Supporting information for:

Invader success and changing climate: Comparisons in the native and introduced range of seven plant species

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Contents

1 Additional methods

1.1 Defining Invasive Species

There is no consensus on how to classify a species as invasive (Colautti & MacIsaac, 2004). The most common terms include 'exotic,' 'introduced,' 'naturalized,' 'nonindigenous,' 'established,' 'alien,' 'noxious,' 'weedy,' and 'invasive.' These terms can be grouped into those that describe the provenance of the species (e.g., exotic, introduced, alien, non-indigenous), those that describe its ability to grow and compete in the new ecosystem (e.g., naturalized, established), and those that describe its impact on the receiving ecosystem (e.g., noxious, weedy, harmful). The International Union for the Conservation of Nature (IUCN, 2008) describes invasive species as: "organisms introduced by man [sic] into places out of their natural range of distribution, where they become established and disperse, generating a negative impact." However, this definition contains three subjective elements: what timepoint of a species' range is 'natural,' whether humans are a natural part of nature, and what is defined as a negative impact (Munro et al., 2019). To both acknowledge and allay some of these subjective elements, this paper will follow Richardson et al.'s (Richardson et al., 2011; Richardson et al., 2000) definition of invasive species. Invasive species are thus those that (1) are introduced across a previously unpenetrated barrier, (2) successfully reproduce in the place of introduction to create a stable local population, and finally (3) spread to produce fit offspring a substantial distance from the place of introduction.

1.2 Study species details

Capsella bursa-pastoris (CAPBUR; Shepard's Purse) is an annual or biennial herbaceous plant in Brassicaceae. It grows 10 to 80 cm tall, typically blooming in late spring (Defelice, 2001). It originated in Europe, and was introduced to the New World as a medicinal herb—it is now found across Canada, the US, and Mexico (Westrich, 1989).

Chelidonium majus (CHEMAJ; Greater Celandine) is an herbaceous biennial member of Papaveraceae. It is native to Eurasia and North Africa and was introduced to the US by the 1670s as a medicinal. It is now found across the Eastern US and Canada and portions of the west (Holm et al., 1979).

Dactylis glomerata (DACGLO; Orchard Grass) is a cool-season, perennial grass (Poaceae). Plants grow up to 120 cm tall and have roots up to 60 cm long (Moser & Buxton, 1996). This plant originated in central and western Europe, and was intentionally introduced into the US in the 1750s (Bush et al., 2012) as a forage grass for pasture and hay (Ogle et al., 2011).

Plantago lanceolata (PLALAN; Narrow-leaved Plantain) is a perennial member of Plantaginaceae. It has narrow, ribbed leaves and grows to 1m tall. It is native to Eurasia, and has successfully colonized the world's mid-latitudes (Holm et al., 1977).

Plantago major (PLAMAJ; Broad-leaved Plantain) is a perennial member of Plantaginaceae. It has broad, smooth leaves, and grows to 15cm tall. Native to Europe, it was introduced into North America for its medicinal uses (Knobloch, 1996; Samuelsen, 2000).

Rumex crispus (RUMCRI; Curly Dock) is a perennial herbaceous plant in Polygonaceae, and grows to 160 cm. It is native to Europe, Asia, and Africa, and was introduced for its medicinal uses into North America where it now found across much of the continent (USDA, 2010).

Taraxacum officinale (TAROFF; Dandelion) is a perennial herbaceous plant in the Asteraceae family, and grows to 60 cm. It is native to Eurasia, but is now found in all 50 US states, much of Canada, and Mexico (USDA Agricultural Research Service, 1971).

1.3 Sampling details

Table S1: Total number of seed-producing individuals and populations from which seeds were collected.

US populations	**US individuals**	**European populations**	**European individuals**
3	21	13	63

1.4 Period/light luminance

Some species have sufficient Pfr (the active form of phytochrome pigment, often necessary to induce germination) and so do not need any light to break dormancy, others just need a pulse of red light to break dormancy (the red light converts the inactive phytochrome into Pfr) (Casal & Sánchez, 1998). Other species, including *Plantago major*, take much longer to build up the requisite Pfr, and so have much higher germination success when exposed to longer periods of light (with nearly 100% germination after 48 hours of exposure for *P. major*) (Pons, 1991). Finally, some species have a high irradiance response (HIR), germinating poorly when exposed to high luminance light or prolonged light (Roberts et al., 1987). Beyond interspecific variation, there is also intraspecific variation in the relationship between dormancy and light (Probert et al., 1986). Across all populations, germination rate seems to be log-normally related to photon dosage (Ellis et al., 1986). Light may begin inhibiting germination for HIR species at about 0.1 mol/m^2/day–1 mol/m^2/day (Baskin & Baskin, 1998; Ellis et al., 1986), while other species peak above 10

mol/m^2/day (Ellis et al., 1986). The differing levels of light necessary to break dormancy means that any chosen light regime will be better for some species and worse for others.

