

**Manuscript version: Author's Accepted Manuscript**

The version presented in WRAP is the author's accepted manuscript and may differ from the published version or Version of Record.

**Persistent WRAP URL:**

<http://wrap.warwick.ac.uk/111474>

**How to cite:**

Please refer to published version for the most recent bibliographic citation information. If a published version is known of, the repository item page linked to above, will contain details on accessing it.

**Copyright and reuse:**

The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions.

© 2018 Elsevier. Licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International <http://creativecommons.org/licenses/by-nc-nd/4.0/>.



**Publisher's statement:**

Please refer to the repository item page, publisher's statement section, for further information.

For more information, please contact the WRAP Team at: [wrap@warwick.ac.uk](mailto:wrap@warwick.ac.uk).

1 **Adaptive significance of functional germination traits in crop wild relatives of**  
2 ***Brassica***

3 E. Castillo-Lorenzo<sup>ab\*</sup>, W.E. Finch-Savage<sup>b</sup>, C.E. Seal<sup>a</sup> and H.W. Pritchard<sup>a</sup>

4 <sup>a</sup>Department of Comparative Plant and Fungal Biology, Royal Botanic Gardens, Kew,  
5 Wellcome Trust Millennium Building, Wakehurst Place, Ardingly, West Sussex RH17  
6 6TN, United Kingdom. Email ECL: [e.castillolorenzo@kew.org](mailto:e.castillolorenzo@kew.org); CES: [c.seal@kew.org](mailto:c.seal@kew.org);  
7 HWP: [h.pritchard@kew.org](mailto:h.pritchard@kew.org)

8 <sup>b</sup>School of Life Sciences, Warwick University, Wellesbourne, Warwick CV35 9EF,  
9 United Kingdom. Email WEFS: [Bill.Finch-Savage@warwick.ac.uk](mailto:Bill.Finch-Savage@warwick.ac.uk)

10

11 \*Corresponding author: Elena Castillo-Lorenzo ([e.castillolorenzo@hotmail.com](mailto:e.castillolorenzo@hotmail.com))

12 **Abstract**

13 Functional germination traits contribute to both niche competitiveness and crop yield  
14 outcomes. However, there is little understanding of the adaptive significance of the  
15 germination thermal- and hydro-parameters in crop wild relatives (CWRs), yet these  
16 species are anticipated to be the source of adaptive traits for future agriculture. Seeds of  
17 10 lots of *Brassica* species, sub-species and inbred lines from across Europe, North  
18 Africa and the Middle East were subjected to a range of temperature and water potential  
19 conditions. The germination progress curves recorded were analysed using repeated  
20 probit analysis and the functional trait parameters (thermal- and hydro thresholds and  
21 times) determined. Relationships between these seed parameters (and the physical trait,  
22 seed mass) and the seed source environment were investigated.

23 The *Brassica* genus was found to have diverse seed germination phenotypes, with  
24 thermal ( $\theta_T$ ) and hydro times ( $\theta_H$ ) differing by 3 to 7-fold, base temperatures ( $T_b$ ) by c. 9  
25 °C and base water potentials ( $\Psi_b$ ) by -1.5 MPa. Crop seed lots of *Brassica oleracea* had  
26 shorter  $\theta_H$  for germination and higher values of  $\Psi_b$ , but longer  $\theta_T$  for germination than  
27 their CWR. For the CWRs, the mean monthly precipitation or the precipitation of the  
28 predicted month of germination of the seed collection site, was linearly correlated with  
29  $T_b$ ,  $\theta_T$ , and  $\Psi_b$ . This increases the predictability of identifying valuable brassica  
30 germplasm for crop development through regeneration trait screening.

31 In conclusion, the selection of the crop *B. oleracea* for fastest germination under  
32 irrigated conditions likely limits the capacity of the current genepool to cope with  
33 erratic periods of drought predicted in future European climates.

34 **Keywords:** Seed functional traits; thermal time; hydro time; vigor; precipitation; seed  
35 mass.

## 36 **1. Introduction**

37 Global climate change is predicted to increase environmental temperatures, but may  
38 have other consequences such as earlier frosts and changes to the frequency of flooding  
39 and drought (IPCC, 2013), all of which may affect the outcome of germination and  
40 seedling emergence. In particular, warming temperatures and fluctuations in  
41 precipitation are known to increase the risk to yield in the most economically important  
42 crops, such as wheat, rice, maize and barley (Lobell and Field, 2007; Porter and  
43 Semenov, 2005). Moreover, crops bred for predictable and more uniform germination  
44 and harvest may contribute to loss of variability in responses to environmental  
45 conditions (Gepts, 2010). In contrast, crop wild relatives (CWRs) represent a genepool  
46 that is potentially adapted to a large range of habitats and, therefore, likely better  
47 equipped to survive the challenges associated with climate change (Dempewolf et al.,  
48 2014). In addition to possessing high genetic diversity, CWR species may also have  
49 greater plasticity in traits enabling them to cope better with rapid environmental change  
50 (Nicotra et al., 2010).

51 Global plant variability can be explained by just six adult plant-functional traits, only  
52 one of which relates to the regenerative phase, specifically diaspore mass (Díaz et al.,  
53 2016). This seed physical trait has been shown to be predictive of a light requirement  
54 for germination, persistence in the soil and dispersal (Baskin and Baskin, 2014).  
55 However, increasing importance is being attributed to germination functional traits such  
56 as germination rate, thermal time and hydro time, determined by the quantification of  
57 the physiological process of germination as a descriptor of regeneration potential.

58 Germination rate is an important and widely used descriptor of seed vigour (Pollock and  
59 Roos 1972). These traits are now recognised as critical components of the multiple  
60 environmentally regulated factors that define the ecological niche for population growth  
61 (Dürr et al., 2015; Fernández-Pascual et al., 2015; Grubb, 1977; Poschlod et al., 2013)

62 Recent characterisation of germination functional traits (base temperature,  $T_b$ ; and  
63 thermal time,  $\theta_T$ ) in CWRs of grapevine have identified populations at greater risk of  
64 climate change on the basis of insufficient cold to remove seed dormancy (Orru et al.,  
65 2012). In consideration of future proofing agriculture in France, 36 cover crops (across  
66 six plant families including the *Brassicaceae*) have been characterised for germination  
67 functional traits (Tribouillois et al., 2016). Four *Brassicaceae* (*B. juncea*, *B. rapa*, *B. napus*,  
68 *B. carinata*) had  $T_b$  of c. 7°C and three species had similar base water potentials,  $\Psi_b$ , for  
69 germination (-0.9 to -1 MPa), the exception being *B. rapa* (-2.2 MPa) (Tribouillois et  
70 al., 2016). These findings lend weight to the argument that a species geographical origin  
71 defines its ability to germinate (Cochrane et al., 2014; Dürr et al., 2015).

72 The convergence of functional traits in species occupying similar environments can be  
73 considered an adaptation to environmental filtering (Keddy, 1992). Precipitation and  
74 temperature are the main environmental factors that have an impact on plant traits, e.g.,  
75 leaf mass, yield, height and flowering time; and seed traits, such as seed mass,  
76 germination and dormancy, show similar ecological associations (Ackerly et al., 2000;  
77 Baskin and Baskin, 1998; Dornbos and Mullen, 1991; Franks et al., 2007; Menzel et al.,  
78 2006; Peñuelas et al., 2004; Porter, 2005). Seed germination (i.e., radicle emergence)  
79 and seedling establishment are thought to be the most sensitive stage of a plant to  
80 environmental changes (Fay and Schultz, 2009; Kimball et al., 2010; Lloret et al.,  
81 2004). Consequently, the effects of both precipitation and temperature on germination

82 rate (Céspedes et al., 2012; Clauss and Venable, 2000; Levine et al., 2008; Meyer et al.,  
83 1990), final germination (Alexander and Wulff, 1985; Gareca et al., 2012; Gutterman,  
84 2000b) and seedling establishment (Cochrane et al., 2015; Jump et al., 2008; Lloret et  
85 al., 2004; Smith et al., 2000) have been widely explored.

86 Crop domestication has resulted in larger seed size (Preece et al., 2017) and seed mass  
87 is also known to be responsive to environmental fluctuations (Donohue et al., 2005;  
88 Nicotra et al., 2010; Roach and Wulff, 1987). In particular, seed filling is influenced by  
89 environmental conditions and mean seed mass of a population has been positively  
90 correlated with annual rainfall (Harel et al., 2011) or with mean annual temperature  
91 (Murray et al., 2004). Whilst seed size is thought to affect germination rate (Norden et  
92 al., 2009), seed mass is rarely co-analysed with seed physiological traits of germination  
93 base temperature ( $T_b$ ) or base water potential ( $\Psi_b$ ). In this context, seed mass and  $T_b$  of  
94 tree seeds of *Aesculus hippocastanum* from across Europe had no correlation (Daws et  
95 al., 2004), and a negative correlation was found between seed mass and  $\Psi_b$  of  
96 neotropical forest species (Daws et al., 2008).

