, 1974
Allodapula_acutigera	intermediate		Michener, 1974
Allodapula_dichroa	intermediate		Michener, 1974
Allodapula_exoloma	intermediate		Mason, 1988; Michener, 1974
Allodapula_melanopus	intermediate		Michener, 1974
Allodapula_turneri	intermediate		Michener, 1974
Allodapula_variegata	intermediate		Michener, 1974
Braunsapis_bouyssoui	intermediate		Michener, 1974
Braunsapis_draconis	intermediate		Michener, 1974
Braunsapis_facialis	intermediate		Michener, 1974
Braunsapis_foveata	intermediate		Mason 1988
Braunsapis_leptozonia	intermediate		Michener, 1974
Braunsapis_luapulana	intermediate		Michener, 1974
Braunsapis_simplicipes	intermediate		Michener, 1974
Braunsapis_stuckenbergorum	intermediate		Michener, 1974
Exoneura_hamulata	intermediate		Michener, 1974
Exoneura_variabilis	intermediate		Michener, 1974
Exoneurella_lawsoni	intermediate		Michener, 1974
Halterapis_nigrinervis	intermediate		Chenoweth, Tierney, Smith, Cooper, & Schwarz, 2007
Augochlorella_persimilis	intermediate	39	Ordway, 1966
Augochlorella_striata	intermediate	39	U. G. Mueller, 1996; Packer, 1990
Agapostemon_nasutus	intermediate	37.5	Roberts, 1969; 1973
Lasioglossum_aeneiventre	intermediate	35	Wcislo, Wille, & Orozco, 1993
Lasioglossum_laevissimum	intermediate	35	Packer, 1992
Megalopta_genalis	intermediate	35	Wcislo & Gonzalez, 2006; Wcislo, Arneson, & Roesch, 2004
Lasioglossum_duplex	intermediate	34.5	Packer & Knerer, 1985
Agapostemon_texanus	intermediate	32	Roberts, 1969; 1973
Halictus_farinosus	intermediate	28	G. C. Eickwort, 1985
Halictus_ligatus	intermediate	28	Packer, 1986; Richards, 2001; Roberts, 1973
Lasioglossum_imitatum	intermediate	25.5	Danforth et al., 2003
Lasioglossum_rohweri	intermediate	25.5	Michener, 1974; Breed 1975
Lasioglossum_umbripenne	intermediate	22	Danforth et al., 2003

Augochlora_nominata	intermediate			G. C. Eickwort & Eickwort, 1972
Halictus_poeyi	intermediate			Knerer, 1980
Lasioglossum_breedi	intermediate			Michener, 1974
Lasioglossum_laticeps	intermediate			Danforth et al., 2003
Lasioglossum_lineatulum	intermediate			G. C. Eickwort, Eickwort, Gordon, Eickwort, & Wcislo, 1996
Lasioglossum_ohei	intermediate			Sakagami & Hayashida 1968
Lasioglossum_rhytidiophorum	intermediate			Sakagami & Hayashida 1968
Lasioglossum_seabrui	intermediate			Michener, 1974
Lasioglossum_versatum	intermediate			Michener, 1966
Lasioglossum_zephyrum	intermediate			Danforth et al., 2003
Pseudagapostemon_divaricatus	intermediate			Michener & Lange, 1958
Pseudaugochloropsis_graminea	intermediate			Michener & Kerfoot, 1967
Pseudaugochloropsis_nigerrima	intermediate			Michener & Kerfoot, 1967
Systropha_planidens	solitary	164.4272		Michener, 1974
Systropha_curvicornis	solitary	160.8967		Michener, 1974
Lasioglossum_lucidulum	solitary	144.76966		Danforth et al., 2003
Lasioglossum_limbellum	solitary	141.68608		Danforth et al., 2003
Lasioglossum_majus	solitary	140.6014		Boesi, Polidori, & Andrietti, 2008
Lasioglossum_puncticolle	solitary	138.41752		Danforth et al., 2003
Rophites_quinquespinosus	solitary	135.98898		Michener, 1974
Lasioglossum_zonulum	solitary	134.4815		Stoeckhert, 1933
Lasioglossum_villosulum	solitary	127.7814		Danforth et al., 2003
Lasioglossum_lativentre	solitary	126.0838		Westrich, 1990
Halictus_confusus	solitary	116.8145	32	Roberts, 1973
Lasioglossum_leucozonium	solitary	110.9423		Atwood, 1933; Stoeckhert, 1933
Lasioglossum_fulvicorne	solitary	100.9251		Danforth et al., 2003
Rhophitoides_canus	solitary	94.838372		Wilkaniec, Wójtowski, & Szymas, 1985
Halictus_quadricinctus	solitary	94.34113		Knerer, 1980
Lasioglossum_xanthopus	solitary	94.34113		Packer, 1998
Rophites_algirus	solitary	94.34113		Michener, 1974
Lasioglossum_costulatum	solitary	94.061242		Stoeckhert, 1933