The goal of these experiments is to create germination rates that are sufficient to observe variation in responses to treatments. Thus, we chose an intermediate light exposure at which all of the species should germinate at substantial levels, but which may not be ideal for any species. In selecting how much light to use, this experiment erred on the side of too much light rather than not enough, since at least one of our species is known to need large amounts of light (*Plantago major*—Pons (1991)), and none are known to exhibit HIR (although a *D. glomerata* subspecies in southern Europe does exhibit HIR (Probert et al., 1986), but this subspecies is not thought to have been collected for this study). Thus this experiment used a length of eight hours at a luminance of 75 micromol/m^2/second to yield a daily photon dosage of 2.16 mol/m^2. Baskin and Baskin (1998) recommend that the light period coincide with the high-temperature period. Thus, this experiment exposed the seeds to eight hours of fluorescent light during the high-temperature thermoperiod.

1.5 Substrate and planting depth:

Popay and Roberts (1970) show that *C. bursa-pastoris* seeds germinated about equally on filter paper as on top of soil, but showed much decreased germination when inserted into soil. The effects of planting substrate and depth have not been studied in most of the study species. However, a study on a species related to *D. glomerata* suggests that *D. glomerata* may germinate better in soil (Andrews & Burrows, 1974). Additionally, a difference in depth of just a couple millimeters can result in extreme differences in light availability (Tester & Morris, 1987). Thus each seed was placed on top of Fafard Growing Mix (a mixture of fine peat moss, fine perlite, and vermiculite) soil, with each seed in its own individual tray cell.

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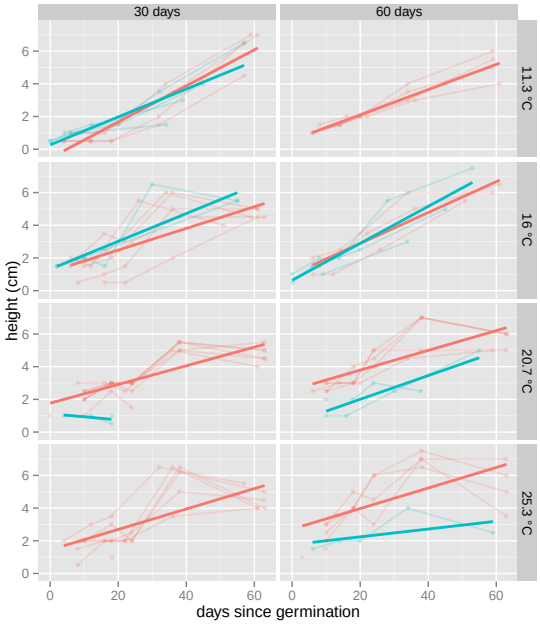
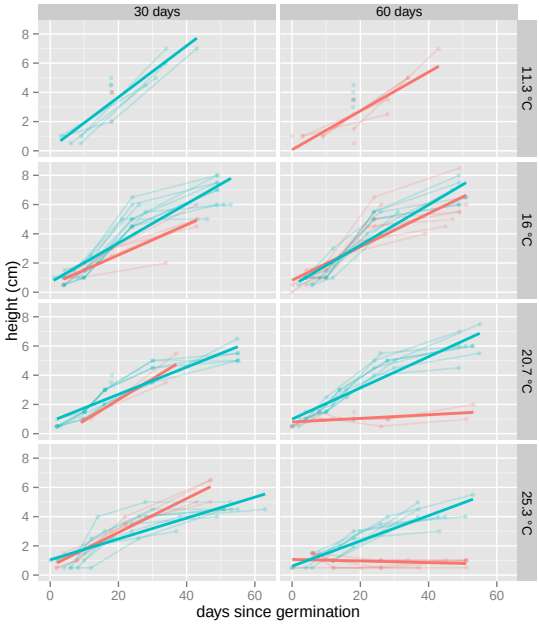
2 Raw Data Plots