97 Our aim was to investigate how the originating environment of *Brassica* CWRs impact  
98 on their germination functional traits, testing the assumption that current *Brassica*  
99 crops may have been selected for fast germination under managed, irrigated conditions.  
100 We used seven geo-referenced seed collections (from across Europe, North Africa and  
101 the Middle East) and three commercially available crop seed lots and research  
102 genotypes. The genus *Brassica* possesses a wide diversity in morphology, genetics  
103 (Arias et al., 2014), environment stress tolerance and is economically important around  
104 the world for its edible roots crops, vegetables and oilseeds (Tsunoda et al., 1980). We  
105 selected wild taxa from locations with variable mean monthly precipitation (1 – 94 mm)

106 and temperature (5 – 25 °C). We show an intimate relationship between *Brassica* seed  
107 collection site and germination functional traits.

## 108 **2. Material and Methods**

### 109 *2.1 Seed material*

110 Studies were performed on seven seed lots of non-dormant wild brassica: three species  
111 (*Brassica rapa*, *B. nigra* and *B. tournefortii*) and two sub-species (*Brassica rapa* subsp.  
112 *campestris* and *B. rapa* subsp. *sylvestris*). (Table 1A). These CWR seed lots were  
113 obtained from the Millennium Seed Bank, Royal Botanic Gardens, Kew, UK. Seed lots  
114 used were from across Europe, North Africa and the Middle East. Selection was based  
115 on an environmental cline typical of *Brassica* species: annual mean temperature from 5  
116 to 26 °C; and a mean monthly precipitation from 1 mm to 94 mm, in seed lots with  
117 sufficient quantity of seeds. The values were calculated as the mean monthly  
118 precipitation and annual mean temperature, i.e. the sum of all 12-monthly means,  
119 divided by 12. Seeds were handled in a consistent way on receipt at the seed bank:  
120 equilibration to 15 % RH and 15 °C, hermetical sealing in containers and then storage at  
121 -20 °C (FAO/IPGRI, 1994). On withdrawal from the bank, seeds were re-equilibrated to  
122 15 °C in a room operating at c. 15 % RH.

123 A commercial seed lot of *B. oleracea* (cabbage) was obtained from B&T World Seeds  
124 (France) (Table 1B) and seeds of two research genotypes derived from *B. oleracea*  
125 crops (A12DHd from kale and AGSL101 from kale and broccoli) were provided by the  
126 University of Warwick. Both crop research genotypes have the same genetic  
127 background (A12) but SL101 has introgressions from at least two QTL (RABA1 and  
128 SOG1) from a faster germinating genotype (GD33DH, broccoli) that confers higher

129 vigour (Morris et al., 2016). For simplicity, henceforth A12DHd and AGSL101 will be  
 130 called RG\_L (low vigour research genotype) and RG\_H (high vigour research  
 131 genotype). The commercial genotype will be called CG. Both crop research genotypes  
 132 were grown under the same controlled conditions at 18/22 °C (night/day) in a  
 133 glasshouse to produce seeds. On receipt at RBG Kew, all seed lots were equilibrated to  
 134 15 % RH and 15 °C and stored under these conditions for a few weeks until use.

A.		Annual mean temperature			
Species	Collection site	Mean monthly precipitation (mm)	Min T (°C)	Mean T (°C)	Max T (°C)
<i>B. rapa</i> (CWR)	Chur (Switzerland)	94.17	4.8	9.2	13.7
<i>B. nigra</i> (CWR)	Dorset (England)	68.83	6.2	9.9	13.8
<i>B. rapa</i> (CWR)	Memsault (France)	64.08	6.5	10.9	15.4
<i>B. rapa</i> subsp. <i>campestris</i> (CWR)	Göle-Kars (Turkey)	40.84	-1.6	4.8	11.5
<i>B. rapa</i> subsp. <i>sylvestris</i> (CWR)	Ait Marghad (Morocco)	26.8	3.8	12.1	20.4
<i>B. tournefortii</i> (CWR)	Natrun – Alamin (Egypt)	4.83	14.3	20.7	27.1
<i>B. rapa</i> subsp. <i>sylvestris</i> (CWR)	S. Oran (Algeria)	0.83	17.5	25.7	34.0

B.	Provider	Genotype	Vigour	Growth conditions	
				Day (°C)	Night (°C)
		CG			
<i>B. oleracea</i> (crop)	B&T World Seeds (France)	(Commercial seed lot)	Unknown	Unknown	Unknown
<i>B. oleracea</i> (crop research genotype)	University of Warwick (UK)	RG_H (AGSL101)	High	22	18
<i>B. oleracea</i> (crop research genotype)	University of Warwick (UK)	RH_L (A12DHd)	Low	22	18

135 **Table 1.** Details of the 10 *Brassica* seed lots used. (A) The environment information  
136 was obtained by combining seed collection geo-locations (GIS coordinates) for the  
137 *Brassica* crop wild relatives (CWRs) and WorldClim data, as historical annual mean  
138 temperature (T) and mean monthly precipitation since 1960. (B) Plant growth and seed  
139 production conditions are shown for the research genotype seed lots, but are unknown  
140 for the commercially purchased *B. oleracea* crop seed lot.

## 141 2.2 Seed mass and germination

142 To characterise the seed mass of the *Brassica* seed lots, 100 seeds were individually  
143 weighed to 0.0001 mg accuracy. The distribution of seed mass at 0.5 mg intervals was  
144 analysed and the mean and coefficient of variation (CV) calculated.

145 For germination, seeds were sown at constant temperatures from 5 to 45 °C, at 5 °C  
146 intervals. Seeds were also sown at a range of water potentials (0, -0.3, -0.5, -0.8 and -1.0

147 MPa) using water and increasing concentrations of polyethylene glycol 8000 (PEG,  
148 Fisher Scientific, UK) solution, but only at constant temperatures of 25 and 30 °C. Due  
149 to limited seed availability, *B. nigra* seeds were sown under constant temperatures  
150 without water stress. Either three replicates of 25 seeds, for the CWRs, or four replicates  
151 of 25 seeds for the crops, were used in each treatment. Seeds were sown onto two layers  
152 of germination test paper (90 mm diameter; Fisher Scientific, UK) in Petri dishes. The  
153 volume of PEG solution used (7 mL) was calculated following the equation of  
154 Hardegree and Emmerich (1990) to account for the weight of the dry germination paper.  
155 The water potential of the solutions was confirmed with an osmometer (Camlab, UK).  
156 For consistency, the same volume (7 mL) of solution was used for all PEG and water  
157 treatments. The vented Petri dishes were placed in sealable plastic bags and incubated at  
158 the relevant temperature with a 12 hour photoperiod (radiometric flux density of 50-100  
159 W/m<sup>2</sup>). Germination (radicle emergence of 2 mm) was recorded every hour during the  
160 first 24 hours and then every two-three hours until no more germination was observed.  
161 Non-germinated seeds that were still firm after PEG treatment were briefly washed with  
162 distilled water to remove the PEG and transferred to a new Petri dish with germination  
163 test paper and 7 mL of water. After 15 days in this recovery assessment, if the seeds did  
164 not germinate, the seed coat was removed and the viability was tested with 1 %  
165 triphenyl tetrazolium chloride (TZ) in the darkness at 30 °C (ISTA, 2003) for 18 hours.  
166 Stained red embryos were considered to be viable.

### 167 2.3 Data analysis

168 Germination was quantified as final germination percentage and germination rate (GR).  
169 Germination progress over time was represented as a sigmoidal curve (fitted using the  
170 Boltzmann distribution) from which the GR was estimated for all treatments in each

171 population. The GR at the 50<sup>th</sup> percentile (t<sub>50</sub>) is the reciprocal of time the population  
172 needs to reach 50 % germination of viable seeds. The seeds were germinated at a range  
173 of temperatures and the GR describes a positive (sub-optimal range of temperatures) or  
174 negative (supra-optimal range of temperatures) regression line when plotted against  
175 temperature. The intercept of both lines is the optimal temperature (T<sub>o</sub>) where the GR is  
176 estimated to be at a maximum. Base temperature (T<sub>b</sub>) and ceiling temperature (T<sub>c</sub>) are  
177 the intercept of the lines when GR is estimated to be zero, and germination does not  
178 proceed to completion when seeds are below T<sub>b</sub> and above T<sub>c</sub> (García-Huidobro et al.,  
179 1982). Thermal time (θ<sub>T</sub>) was estimated by repeated probit analysis in GenStat 12.1  
180 software (VSN International Ltd, 2009). This method consisted of varying T<sub>b</sub> until the  
181 best fit was obtained (minimum residual) (Bradford, 1995; Ellis et al., 1986) based on  
182 the following two equations:

183 Sub-optimal θ<sub>T</sub> is  $\text{Probit}(g) = K + (\log \theta_T(g)) / \sigma_{\theta_T}$  (Bradford, 1995; Ellis et al., 1986) (1)

184 Supra-optimal θ<sub>T</sub> is  $\text{Probit}(g) = K + \theta_{T\text{supra}}(g) / \sigma_{\theta_T}$  (Covell et al., 1986; García-Huidobro  
185 et al., 1982). (2)

186 In both equations, K is the intercept constant when θ<sub>Tsupra</sub> is zero. θ<sub>T</sub> is the heat units the  
187 seed needs to accumulate for a given percentile (g) to complete germination in  
188 chronological time and σ is the standard deviation of the seed population response.