Lasioglossum_brevicorne	solitary	93.30192		Danforth, Conway, & Ji, 2003
Lasioglossum_laevigatum	solitary	93.18486		Stoeckhert, 1933
Halictus_eurygnathus	solitary	90.408066		Oertli, Mueller, & Dorn, 2005
Halictus_rubicundus	solitary	88.976852		Soucy & Danforth, 2002; Plateaux-Quenu, Plateaux, & Packer, 2000
Lasioglossum_albipes	solitary	84.74418		Plateaux-Quenu, 1992
Tetrapedia_maura	solitary		113	Thiele & Inouye, 2007
Centris_vittata	solitary		98.5	Thiele & Inouye, 2007
Xylocopa_varians	solitary		70	Thiele & Inouye, 2007
Centris_labrosa	solitary		61.5	Thiele & Inouye, 2007
Ptilothrix_plumata	solitary		60	*Same Season Eggs; Martins & Guerra, 2001
Centris_analis	solitary		59	Thiele & Inouye, 2007; Vieira & Garófalo, 2000
Centris_biocornuta	solitary		58	Thiele & Inouye, 2007; Vinson & Frankie, 2000
Ceratina_smaragdula	solitary			Kapil & Kumar, 1969; Rehan, Richards, & Schwarz, 2009
Euplusia_surinamensis	solitary			Michener, 1971; Bennett, 1972 ; Dodson, 1966; Myers & Loveless, 1976
Lasioglossum_baleicum	solitary		41.5	Cronin & Hirata, 2003; Hirata & Higashi, 2008
Augochlora_pura	solitary		37.5	Stockhammer, 1966
Lasioglossum_apristum	solitary			Miyanaga, Maeta, & Sakagami, 1999
Neocorynura_fumipennis	solitary			Michener, Kerfoot, And Ramirez, 1966
Osmia_rufa	solitary		109.8	Thiele & Inouye, 2007
Osmia_lignaria	solitary		97.1	Bosch & Kemp, 2000
Duckeanthidium_thielei	solitary		69.5	Thiele, 2002; Thiele & Inouye, 2007
Megachile_rotundata	solitary		36.9	Kemp & Bosch, 2000
Osmia_excavata	solitary			Hirashima, 1958

Figure S2. There is a strong correlation between elevation and foraging days.