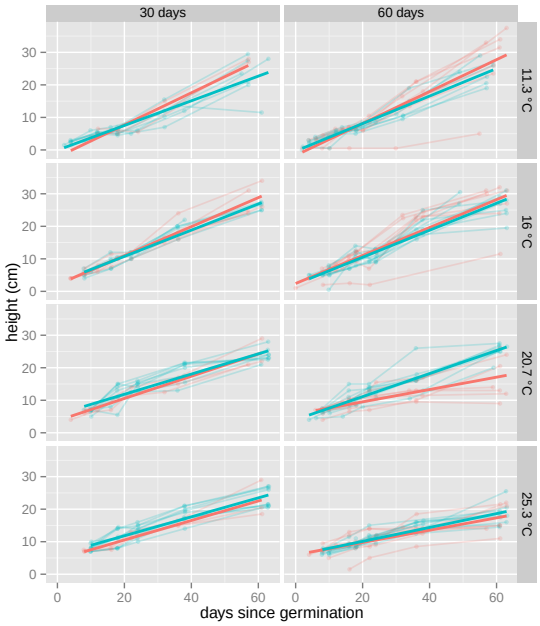
(a) CAPBUR



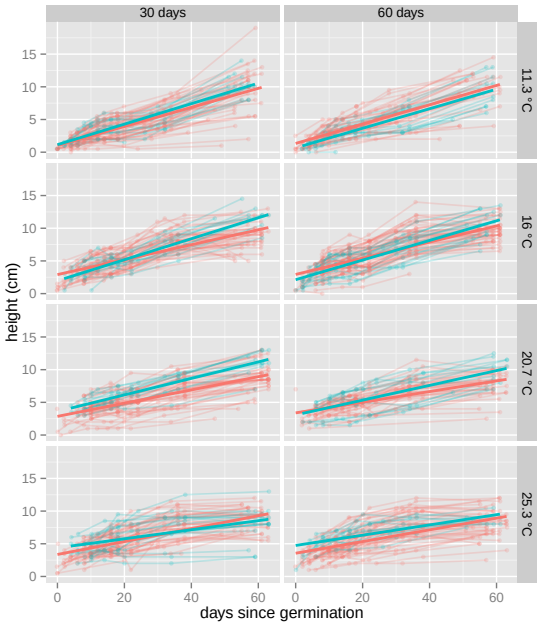
(b) CHEMAJ



(c) DACGLO

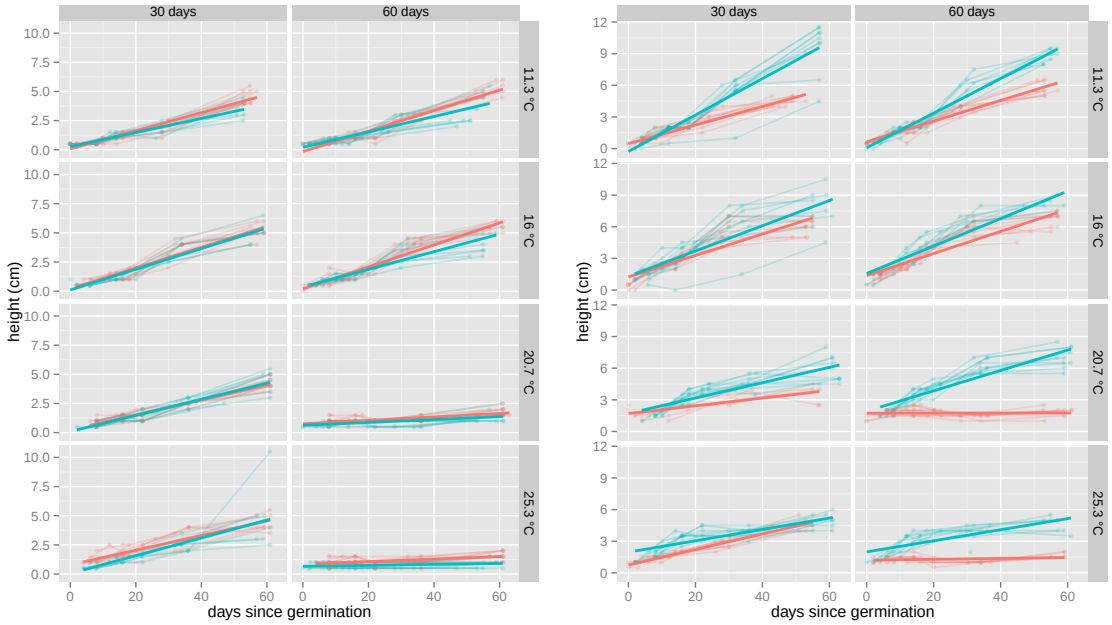


(d) PLALAN



(e) PLAMAJ

(f) RUMCRI



(g) TAROFF

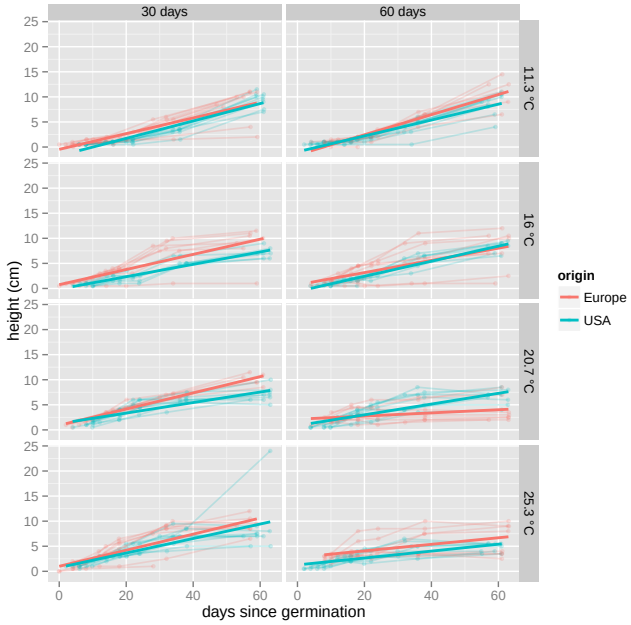


Figure S1: Height vs. age by stratification and temperature. Growth rate can be approximately linear. Pink represents European plants, while blue represents those from North America