189 The basis of estimating hydro-time is the positive regression line between the GR and  
190 water potentials. The base water potential (Ψ<sub>b</sub>) is calculated as the intercept of the  
191 regression line of GR on water potential. Hydro time (θ<sub>H</sub>) was also estimated by  
192 repeated probit analysis. In this case, the method consisted of varying θ<sub>H</sub> until the best  
193 fit was obtained (minimum residual) (Bradford, 1995) using equation 3:

194  $\theta_H$  at  $T_o$  is  $\text{Probit}(g) = K - (\Psi_b(g) / \sigma_{\theta_H})$  (Bradford, 1995; Gummerson, 1986) (3)

195 where  $K$  is the intercept constant,  $\Psi_b$  is the base water potential (below this water  
196 potential no germination is predicted to occur) for a given percentile ( $g$ ) and  $\sigma$  is the  
197 standard deviation.

198 Additionally, analysis of variance (ANOVA) and t-tests were used to compare the seed  
199 mass and seed germination parameters between wild seed lots and between crop seed  
200 lots.

#### 201 2.4. *Environmental parameters associated with seed lot provenance*

202 The original, geo-referenced location of the CWR seed lots was used to extract climate  
203 data from WordClim with an accuracy of one kilometre for historical data over the  
204 period 1960 – 1990 (Hijmans et al., 2005). Associations between germination  
205 parameters and the following environmental factors were assessed: annual mean  
206 temperature (minimum, maximum and median in °C), mean monthly precipitation  
207 (mm), mean precipitation and temperature of the month of germination and the altitude.  
208 The month of germination was the first month after seed collection date that the  
209 following assumptions were met: (1) the minimum rainfall required for germination is a  
210 monthly mean of 15 mm (Freas and Kemp, 1983; Gutterman, 1993; Gutterman, 2000a)  
211 and (2) the temperature exceeded  $T_b$  but did not exceed  $T_c$  (Figure S1). The exception  
212 was *B. rapa* subsp. *sylvestris* from Algeria where the maximum monthly precipitation  
213 did not exceed 2 mm (Figure S1). For this species, the first period of significant rainfall  
214 was taken as the precipitation threshold. In addition, correlations between the  
215 environmental factors and the seed germination parameters of the wild species,  $\theta_T$ ,  $\theta_H$

216 time,  $T_b$  and  $\Psi_b$  were tested with scatter matrix and linear correlations in Origin 9.0  
217 software (OriginLab Corporation, 2013).

### 218 **3. Results**

219 The seeds of all *Brassica* seed lots had high viability. Seed germination of the CWRs  
220 varied from 93 % (*B. rapa*) to 100 % (*B. tournefortii*) and seeds of the crop genotypes  
221 of *B. oleracea* reached 100 % germination.

#### 222 *3.1 Germination trait parameters*

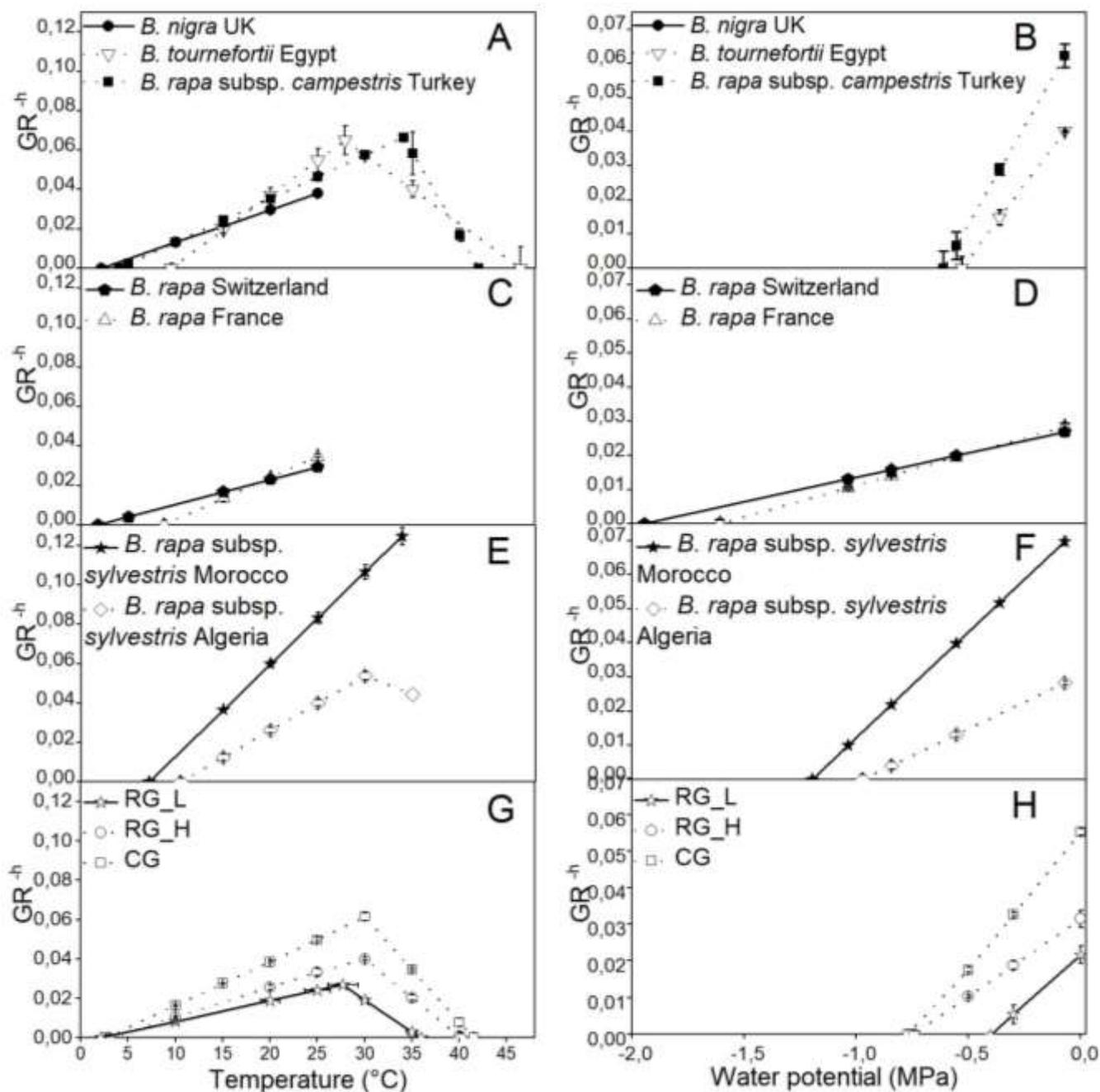
223 Seed germination of the 10 *Brassica* seed lots (CWRs and crops) showed a *c.* 9 °C  
224 range in each of the cardinal temperatures:  $T_b$  from 1.7 to 10.5 °C;  $T_o$  from 25 to 35 °C;  
225 and  $T_c$  from 36 to 45 °C (Figures 1A, C, E and G). Intra-specific variability in trait  
226 parameters was observed in two wild seed lots of *B. rapa* from France and Switzerland  
227 (Figure 1C) and two wild seed lots of *B. rapa* subsp. *sylvestris* from Morocco and  
228 Algeria (Figure 1E), with significant differences ( $P < 0.05$ ) in germination rate (GR)  
229 and  $T_b$  (Table S1). Thermal time ( $\theta_T$ ) values also differed three-fold amongst CWRs  
230 (from 214.7 °Ch for *B. rapa* subsp. *sylvestris* from Morocco to 775.5 °Ch for *B. rapa*  
231 from Switzerland) and the crop research genotype *B. oleracea* RG\_L had the longest  $\theta_T$   
232 of 951.6 °Ch (Table S1).

233 In general, seeds of the crop genotypes *B. oleracea* (RG\_L, RG\_H and CG) were slower  
234 to germinate compared with the CWRs in terms of  $\theta_T$  in the sub-optimal range of  
235 temperatures (Table S1). The high vigour crop genotype, RG\_H, had faster germination  
236 (i.e. shorter  $\theta_T$ ) than the low vigour crop genotype, RG\_L ( $P < 0.01$ ); whilst the CG had  
237  $\theta_T$  very similar to the CWR *B. rapa* subsp. *campestris* (i.e., *c.* 445 °Ch). In contrast,  $T_b$

238 for the *B. oleracea* seed lots did not differ (Figure 1G). However,  $T_c$  was higher in the  
239 crop genotype RG\_H and CG than the genotype RG\_L (40 °C and 41.5 °C vs 36 °C,  
240 respectively,  $P < 0.001$ ). In the supra-optimal temperatures,  $\theta_{Tsupra}$  was shorter in CG,  
241 but the other two crop genotypes did not differ.

242 Seeds were also germinated under five water potentials. GR slowed and final  
243 germination decreased with more negative water potentials, and  $\Psi_b$  values varied  
244 between -0.4 MPa and -2 MPa (Figure 1B, D, F and H). Both seed lots of the CWR *B.*  
245 *rapa* (France, Switzerland) had the lowest  $\Psi_b$  of -1.59 MPa and -1.94 MPa respectively  
246 (Figure 1D). The hydro time ( $\theta_H$ ) values also differed among all CWRs from 9.0 MPah  
247 for *B. rapa* subsp. *campestris* to 72 MPah of *B. rapa* Switzerland (Table S1). At the end  
248 of the experiment, all non-germinated seeds were transferred to water and subsequently  
249 germinated within 48 hours, except for *B. rapa* subsp. *sylvestris* (Algeria) which only  
250 achieved 40 % of germination after 15 days. However, a tetrazolium test showed that all  
251 the seeds of *B. rapa* subsp. *sylvestris* (Algeria) were viable.