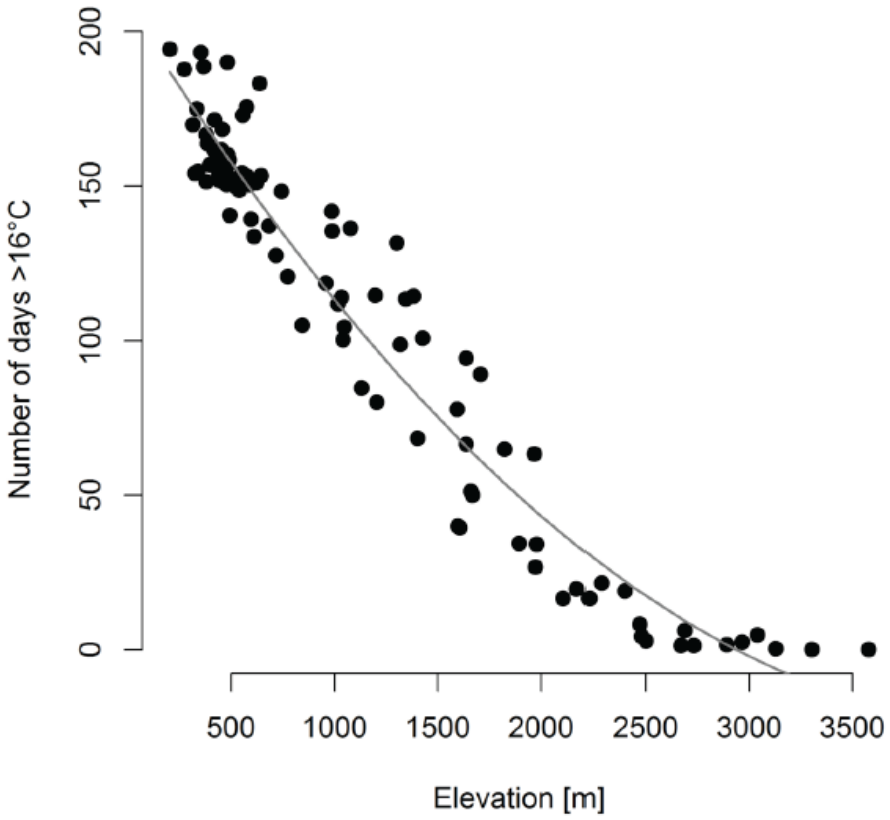


Table S3. The correlations (reported as R^2 values) between the number of days with temperatures reaching 12°C, 14°C, 16°C, 18°C, 20°C, 22°C, altitude, and our selected temperature threshold of 16°C. Note that there is a strong correlation between all temperature thresholds and altitude, as well as between the number of days above 16°C and the rest of the temperature thresholds. All correlations were significant ($p<0.05$).

	Altitude	**Days >16°C**
>12°C	-0.969	0.988
>14°C	-0.965	0.997
>16°C	-0.920	.
>18°C	-0.936	0.996
>20°C	-0.921	0.985
>22°C	-0.896	0.955

Figure S4. A large part of the variation in development times seems to occur *within* subfamilies rather than between them.