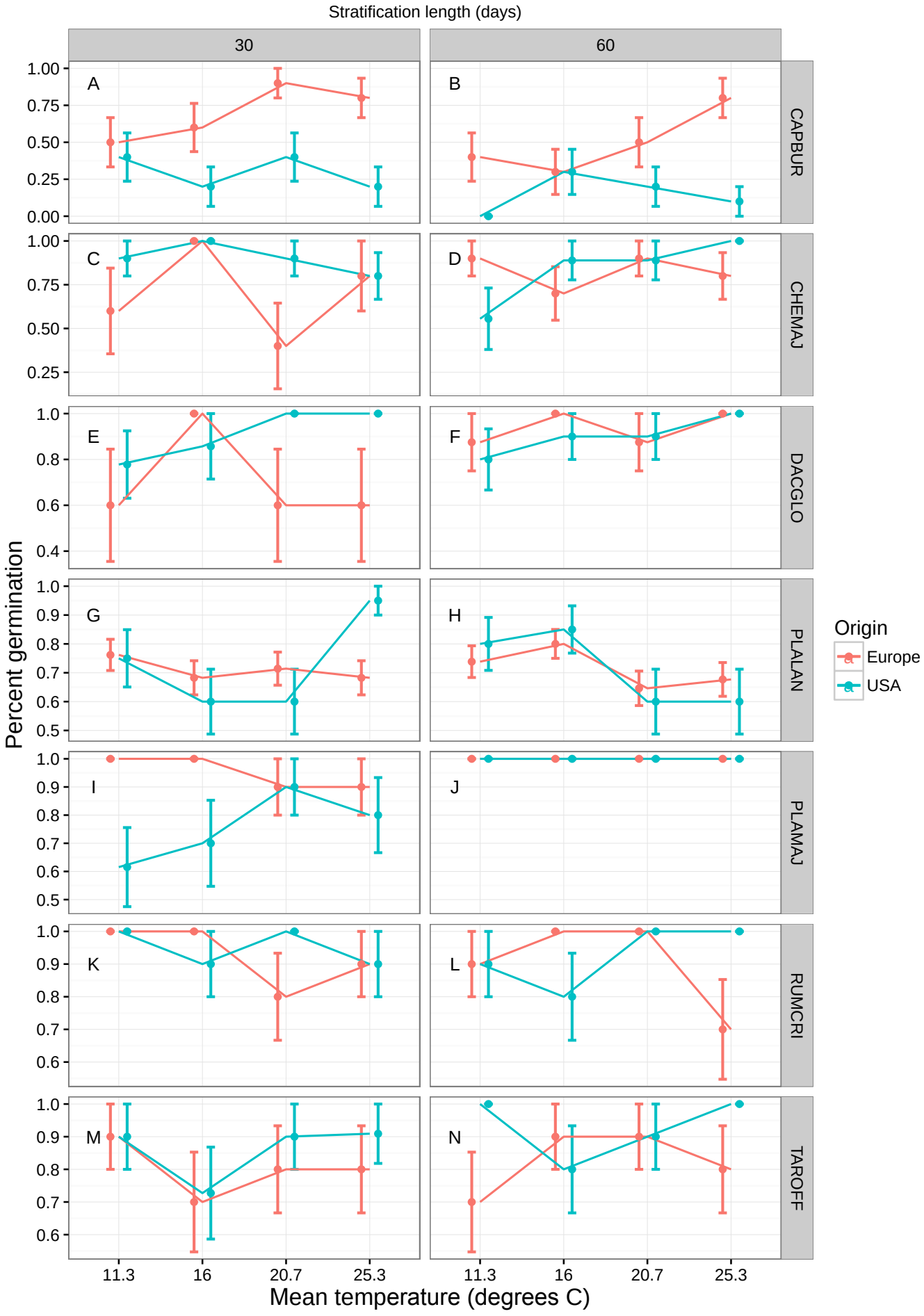


Figure S2: Unmodeled germination rate by population origin, and across stratification length and temperature treatments for each species (mean +/- standard error). Note the variable y-axis scale.