252 Whilst the  $\theta_H$  of the crop seed lots was within the range of the CWRs,  $\Psi_b$  of the crop  
253 seed lots was higher (less negative) than the CWRs, except for *B. tournefortii* and *B.*  
254 *rapa* subsp. *campestris* (Table S1). Within the crop seed lots, the high vigour genotype,  
255 RG\_H, had a larger  $\theta_H$  than RG\_L ( $P < 0.05$ ), with CG of *B. oleracea*, having the  
256 smallest  $\theta_H$  (Table S1). In contrast, the  $\Psi_b$  was lower in both crop seed lots, RG\_H and  
257 CG, than in RG\_L (-0.74 MPa in RG\_H, -0.78 MPa in the CG and -0.40 MPa in  
258 RG\_L). Therefore, seeds of RG\_H and CG could germinate over a wider range of water  
259 potentials than RG\_L (Figure 1H).

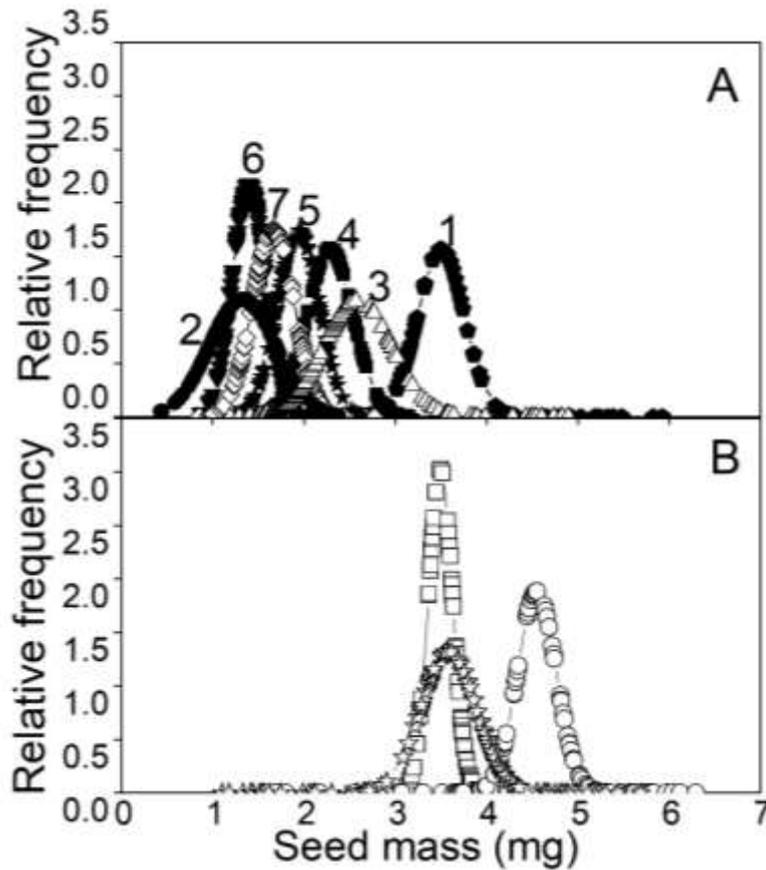


260 **Figure 1:** The germination rate (GR) was plotted against temperature (A, C, E and G)  
 261 to describe cardinal temperatures and the water potential thresholds (B, D, F and H) of  
 262 seven wild *Brassica* seed lots, two research genotypes of *B. oleracea* (RG\_L and  
 263 RG\_H) and the crop genotype CG. The seeds were germinated under a range of sub and  
 264 supra optimal temperatures between 5 to 35 °C and on PEG solutions at 0, -0.3, -0.5, -  
 265 0.8 and -1.0 MPa at one temperature (between 20 and 25 °C). The regression lines were  
 266 calculated from repeated probit analysis estimations and the error bars are the standard

267 deviation (SD) of three replicates for each treatment in CWRs and four replicates for  
268 crops.

269 Variation in seed mass of the CWRs was normally distributed, based on a normality test  
270 (D'Agostino's test,  $P < 0.05$ ) (Figure 2A). Two CWRs (*B. rapa* from France and *B.*  
271 *nigra* from UK) had the highest variability (CV 36 %) and *B. tournefortii* had the  
272 smallest variability in seed mass (CV 18.3 %). The crop seed lot variability in mass was  
273 similar to that of the CWRs from CV 13% for CG to CV 30% for RG\_L.

274 Of the CWRs, mean seed mass of *B. rapa* from Switzerland was the largest ( $P < 0.05$ )  
275 (Figure 2A). In general, the crop seed lots had heavier seeds than the CWRs, with the  
276 seeds of RG\_H heavier than those of RG\_L and CG of *B. oleracea* (Figure 2B).

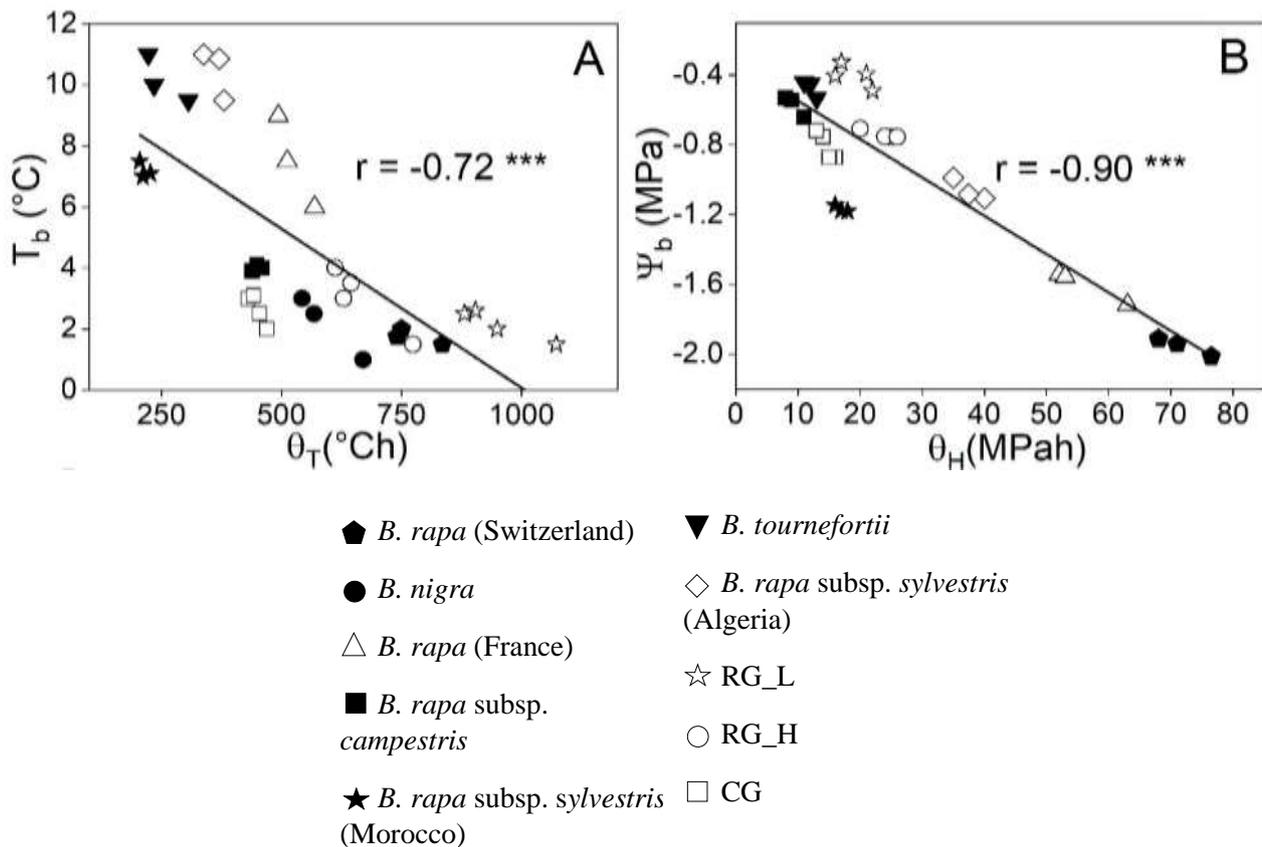


277 **Figure 2.** Seed mass of 100 individual seeds were shown as normal distribution for **A)**  
 278 CWRs, 1) *Brassica rapa* (Switzerland), 2) *B. nigra* (England), 3) *B. rapa* (France), 4) *B.*  
 279 *rapa* subsp. *campestris* (Turkey), 5) *B. rapa* subsp. *sylvestris* (Morocco), 6) *B.*  
 280 *tournefortii* (Egypt) and 7) *B. rapa* subsp. *sylvestris* (Algeria); and **B)** two research  
 281 genotypes of *B. oleracea*, RG\_L (open stars) and RG\_H (open circles) and one CG  
 282 (open squares). Each symbol is the mass of an individual seed.