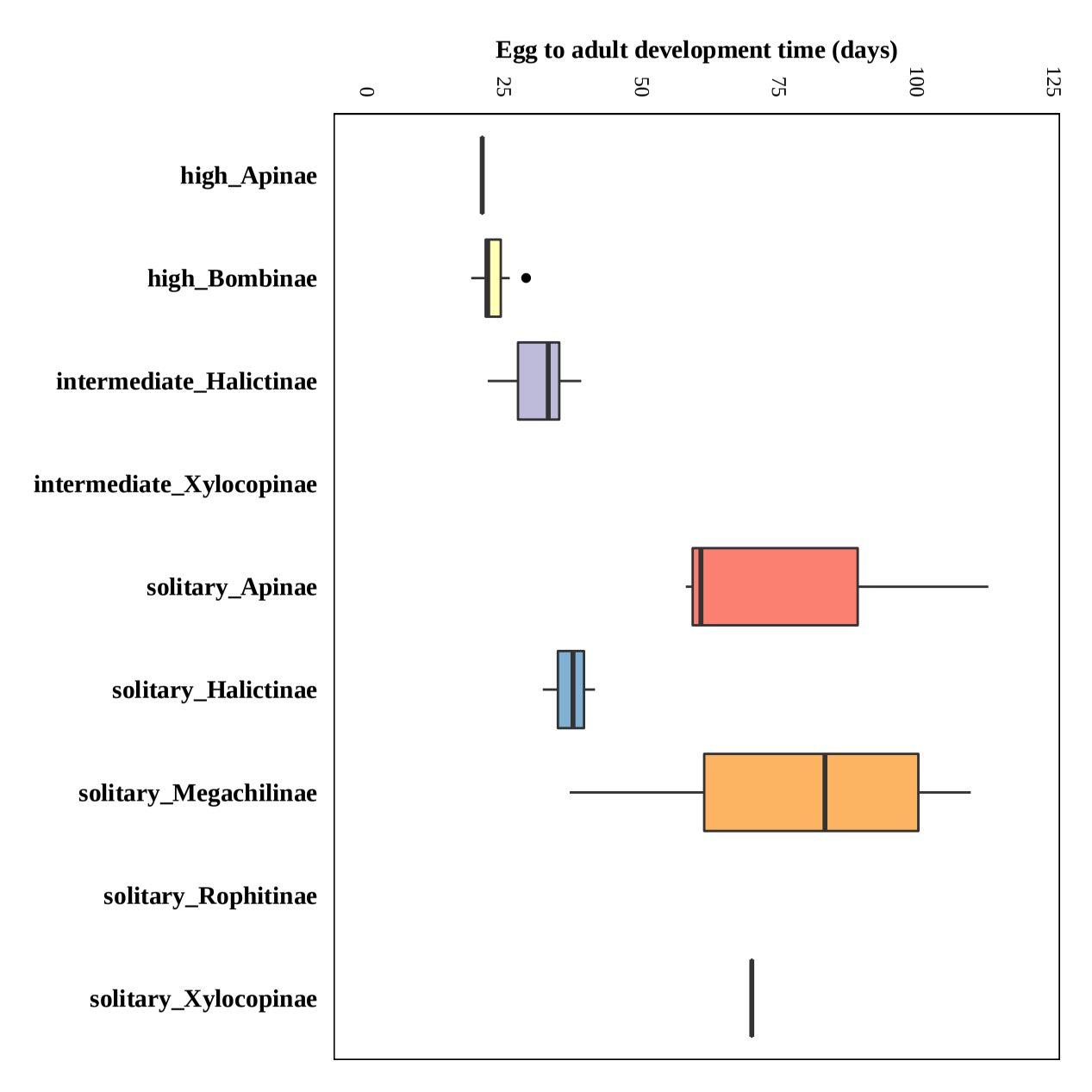
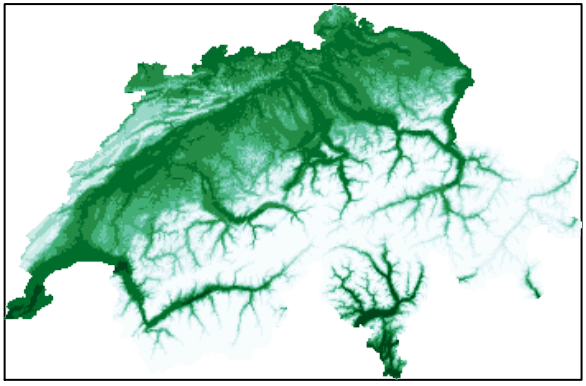
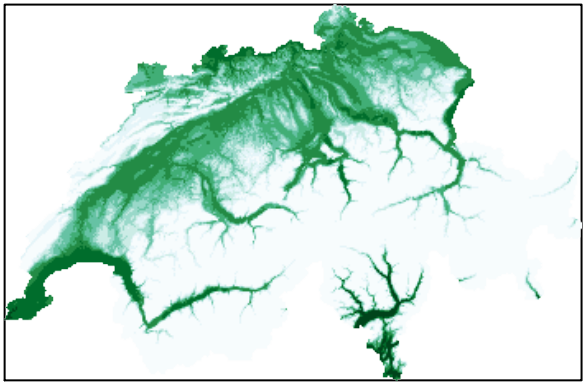

Egg to adult development time (days)
0
25
50
75
100
125
high_Apinae
high_Bombinae
intermediate_Halictinae
intermediate_Xylocopinae
solitary_Apinae
solitary_Halictinae
solitary_Megachilinae
solitary_Rophitinae
solitary_Xylocopinae

Figure S5. These maps illustrate the distributions of each social form across Switzerland. To map these distributions of each behavioural category, “solitary”, “intermediate” and “highly” social, we mapped the probabilities of finding each behavioural form at a given site based on the number of days above 16°C at each site. To complement the observation of species within the three social categories, we used 5000 pseudo-absences representing the background conditions available to the species and then used generalized linear models (GLM) with a binomial distribution and a logistic link function accounting for linear and quadratic relationships.

Solitary



Intermediate



High

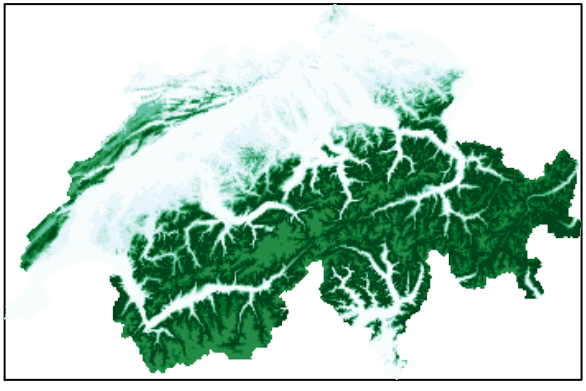


Figure S6. Distributions of development time for each social form used in the ecological model. A. Solitary taxa, B. Intermediate social taxa, C. Highly social taxa.