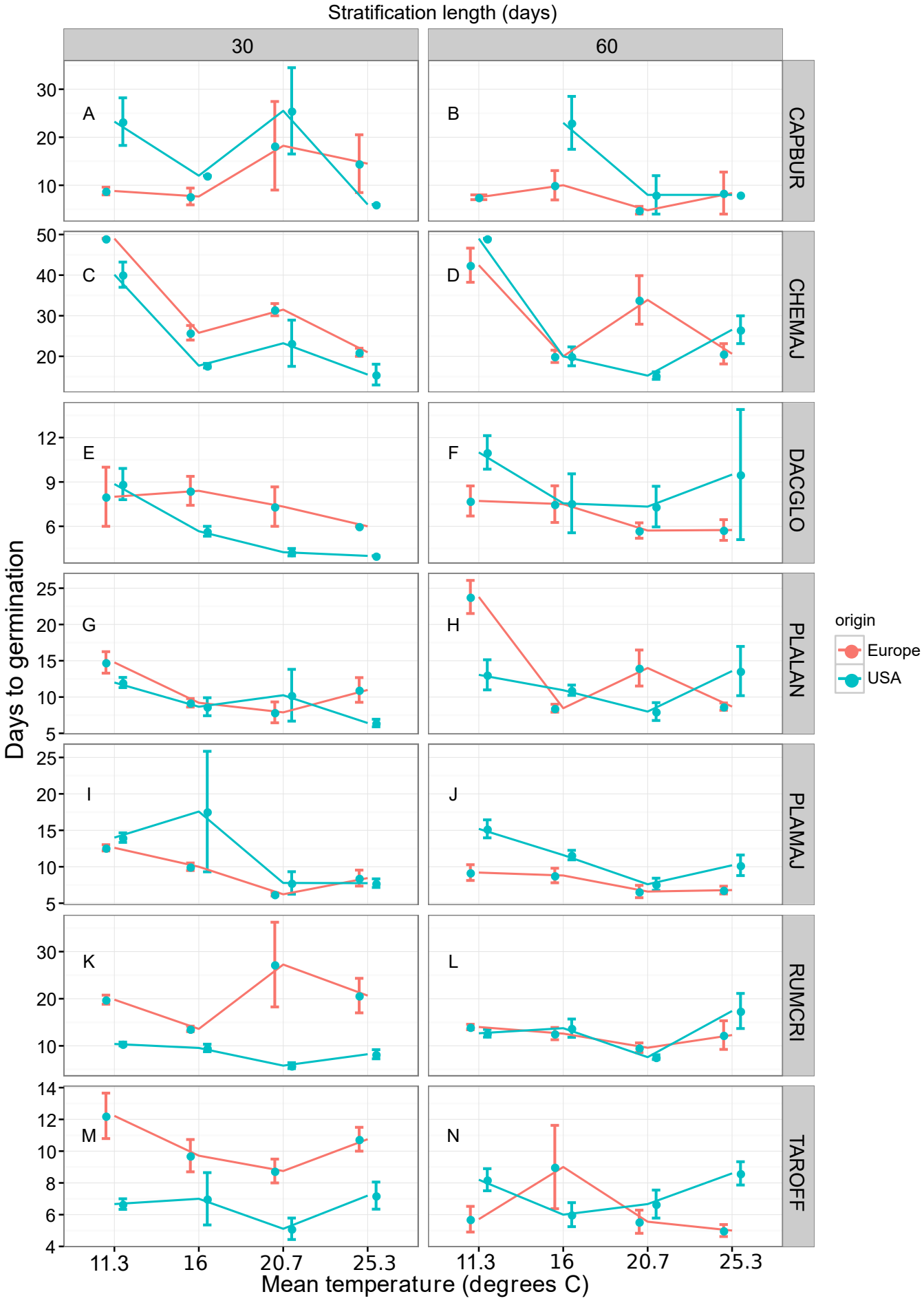


Figure S3: Unmodeled germination timing by population origin, and across stratification length and temperature treatments for each species (mean +/- standard error). Note the variable y-axis scale.