### 283 3.2 Inter-relations between seed traits

284 The seed traits of all *Brassica* seed lots (including both crop and wild) were compiled  
 285 and subjected to linear regression models. A negative relationship was found between  
 286  $T_b$  and  $\theta_T$  for all *Brassica* seed lots tested ( $P < 0.0001$ ;  $r = -0.72$ , Figure 3A).  $\Psi_b$  and  $\theta_H$   
 287 were also negatively correlated ( $P < 0.0001$ ;  $r = -0.90$  Figure 3B). In both cases the  
 288 lower the base threshold (temperature or water potential) the longer the germination

289 process (thermal or hydro-time). A trend was found between the mean seed mass and  
290 the  $\theta_T$  and  $T_b$  ( $r = 0.53$  and  $-0.61$ , respectively) so that heavier seeds need to accumulate  
291 more  $\theta_T$  to germinate and had a lower  $T_b$ , but it was not significant ( $P = 0.1$  and  $0.06$ ,  
292 respectively). Furthermore, the CV of the seed mass was positively correlated with  $\theta_T$  ( $P$   
293  $< 0.05$ ;  $r = 0.40$ ), but not with  $T_b$ . Neither  $\theta_H$  nor  $\Psi_b$  were correlated with mean seed  
294 mass, however,  $\theta_H$  was positively correlated with the CV of seed mass ( $r = 0.48$ ;  $P <$   
295  $0.01$ ).

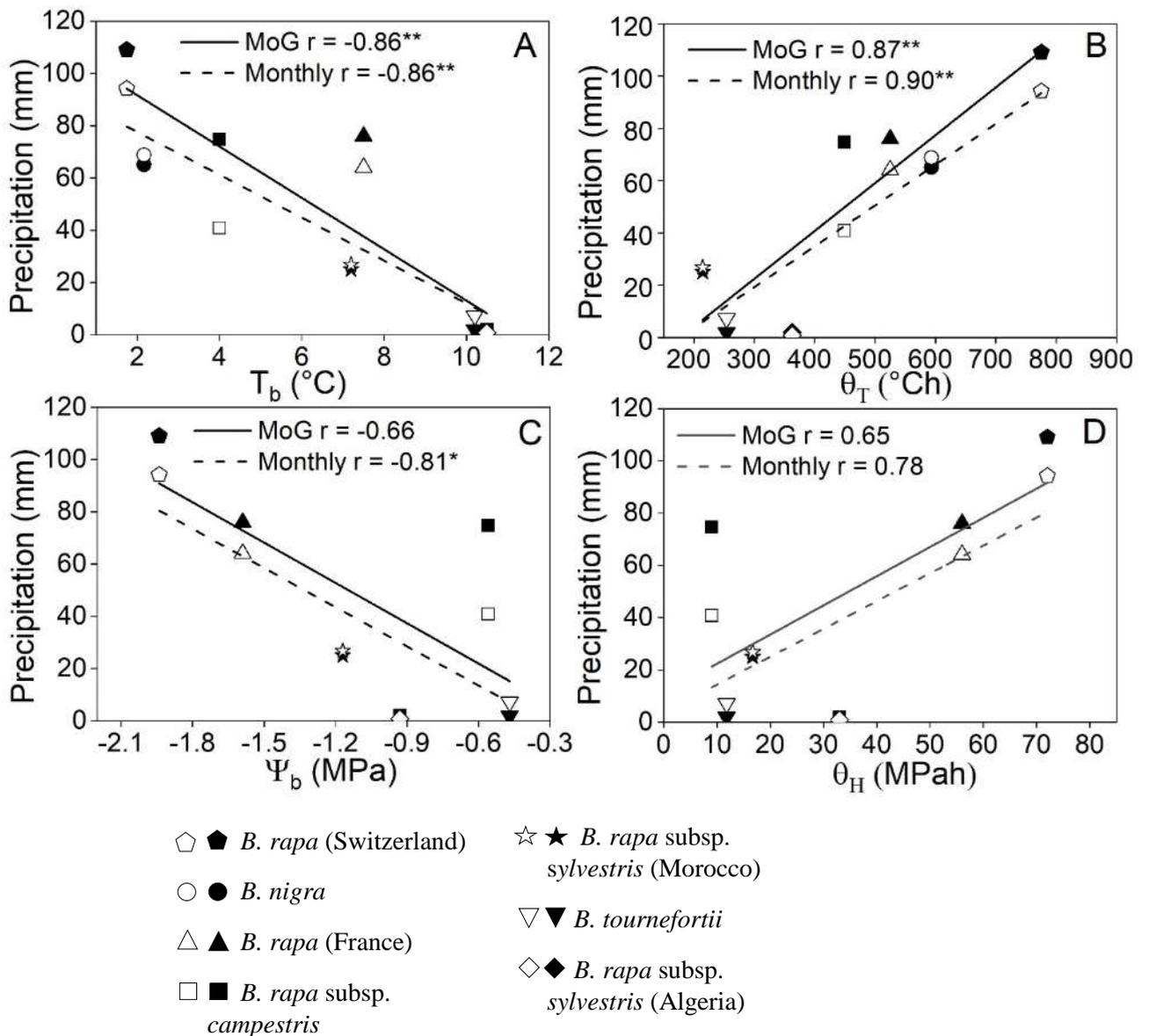


296 **Figure 3.** Correlations between seed traits of 10 *Brassica* seed lots (7 CWRs and 3  
 297 crops). **A)** Base temperature ( $T_b$ ) and thermal time ( $\theta_T$ ); **B)** base water potential ( $\Psi_b$ ) and  
 298 hydro time ( $\theta_H$ ) and. The values of  $\theta_T$ ,  $T_b$ ,  $\theta_H$  and  $\Psi_b$  were calculated on the 50<sup>th</sup>  
 299 percentile. Each point represents a replicate of each population, three replicates for  
 300 CWRs and four replicates for crops. Asterisks indicating the significance at  $P <$   
 301  $0.001^{***}$  DF = 30 in A, 27 in B

### 302 3.3 Relations between environment and CWR seed traits

303 The dependencies of CWR functional seed traits on the collection site environment were  
 304 assessed for the seven wild *Brassica* seed lots (Table S2).  $T_b$  was lower when the  
 305 monthly precipitation, and the precipitation of the predicted month of germination based  
 306 on the quantified responses, were higher (Figure 4A). Seed lots of species from wetter  
 307 environments also had slower germination (i.e., longer  $\theta_T$ ; Figure 4B). The mean

308 monthly precipitation was negatively correlated with  $\Psi_b$  (Figure 4C). However, the  
 309 precipitation was not significantly correlated with  $\theta_H$  (Figure 4D). With regard to  
 310 temperature,  $T_b$  and the annual mean temperature (minimum, mean and maximum) were  
 311 correlated (Table S2). Finally, the altitude was not correlated ( $P > 0.05$ ) with any  
 312 germination parameter; and seed functional traits did not correlate with the temperatures  
 313 at other times of the year when plant developmental events such as flowering would  
 314 have occurred.



315 **Figure 4.** Correlation of the seed germination traits of seven CWRs and the  
 316 environment of the seed collection site. Mean monthly precipitation (open symbols and

317 dashed line) and the precipitation of the month of germination (MoG) (solid symbols  
318 and solid line) were plotted against the base temperature ( $T_b$  **A**), the thermal time ( $\theta_T$ ,  
319 **B**), the base water potential ( $\Psi_b$ , **C**) and the hydro time ( $\theta_H$ , **D**). The values of  $\theta_T$ ,  $T_b$ ,  $\theta_H$   
320 and  $\Psi_b$  were calculated on the 50<sup>th</sup> percentile. Each point is one of the three replicates of  
321 each population. Asterisks indicating the significance at  $P < 0.05^*$  and  $P < 0.01^{**}$  DF =  
322 5 in A and B, and 4 in C and D

## 323 **4. Discussion**

### 324 4.1. *Comparative seed germination thresholds*

325 The variation in *Brassica* germination thresholds (c. 9 °C) amongst 10 seed lots is wider  
326 than that observed for other comparative studies based on taxonomy or habitat. For  
327 example, in cold and warm season grasses,  $T_b$  ranges by 2.6 °C to 5.9 °C, respectively  
328 (Jordan and Haferkamp, 1989). Pasture species (e.g., clover, ryegrass and chicory) also  
329 display a relatively narrow  $T_b$  range of 3.5 °C (Moot et al., 2000). As the local  
330 environment is known to influence the expression of this trait, such variation in CWRs  
331 of *Brassica* can be explained by the selection of taxa from seven countries with widely  
332 differing environments, having annual mean temperatures varying from 5 to 26 °C,  
333 across a latitudinal span of c. 20°. In more than 50 species of Cactaceae, sampled across  
334 an environmental envelope that covers 70° of latitude, seed  $T_b$  varies by c. 20 °C (Seal  
335 et al., 2017).

336 The range of  $\Psi_b$  for the 50<sup>th</sup> percentile of germination was also wide for species in the  
337 *Brassica* genus (i.e., -1.54 MPa) from -0.40 to -1.94 MPa. This range is similar to that  
338 for other crop seeds from different families [such as, *Daucus carota* (Apiaceae),  
339 *Helianthus annuus* (Asteraceae), *Hordeum vulgare* and *Zea mays* (Poaceae)], that have

340 a range extending to -2.1 MPa (Dürr et al., 2015). Interestingly, *B. rapa* has been  
341 estimated to have a  $\Psi_b$  as low as -2.2 MPa (Tribouillois et al., 2016). However, this  
342 study used data for only the 20<sup>th</sup> and 30<sup>th</sup> percentiles of germination as viability was  
343 poor. We also found an average  $\Psi_b$  for the same percentiles of germination to be -2.2  
344 and -1.99 MPa for wild *B. rapa* from Switzerland and France, respectively. However,  
345 the 50<sup>th</sup> percentile of the population is a better descriptor of germination performance if  
346 seed viability is above 50 % (Soltani et al., 2016).