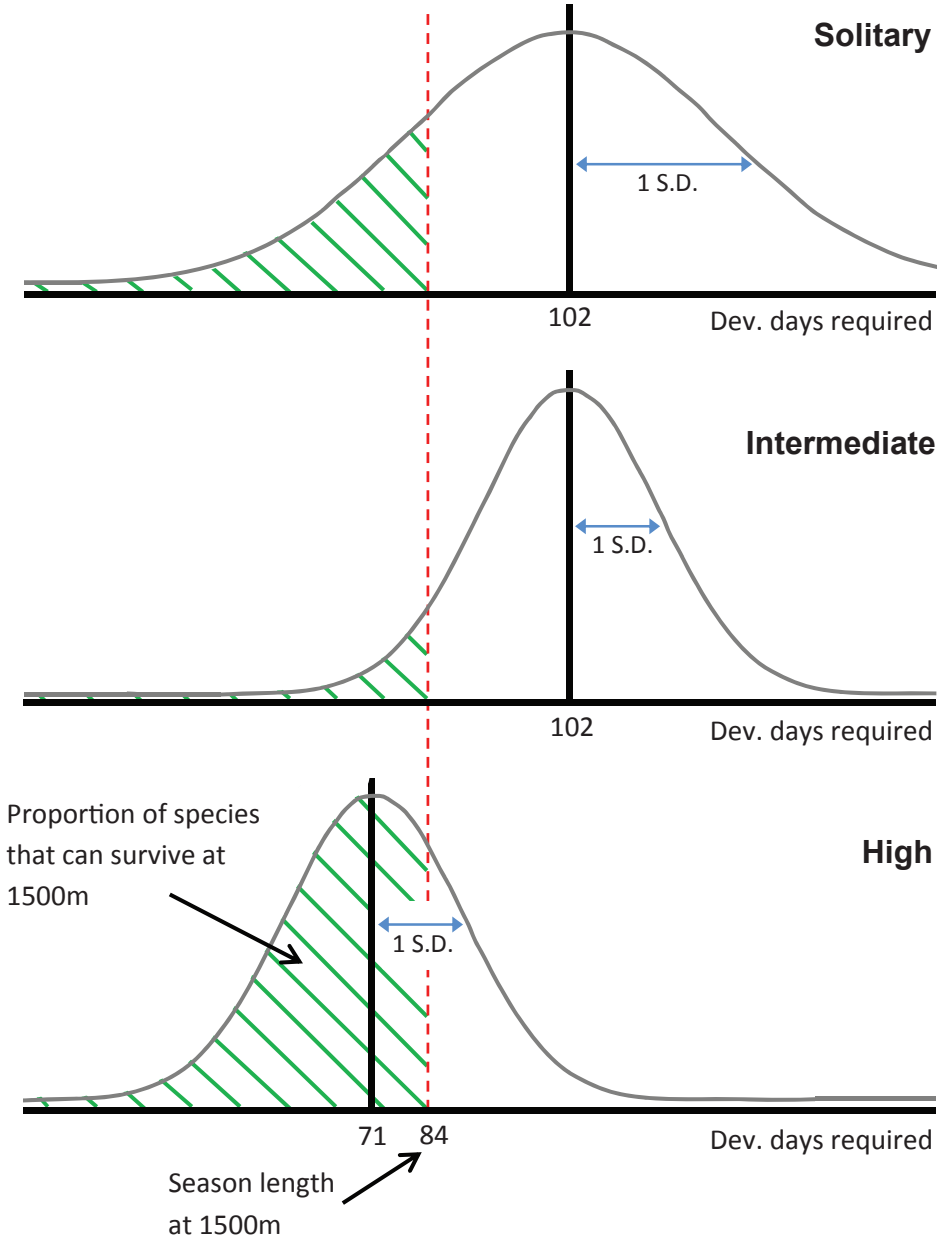
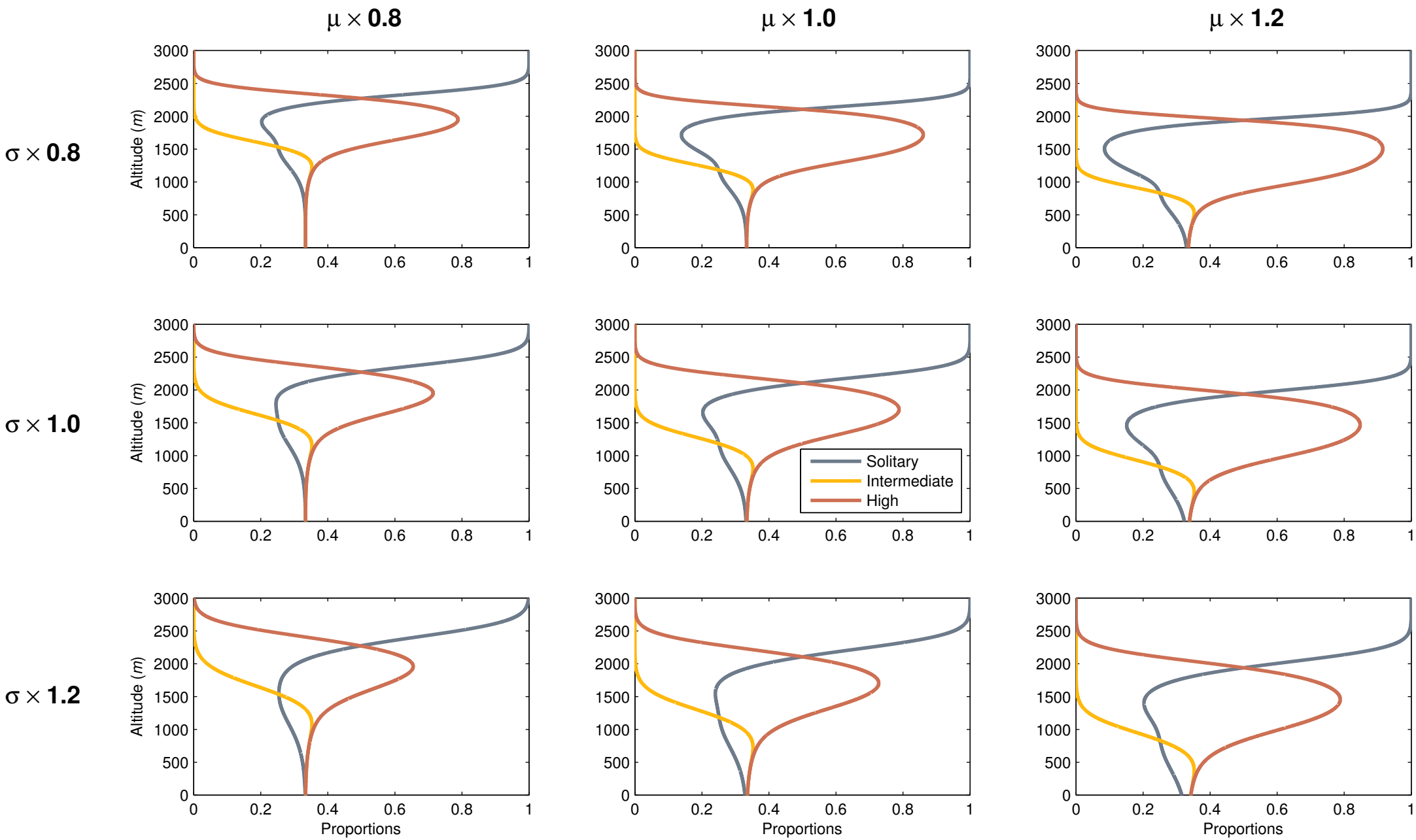

Solitary
1 S.D.
102
Dev. days required
Intermediate
1 S.D.
102
Dev. days required
Proportion of species
that can survive at
1500m
High
1 S.D.
71
84
Dev. days required
Season length
at 1500m

Figure S7. The qualitative results of the model are robust to sizable changes in the parameters of the underlying distributions. Here, we report the relative proportions of the three sociality levels across altitude for a range of distribution parameter values. The base case, as in Fig. 4, is shown in the central panel. The means of the distributions increase from left to right; the standard deviations increase from top to bottom.


μ × 0.8
μ × 1.0
μ × 1.2
σ × 0.8
σ × 1.0
σ × 1.2
Altitude (m)
Proportions
Solitary
Intermediate
High

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