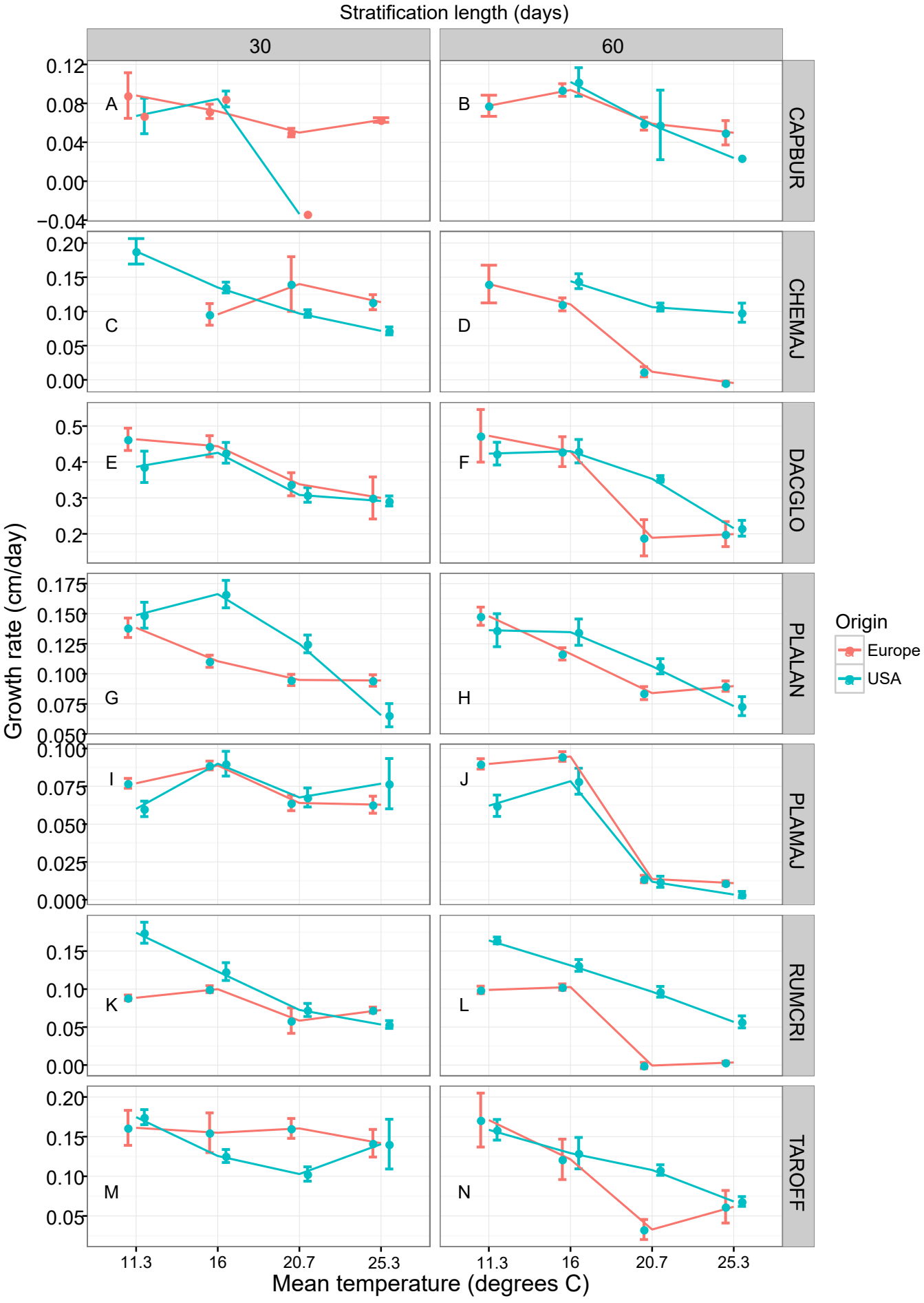


Figure S4: Unmodeled growth rate by population origin, and across stratification length and temperature treatments for each species (mean +/- standard error). Note the variable y-axis scale.