347 The diversity of germination performance in terms of the thermal and hydro traits  
348 observed in the *Brassica* genus is due to both, their genetic variability (Arias et al.,  
349 2014; Arias and Pires, 2012) and the influence of the environment (phenotypic  
350 plasticity) (Mousseau and Fox, 1998; Schmid and Dolt, 1994; Van Kleunen et al.,  
351 2007). In this study, we cannot definitively distinguish between genetic or phenotypic  
352 variability in the CWRs. However, by studying two *Brassica* seed lots, each of two  
353 CWRs from different environments, along with different species from across a broad  
354 environmental range, we were able to assess the influence on seed functional traits of  
355 the collection site abiotic features. Moreover, studying two *B. oleracea* research crop  
356 genotypes selected for differences in vigour (RG\_L and RG\_H), and grown under  
357 identical glasshouse conditions, enabled us to consider the impact of high vigour alleles  
358 in these research lines on germination traits.

#### 359 4.2. *Selecting for seed performance in Brassica*

360 Seed quality is an essential trait for crop production and food security (Finch-Savage  
361 and Bassel, 2015). As a consequence, the seed industry strives to produce seed lots with  
362 enhanced performance, particularly vigour which is often assessed under non-optimal  
363 conditions. Vigour is a property of the seed that determines performance in a wide range

364 of environments (ISTA, 2017). Amongst 10 *Brassica* seed lots assessed over many  
365 temperature and water potential conditions we show strong correlations between  $T_b$  and  
366  $\theta_T$  and  $\Psi_b$  and  $\theta_H$  (Figure 3) in addition to the correlations with the precipitation of the  
367 climate of seed collection site of the CWRs (Figure 4). A relationship between  $\Psi_b$  and  
368  $\theta_H$  is anticipated, as the hydro time model shows that germination rate is inversely  
369 proportional to the difference between the actual water potential ( $\Psi$ ) and the  $\Psi_b$   
370 (Bradford, 1995). Thus, seeds with lower  $\Psi_b$  (more negative water potentials) will  
371 require more hydro time to germinate, i.e., have longer  $\theta_H$  (Bradford, 1995). On the  
372 other hand, the correlation between  $T_b$  and  $\theta_T$  has been reported previously for a range  
373 of different species (Dürr et al., 2015; Gardarin et al., 2011; Seal et al., 2017; Trudgill et  
374 al., 2005; Trudgill et al., 2000). This might reflect ecological adaptation such that the  
375 seeds with a high threshold then proceed to germinate faster, i.e., shorter thermal times  
376 (Gardarin et al., 2011; Trudgill et al., 2005). As there is intra- and inter-specific  
377 variation in the thresholds for seed germination progress under a wide range of (thermal  
378 and water potential) environments (Dürr et al., 2015), it is critical that these parameters  
379 are determined for each seed lot so that vigour can be more accurately described.

380 In general, the CWRs had a lower  $\Psi_b$ , hence a wider window for water potential  
381 tolerance than the crops. Whereas the seed selection of the crop *B. oleracea* for growth  
382 under optimal, irrigated monoculture agricultural conditions may have led to a higher  
383  $\Psi_b$  that increases the risk of crop failure in a future climates of variable water  
384 availability. The low  $\Psi_b$  are a greater ability to cope with variable water conditions  
385 indicated in the CWRs may provide a means to improve crop genotypes in the future.

386 The CWRs tended to have similar  $\theta_T$  compared to the crops. Therefore, the selection and  
387 breeding of *B. oleracea* has not resulted in particularly faster germination in terms of

388 thermal time, based on the seed lots characterised here. Even though crop genotype  
389 RG\_H was the product of the introgression of two high vigour alleles, the impact of this  
390 on thermal time was not beneficial compared with CWRs, but it was beneficial  
391 compared with the low vigour genotype. RG\_L had the longest  $\theta_T$  compared with the  
392 other crops and CWRs, i.e. germination is slower, which would increase the risk of  
393 inclement drought or seedbed deterioration impacting on the more slowly emerging  
394 seedlings. Such subtle differences in thermal and hydro-time characteristics amongst a  
395 range of *Brassica* seed lots (Figure 3, Dürr et al., 2015; Tribouillois et al., 2016) tends  
396 to suggest a continuum of responses within the genus.

#### 397 4.3. *Seed mass*

398 Crops were compared to CWRs to observe the effect of breeding and domestication on  
399 the *Brassica* genus, one of the main effects of which can be greater seed mass (Doganlar  
400 et al., 2000). Research crop genotype RG\_H had the heaviest seeds compared to the  
401 other *B. oleracea* seed lots and the CWRs (Figure 2). Moreover, less population  
402 variation in seed mass (CV) would be expected for crops and this was generally the  
403 case. A trend was found where heavier seeds tended to germinate slower than lighter  
404 seeds on a thermal basis (longer  $\theta_T$ ). This finding was contrary to that of Huang et al.  
405 (2016) who found that larger seeds germinated faster in wild desert species. Smaller  
406 seeds germinating faster than larger seeds has been found in other species. For example,  
407 Grime et al., 1981, who studied 400 species and reported a decrease of germination rate  
408 with increased seed weight. Norden et al. (2009) found a similar correlation between the  
409 mean seed mass and the mean time to germination (MTG) in more than 1000 tropical  
410 forest trees. Kikuzawa and Koyama (1999) determined that small seeds had the capacity  
411 to imbibe water faster than larger seeds, thus the germination process could start earlier.

412 There was also a tendency for heavier seeds to have lower  $T_b$ . Thus, small seeds should  
413 require less time to germinate because they need to accumulate less heat units above a  
414 higher  $T_b$ . Counterintuitively, it seems that breeding to increase seed mass in *Brassica*  
415 crops is likely to have unintended consequences on germination rate based on thermal  
416 time characteristics. However, further investigation using a higher number of *Brassica*  
417 accessions and/or species is needed to confirm these trends.

#### 418 4.4. *Ecological correlates of seed performance*

419 In addition to temperature, precipitation controls the timing of germination in the wild.  
420 One general assumption is that germination occurs only if the monthly precipitation is  
421  $>15$  mm (Freas and Kemp, 1983; Gutterman, 1993; Gutterman, 2000a). On this basis,  
422 we predicted in which month the seeds will germinate. However, that assumption was  
423 not true for *B. rapa* subsp. *sylvestris* from Algeria, where the maximum monthly  
424 precipitation was not above 2 mm (Figure S1). The behaviour of *B. rapa* subsp.  
425 *sylvestris* from Algeria is similar to that of annual plants in an extreme desert climate  
426 (Gutterman, 1993) and also coincides with one of the fastest seed lots to germinate.  
427 When water is regularly available, temperature becomes the major influence of  
428 germination timing.

429 In *Brassica* CWRs,  $\theta_T$  was positively correlated with precipitation, which is in  
430 agreement with the suggestion that seeds from drier environments might be adapted to  
431 germinate faster to avoid drought periods during seedling establishment (Evans and  
432 Etherington, 1990; Fenner and Thompson, 2004; Gardarin et al., 2011; Moles and  
433 Westoby, 2004). At the same time,  $T_b$  and  $\Psi_b$  were negatively correlated with  
434 precipitation which means that: 1) the  $T_b$  might be higher in drier environments; and 2)  
435 in drier environments the seeds might be adapted to germinate rapidly in response to

436 sporadic rainfall events that increase soil water potential. According to these findings,  
437 the germination of wild *Brassica* seed lots, especially thermal time parameters ( $\theta_T$  and  
438  $T_b$ ) seem to be closely adapted to the precipitation of the maternal environment.

439 There are many reports of correlations between the mean seed mass and the maternal  
440 environment (mainly precipitation) including species such as *B. campestris* (Sinniah et  
441 al., 1998), 15 herbaceous species from UK (Evans and Etherington, 1990), annual  
442 species (e.g. *Glycine* genus) from a Mediterranean climate (Murray et al., 2004) and two  
443 wild species of barley and oat (Volis, 2012). Pakeman et al. (2008) found the  
444 temperature of several vegetation types across Europe was positively correlated with  
445 seed mass. In this study, the mean seed mass was only correlated with the precipitation  
446 of the month of germination (Table S2;  $P < 0.05$ ). This finding is in agreement with that  
447 on wheat, soya and walnut (Brocklehurst et al., 1978; Meckel et al., 1984; Stromberg  
448 and Patten, 1990). Since the size of the seed and number of seeds is limited by the  
449 availability of resources (Baskin and Baskin, 1998; Wulff, 1986), in this case, mother  
450 plants from environments with low precipitation are likely to produce fewer and small  
451 seeds.

## 452 **5. Conclusions**

453 Based on the thermal and hydro-time characteristics (thresholds and rates) *Brassica*  
454 CWRs appear better equipped to adapt to changes in the environment than the crop *B.*  
455 *oleracea*. CWRs tended to have lower  $\Psi_b$  than crops with suggest more tolerance to low  
456 water potentials. These adapted traits are somewhat predictable as the interspecific  
457 variation in germination functional traits ( $T_b$ ,  $\Psi_b$ ,  $\theta_T$ ) correlate strongly to the climate at  
458 the seed collection site, particularly to precipitation (the mean monthly and the mean of  
459 the month of cumulative thermal time germination). Our findings reinforce the need to

460 characterise each seed lot, with the additional benefit of more precisely defining seed  
461 vigour ‘under a wide range of environments’.

462

### 463 **Acknowledgements**

464 We gratefully thank Catherine Jacott and Pauline Lewis for assistance in the laboratory.  
465 The Royal Botanic Gardens, Kew, receives grant-in-aid from the Department of  
466 Environment, Food and Rural Affairs, UK.

467

468 **Funding:** This work was supported by the EU (FP7 grant 311840 EcoSeed) and The  
469 Royal Botanic Gardens, Kew.

470

### 471 **Supplementary data**

472 Supplementary data is associated with this manuscript.

473

### 474 **References**

475 Ackerly, D.D. et al., 2000. The Evolution of Plant Ecophysiological Traits: Recent  
476 Advances and Future Directions: New research addresses natural selection,  
477 genetic constraints, and the adaptive evolution of plant ecophysiological traits.

478 AIBS Bulletin, 50, 979-995.

479 Alexander, H.M. and Wulff, R.D., 1985. Experimental ecological genetics in *Plantago*.

480 X. The effects of maternal temperature on seed and seedling characters in *P.*

481 *lanceolata*. J. Ecol. 73, 271-282.

482 Arias, T., Beilstein, M.A., Tang, M., McKain, M.R. and Pires, C.J., 2014.  
483 Diversification times among *Brassica* (Brassicaceae) crops suggest hybrid  
484 formation after 20 million years of divergence. *Am. J. Bot.* 101, 86-91.

485 Arias, T. and Pires, C.J., 2012. A fully resolved chloroplast phylogeny of the brassica  
486 crops and wild relatives (Brassicaceae: Brassiceae): novel clades and potential  
487 taxonomics implications. *Taxon* 61, 980-988.

488 Baskin, C.C. and Baskin, J.M., 1998. *Seeds: ecology, biogeography and evolution of*  
489 *dormancy and germination.* Academic Press, San Diego.

490 Bradford, K.J., 1995. Water Relations in Seed Germination. In: J.K.a.G. Galili (Editor),  
491 *Seed development and germination,* New York, pp. 351-396.

492 Brocklehurst, P., Moss, J. and Williams, W., 1978. Effects of irradiance and water  
493 supply on grain development in wheat. *Ann. Appl. Bot.* 90, 265-276.

494 Céspedes, B., Torres, I., Urbietta, I.R. and Moreno, J.M., 2012. Effects of changes in the  
495 timing and duration of the wet season on the germination of the soil seed bank of  
496 a seeder-dominated Mediterranean shrubland. *Plant Ecolog.* 213, 919-931.

497 Clauss, M.J. and Venable, D.L., 2000. Seed germination in desert annuals: An empirical  
498 test of adaptive bet hedging. *Am. Nat.* 155, 168-186.

499 Cochrane, A., Hoyle, G.L., Yates, C.J., Wood, J. and Nicotra, A.B., 2014. Predicting the  
500 impact of increasing temperatures on seed germination among populations of  
501 Western Australian *Banksia* (Proteaceae). *Seed Sci. Res.* 24, 195-205.

502 Cochrane, J.A., Hoyle, G.L., Yates, C.J., Wood, J. and Nicotra, A.B., 2015. Climate  
503 warming delays and decreases seedling emergence in a Mediterranean  
504 ecosystem. *Oikos* 124, 150-160.

505 Covell, S., Ellis, R.H., Roberts, E.H. and Summerfield, R.J., 1986. The influence of  
506 temperatures on seed germination rate in grain legumes. A comparison of

507 chickpea, lentil, soybean and cowpea at constant temperatures. *Exp. Bot.* 37,  
508 705-715.

509 Daws, M.I., Crabtree, L.M., Dalling, J.W., Mullins, C.E. and Burslem, D.F.R.P., 2008.  
510 Germination responses to water potential in neotropical pioneers suggest large-  
511 seeded species take more risks. *Ann. Bot.* 102, 945-951.

512 Daws, M.I. et al., 2004. Developmental heat sum influences recalcitrant seed traits in  
513 *Aesculus hippocastanum* across Europe. *New. Phytol.* 162, 157-166.

514 Dempewolf, H. et al., 2014. Adapting agriculture to climate change: a global initiative  
515 to collect, conserve and use crop wild relatives. *Agroecol. Sust. Food* 38, 369-  
516 377.

517 Díaz, S. et al., 2016. The global spectrum of plant form and function. *Nature* 529, 167-  
518 171.

519 Doganlar, S., Frary, A. and Tanksley, S., 2000. The genetic basis of seed-weight  
520 variation: tomato as a model system. *TAG 100*, 1267-1273.

521 Donohue, K. et al., 2005. Environmental and genetic influences on the germination of  
522 *Arabidopsis thaliana* in the field. *Evolution* 59, 740-757.

523 Dornbos, D.L. and Mullen, R.E., 1991. Influence of stress during soybean seed fill on  
524 seed weight, germination and seedling growth rate. *Can. J. Plant. Sci.* 71, 373-  
525 383.

526 Dürr, C., Dickie, J.B., Yang, X.Y. and Pritchard, H.W., 2015. Ranges of critical  
527 temperature and water potential values for the germination of species  
528 worldwide: contribution to a seed trait database. *Agr. Forest Meteorol.* 200, 222-  
529 232.

530 Ellis, R.H., Covell, S., Roberts, E.H. and Summerfield, R.J., 1986. The influence of  
531 temperature on seed germination rate in grain legumes. II. Intraspecific variation

532 in chickpea (*Cicer arietinum* L.) at constant temperatures. J. Exp. Bot. 37, 1503-  
533 1515.

534 Evans, C.E. and Etherington, J.R., 1990. The effect of soil-water potential on seed-  
535 germination of some British plants. New Phytol. 115, 539-548.

536 FAO/IPGRI, 1994. Genebank Standards, Food and Agriculture Organization of the  
537 United Nations, Rome. International Plant Genetic Resources Institute, Rome.

538 Fay, P.A. and Schultz, M.J., 2009. Germination, survival and growth of grass and forb  
539 seedlings: Effects of soil moisture variability. Acta Oecol. 35, 679-684.

540 Fenner, M. and Thompson, K., 2004. The ecology of seeds, Cambridge University  
541 Press.

542 Fernández-Pascual, E., Jiménez-Alfaro, B., Hájek, M., Díaz, T. E. and Pritchard, H. W.,  
543 2015. Soil thermal buffer and regeneration niche may favour calcareous fen  
544 resilience to climate change. Folia Geobot. 50, 293-301.

545 Finch-Savage, W.E. and Bassel, G.W., 2015. Seed vigour and crop establishment:  
546 extending performance beyond adaptation. J. Exp. Bot. 67, 567-591.

547 Franks, S.J., Sim, S. and Weis, A.E., 2007. Rapid evolution of flowering time by an  
548 annual plant in response to climate fluctuation. PNAS 104, 1278-1282.

549 Freas, K.E. and Kemp, P.R., 1983. Some relationships between environmental  
550 reliability and seed dormancy in desert annual plants. J. Ecol. 71, 211-217.

551 García-Huidobro, J., Monteith, J.L. and Squire, G.R., 1982. Time temperature and  
552 germination of pearl millet (*Pennisetum typhoides* S&H). I. Constant  
553 temperature. J. Exp. Bot. 33, 288-296.

554 Gardarin, A., Dürr, C. and Colbach, N., 2011. Prediction of germination rates of weed  
555 species: Relationship between germination speed parameters and species traits.  
556 Ecol. Modell. 222, 626-636.

557 Gareca, E.E., Vandeloock, F., Fernandez, M., Hermy, M. and Honnay, O., 2012. Seed  
558 germination, hydrothermal time models and the effects of global warming on a  
559 threatened high Andean tree species. *Seed Sci. Res.* 22, 287-298.

560 Gepts, P., 2010. Crop domestication as a long-term selection experiment. *Plant Breed.*  
561 *Rev.* 24, 1-44.

562 Grime, J., Mason, G., Curtis, A., Rodman, J. and Band, S., 1981. A comparative study  
563 of germination characteristics in a local flora. *J. Ecol.* 69, 1017-1059.

564 Grubb, P.J., 1977. The maintenance of species- richness in plant communities: the  
565 importance of the regeneration niche. *Biol. Rev.* 52, 107-145.

566 Gummerson, R.J., 1986. The effect of constant temperatures and osmotic potentials on  
567 the germination of sugar beet. *Exp. Bot.* 37, 729-741.

568 Gutterman, Y., 1993. *Seed germination in desert plants.* Springer-Verlag, Berlin,  
569 Germany.

570 Gutterman, Y., 2000a. Environmental factors and survival strategies of annual plant  
571 species in the Negev Desert, Israel. *Plant Species Biol.* 15, 113-125.