3 Model Results

3.1 Coefficient tables

Table S2: Summary of multilevel model of germination rate. Output is in logit(fraction germinated)

	mean	sd	2.5%	50%	97.5%	Rhat
(Intercept)	1.82	0.48	0.93	1.80	2.79	1.00
origin	-0.10	0.72	-1.50	-0.09	1.33	1.00
strat	0.17	0.68	-1.11	0.14	1.65	1.00
temp1	0.20	0.54	-0.78	0.17	1.31	1.00
temp2	-0.10	0.45	-0.95	-0.11	0.82	1.00
temp3	-0.18	0.43	-1.03	-0.18	0.68	1.00
origin × strat	-0.01	0.84	-1.63	-0.03	1.72	1.00
origin × temp1	-0.41	0.71	-1.78	-0.42	0.97	1.00
origin × temp2	0.76	0.85	-0.82	0.74	2.50	1.00
origin × temp3	0.88	0.75	-0.54	0.87	2.36	1.00
strat × temp1	0.61	0.73	-0.85	0.60	2.05	1.00
strat × temp2	0.45	0.71	-0.86	0.41	1.98	1.00
strat × temp3	0.59	0.76	-0.82	0.55	2.22	1.00
origin × strat × temp1	0.53	1.09	-1.59	0.52	2.72	1.00
origin × strat × temp2	0.11	1.00	-1.82	0.11	2.11	1.00
origin × strat × temp3	0.80	1.36	-1.65	0.73	3.63	1.00

Table S3: Summary of multilevel model of germination timing. Output is in log(days)

	mean	sd	2.5%	50%	97.5%	Rhat
(Intercept)	2.75	0.25	2.28	2.75	3.26	1.00
origin	-0.15	0.17	-0.48	-0.15	0.21	1.00
strat	-0.11	0.19	-0.50	-0.10	0.22	1.00
temp1	-0.37	0.11	-0.58	-0.37	-0.13	1.00
temp2	-0.47	0.16	-0.75	-0.47	-0.14	1.00
temp3	-0.36	0.14	-0.62	-0.37	-0.07	1.00
origin × strat	0.16	0.20	-0.22	0.16	0.56	1.00
origin × temp1	0.06	0.18	-0.29	0.06	0.41	1.00
origin × temp2	0.05	0.24	-0.43	0.05	0.49	1.00
origin × temp3	-0.21	0.19	-0.59	-0.21	0.16	1.00
strat × temp1	0.05	0.19	-0.32	0.05	0.46	1.00
strat × temp2	-0.09	0.20	-0.48	-0.09	0.33	1.00
strat × temp3	-0.23	0.16	-0.53	-0.24	0.11	1.00
origin × strat × temp1	0.01	0.24	-0.49	0.01	0.48	1.00
origin × strat × temp2	-0.07	0.34	-0.77	-0.06	0.59	1.00
origin × strat × temp3	0.57	0.26	0.05	0.58	1.06	1.00

Table S4: Summary of multilevel model of growth rate. Output is in cm/day

	mean	sd	2.5%	50%	97.5%	Rhat

(Intercept)	0.16	0.05	0.07	0.16	0.25	1.00
origin	0.01	0.01	-0.02	0.01	0.03	1.00
strat	0.01	0.01	-0.01	0.01	0.02	1.00
temp1	-0.02	0.01	-0.04	-0.02	0.01	1.00
temp2	-0.04	0.01	-0.07	-0.04	-0.02	1.00
temp3	-0.04	0.02	-0.08	-0.04	-0.01	1.00
origin × strat	-0.01	0.01	-0.03	-0.01	0.02	1.00
origin × temp1	0.01	0.01	-0.02	0.01	0.03	1.00
origin × temp2	-0.02	0.02	-0.05	-0.02	0.01	1.00
origin × temp3	-0.03	0.02	-0.06	-0.03	0.01	1.00
strat × temp1	-0.00	0.01	-0.03	-0.00	0.02	1.00
strat × temp2	-0.06	0.02	-0.11	-0.06	-0.03	1.00
strat × temp3	-0.06	0.02	-0.11	-0.06	-0.02	1.00
origin × strat × temp1	0.01	0.02	-0.03	0.01	0.04	1.00
origin × strat × temp2	0.07	0.03	0.02	0.07	0.13	1.00
origin × strat × temp3	0.04	0.02	-0.01	0.04	0.09	1.00