572 Gutterman, Y., 2000b. Maternal effects on seeds during development. In: M. Fenner  
573 (Editor), *Seeds: the ecology of regeneration in plant communities.* CAB  
574 International, pp. 27-59.

575 Hardegree, S.P. and Emmerich, W.E., 1990. Effect of polyethylene glycol exclusion on  
576 the water potential of solution-saturated filter paper. *Plant Physiol.* 92, 462-466.

577 Harel, D., Holzappel, C. and Sternberg, M., 2011. Seed mass and dormancy of annual  
578 plant populations and communities decreases with aridity and rainfall  
579 predictability. *Basic Appl. Ecol.* 12, 674-684.

580 Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. and Jarvis, A., 2005. Very high  
581 resolution interpolated climate surfaces for global land areas. *Int. J. Clim.* 25,  
582 1965-1978.

583 Huang, Z., Liu, S., Bradford, K. J., Huxman, T. E., & Venable, D. L. (2016). The  
584 contribution of germination functional traits to population dynamics of a desert  
585 plant community. *Ecol.* 97, 250-261.

586 IPCC, 2013. Intergovernmental Panel on Climate Change. *Climate Change*, Cambridge  
587 University.

588 ISTA, 2003. Working sheets on tetrazolium testing, I and II, Bassersdorf, Switzerland.

589 ISTA, 2017. International Rules for Seed Testing. International Seed Testing  
590 Association, Bassersdorf, Switzerland.

591 Jordan, G.L. and Haferkamp, M.R., 1989. Temperature responses and calculated heat  
592 units for germination of several range grasses and shrubs. *J. Range Manage.* 42,  
593 41-45.

594 Jump, A.S. et al., 2008. Simulated climate change provokes rapid genetic change in the  
595 Mediterranean shrub *Fumana thymifolia*. *Global Change Biol.* 14, 637-643.

596 Keddy, P.A., 1992. Assembly and response rules: two goals for predictive community  
597 ecology. *J. Veg. Sci.* 3, 157-164.

598 Kikuzawa, K. and Koyama, H., 1999. Scaling of soil water absorption by seeds: an  
599 experiment using seed analogues. *Seed Sci. Res.* 9, 171-178.

600 Kimball, S., Angert, A.L., Huxman, T.E. and Venable, D.L., 2010. Contemporary  
601 climate change in the Sonoran Desert favors cold-adapted species. *Global  
602 Change Biol.* 16, 1555-1565.

603 Levine, J.M., McEachern, A.K. and Cowan, C., 2008. Rainfall effects on rare annual  
604 plants. *J. Ecol.* 96, 795-806.

605 Lobell, D.B. and Field, C., 2007. Global scale climate-crop yield relationships and the  
606 impacts of recent warming. *Environ. Res. Lett.* 2, 014002

607 Lloret, F., Peñuelas, J. and Estiarte, M., 2004. Experimental evidence of reduced  
608 diversity of seedlings due to climate modification in a Mediterranean-type  
609 community. *Global Change Biol.* 10, 248-258.

610 Meckel, L., Egli, D., Phillips, R., Radcliffe, D. and Leggett, J., 1984. Effect of moisture  
611 stress on seed growth in soybeans. *Agron. J.* 76, 647-650.

612 Menzel, A. et al., 2006. European phenological response to climate change matches the  
613 warming pattern. *Global Change Biol.* 12, 1969-1976.

614 Meyer, S.E., Monsen, S.B. and McArthur, E.D., 1990. Germination response of  
615 *Artemisia-tridentata* (Asteraceae) to light and chill - patterns of between-  
616 population variation. *Bot. Gaz.* 151, 176-183.

617 Molesl, A.T. and Westoby, M., 2004. Seedling survival and seed size: a synthesis of the  
618 literature. *J. Ecol.* 92, 372-383.

619 Moot, D.J., Scott, W.R., Roy, A.M. and Nicholls, A.C., 2000. Base temperature and  
620 thermal time requirements for germination and emergence of temperate pasture  
621 species. *N. Z. J. Agric. Res.* 43, 15-25.

622 Morris, K., Barker, G.C., Walley, P.G., Lynn, J.R. and Finch- Savage, W.E., 2016.  
623 Trait to gene analysis reveals that allelic variation in three genes determines seed  
624 vigour. *New Phytol.* 212, 964-976.

625 Mousseau, T. and Fox, C.W., 1998. The adaptative significance of maternal effects.  
626 *Trends Ecol. Evol.* 13, 403-407.

627 Murray, B.R., Brown, A.H.D., Dickman, C.R. and Crowther, M.S., 2004. Geographical  
628 gradients in seed mass in relation to climate. *J. Biogeogr.* 31, 379-388.

629 Nicotra, A.B. et al., 2010. Plant phenotypic plasticity in a changing climate. Trends  
630 Plant Sci. 15, 684-692.

631 Norden, N. et al., 2009. The relationship between seed mass and mean time to  
632 germination for 1037 tree species across five tropical forests. Funct. Ecol. 23,  
633 203-210.

634 Orru, M., Mattana, E., Pritchard, H.W. and Bacchetta, G., 2012. Thermal threshold as  
635 predictors of seed dormancy release and germination timing: altitude-related  
636 risks from climate warming for the wild grapevine *Vitis vinifera* subsp.  
637 *sylvestris*. Ann. Bot. 110, 1651-1660.

638 Pakeman, R.J. et al., 2008. Impact of abundance weighting on the response of seed traits  
639 to climate and land use. J. Ecol. 96, 355-366.

640 Peñuelas, J. et al., 2004. Complex spatiotemporal phenological shifts as a response to  
641 rainfall changes. New Phytol. 161, 837-846.

642 Pollock, B.M. & Roos, E.E. (1972) Seed and seedling vigor. *Seed Biology, I.*  
643 *Importance, development and germination*, pp. 314-387.

644 Porter, J.R., 2005. Rising temperatures are likely to reduce crop yields. Nature 436,  
645 174-174.

646 Porter, J.R. and Semenov, M.A., 2005. Crop responses to climatic variation.  
647 Philosophical Transactions of the Royal Society B: Biological Sciences, 360,  
648 2021-2035.

649 Poschlod, P. et al., 2013. Seed ecology and assembly rules in plant communities.  
650 Vegetation Ecology, Second Edition: 164-202.

651 Preece, C. et al., 2017. How did the domestication of Fertile Crescent grain crops  
652 increase their yields? Funct. Ecol. 31, 387-397.

653 Roach, D.A. and Wulff, R.D., 1987. Maternal effects in plants. *Annu. Rev. Ecol. Evol.*  
654 *Syst.* 18, 209-235.

655 Schmid, B. and Dolt, C., 1994. Effects of maternal and paternal environment and  
656 genotype on offspring phenotype in *Solidago altissima* L. *Evolution* 48, 1525-  
657 1549.

658 Seal, C.E. et al., 2017. Thermal buffering capacity of the germination phenotype across  
659 the environmental envelope of the Cactaceae. *Global Change Biol.* 23, 5309-  
660 5317.

661 Sinniah, U.R., Ellis, R.H. and John, P., 1998. Irrigation and seed quality development in  
662 rapid-cycling Brassica: Seed germination and longevity. *Ann. Bot.* 82, 309-314.

663 Smith, S.E., Riley, E., Tiss, J.L. and Fendenheim, D.M., 2000. Geographical variation  
664 in predictive seedling emergence in a perennial desert grass. *J. Ecol.* 88, 139-  
665 149.

666 Soltani, E., Ghaderi-Far, F., Baskin, C. C., & Baskin, J. M. (2016). Problems with using  
667 mean germination time to calculate rate of seed germination. *Austral. J. Bot.* 63,  
668 631-635.

669 Stromberg, J.C. and Patten, D.T., 1990. Variation in seed size of a southwestern riparian  
670 tree, Arizona walnut (*Juglans major*). *Am. Midland Nat.* 124, 269-277.

671 Tribouillois, H., Dürr, C., Demilly, D., Wagner, M.-H. and Justes, E., 2016.  
672 Determination of germination response to temperature and water potential for a  
673 wide range of cover crop species and related functional groups. *PloS one* 11,  
674 e0161185.

675 Trudgill, D.L., Honek, A., Li, D. and Van Straalen, N.M., 2005. Thermal time- concepts  
676 and utility. *Ann. Appl. Biol.* 146, 1-14.

- 677 Trudgill, D.L., Squire, G.R. and Thompson, K., 2000. A thermal time basis for  
678 comparing the germination requirements of some British herbaceous plants.  
679 New Phytol. 145, 107-114.
- 680 Tsunoda, S., Hinata, K. and Gómez-Campo, C., 1980. *Brassica* crops and wild allies.  
681 Biology and breeding, Japan Scientific Societies Press, Tokyo.
- 682 Van Kleunen, M., Lenssen, P.M., Fischer, M. and de Kroon, H., 2007. Selection on  
683 phenotypic plasticity of morphological traits in response to flooding and  
684 competition in the clonal shore plant *Ranunculus reptans*. J. Evol. Biol. 20,  
685 2126-2137.
- 686 Volis, S., 2012. Demographic consequences of delayed germination in two annual  
687 grasses from two locations of contrasting aridity. PPEES. 14, 335-340.
- 688 Wulff, R.D., 1986. Seed size variation in *Desmodium paniculatum*: I. Factors affecting  
689 seed size. J. Ecol. 74, 87-97.