3.2 Inter-population variability

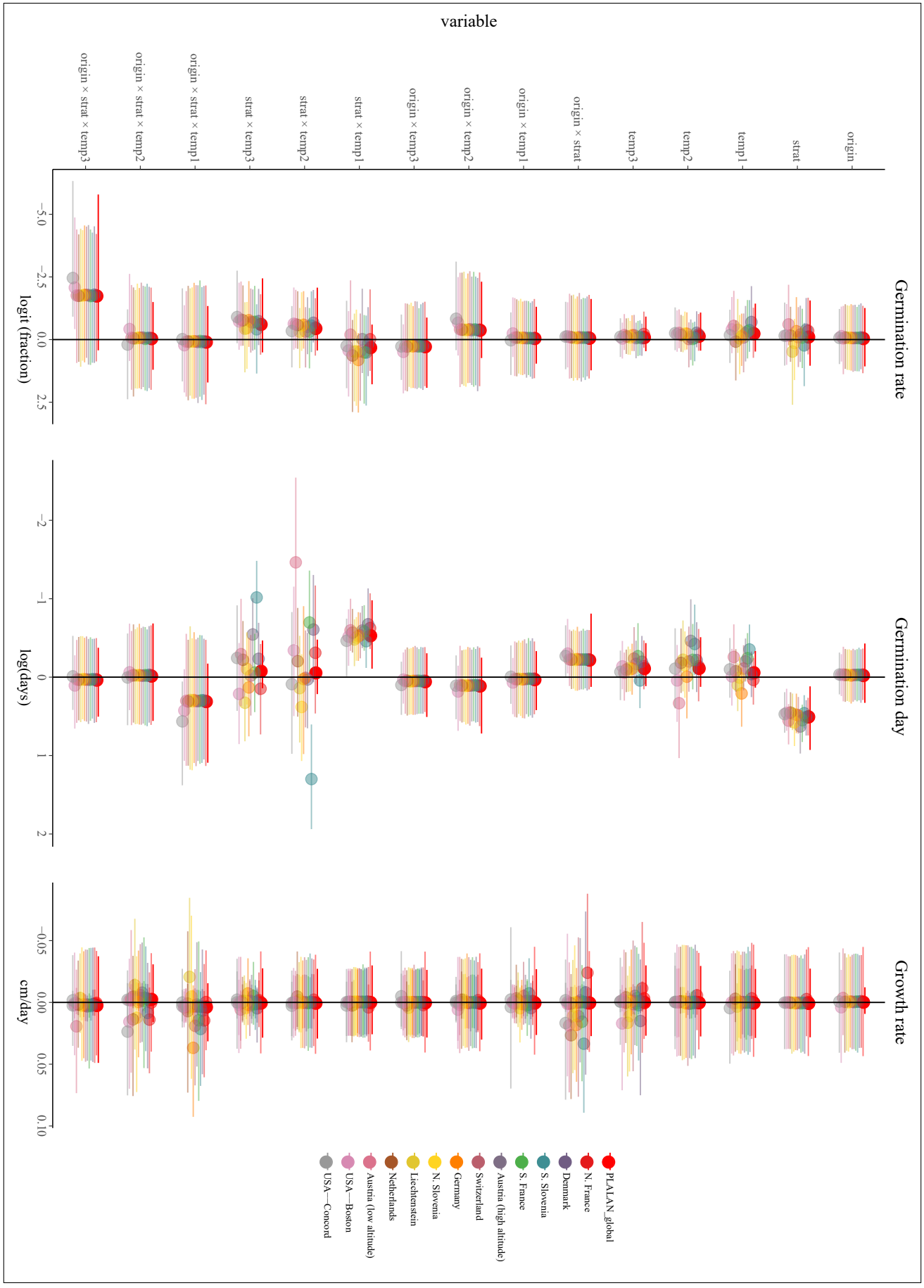


Figure S5: Germinatio rate, germination timing, and growth rate multilevel model coefficients with 95% credible intervals for PLALAN (*Plantago Lanceolata*), showing main random effect of PLALAN, and random effects of each population. Zero represents the global mean fixed effect across all species. Intercept coefficients not shown.