



0 **Transgenerational effects of three global change drivers** 53
on an endemic Mediterranean plant 55

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15 Plant populations are subjected to changes in their natural environment as a result of the incidence of simultaneous global
change drivers. Despite the fact that these changes can largely affect early fitness components, information on the effects of
simultaneous drivers of global change on offspring traits and performance is particularly scant. We analyzed the combined
effect of three global change drivers of critical importance in Mediterranean ecosystems (habitat fragmentation, reductions
in habitat quality and water availability) on germination and seedling performance of the gypsophile shrub *Centaurea*
20 *hyssopifolia*. Seedlings from 39 mother plants from eight different environments (resulting from the combination of the
three global change drivers) were sown and grown in a common garden. First, germination percentage, seedling size and
seedling survival were monitored. Secondly, seedling performance and ecophysiological traits were measured under well
and low-watered conditions. Fragmentation showed the largest negative effect on germination and offspring performance.
Seedlings of mothers from small fragments germinated more slowly, showed lower survival, died faster, and showed
25 lower photosynthetic rates under well-watered conditions compared to seedlings of mother plants from large populations.
Seedlings of different maternal origins did not differ in their response to water stress or in their ability to survive to drought.
Ninety-five percent of the seedlings survived until soil water content was as low as 3%. Our study shows that global change
can have not only immediate impacts on plant populations but also transgenerational effects, and highlights the impor-
tance of studies involving multiple drivers and a more integral understanding of global change. 80

30 In the last decades an increasing number of studies have reported rapid human-mediated changes in the environment
and their impact on plant populations and communities (Chapin et al. 2001, Peñuelas and Filella 2001, Parmesan
and Yohe 2003). Plant populations can respond to these environmental changes via plastic responses in phenotype,
35 but long-term responses that are only observable after one or more generations may also occur. These transgenerational
responses can result either from maternal environmental effects or from evolutionary responses to novel selection
pressures, and are important because they may alter the ultimate ecological impact of the environmental change. 85

Mediterranean-type ecosystems and particularly semi-
arid gypsum habitats are very vulnerable to global change
45 (Lavorel et al. 1998, Mooney et al. 2001). In these habi-
tats, several global change drivers can occur simultaneously,
such as increased aridity (i.e. number and length of dry peri-
ods; Christensen et al. 2007) reductions in habitat quality
and habitat fragmentation (Lavorel et al. 1998, Sala et al.
50 2000). Reductions in water availability (due to increased
aridity) and habitat quality may hinder germination, seed-
ling establishment, growth and seedling survival, thereby
52 affecting the most critical life stages of plant cycle in these
water-limited communities (Harrington 1991, Eliason and
Allen 1997). Habitat fragmentation, caused by agriculture
and land exploitation, transforms the landscape into patches
of natural vegetation interspersed in agriculture fields
(Kosmas et al. 2002, Foley et al. 2005), and leads to the
loss of genetic variability and the increase of inbreeding
(reviewed by Lienert 2004). 90
Overall, different global change drivers interacting simul-
taneously create new scenarios under which the capacity of
species to respond is poorly unknown, primarily because
interactions among drivers may generate non-additive effects
that cannot be easily predicted based on single-factor studies
95 (Sala et al. 2000, Shaver et al. 2000, Alonso and Valladares
2008, Matesanz et al. 2009). Despite several studies address
the effects of global change drivers on the reproductive
output of plant species (Ågren 1996, Aguilar et al. 2006,
Brys et al. 2004), information of their effects on offspring
100 performance is far more scant (Kéry et al. 2000, Kolb 2005,
Yates et al. 2007), and is virtually inexistent for several
drivers considered simultaneously (Lau et al. 2008).
Maternal environmental effects occur when the envi-
ronmental conditions experienced by parents influence
105 offspring traits and refer to the capacity of the maternal

0 environment to induce changes in gene expression, interact with the genotype and directly influence seed provision (Roach and Wulff 1987, Lacey 1996, 1998, Molinier et al. 2006). These maternal effects have been considered especially relevant during the early developmental life stages, such as germination and seedling survival (Gutterman 1993, Weiner et al. 1997, Galloway 2001, Luzuriaga et al. 2006) although they may persist in adult life stages and even affect plant reproductive success (Wulff et al. 1994, Galloway 2001). Recent studies have revealed that plant species are able to express transgenerational phenotypic plasticity as an inherited maternal environmental effect (Donohue and Schmitt 1998, Donohue 1999, Galloway 2001, Etterson and Galloway 2002, Sultan et al. 2009). In this sense, maternal effects can result in reduced or increased plasticity to the offspring environmental conditions (Bezemer et al. 1998, Huxman et al. 2001). When maternal and offspring environments are correlated, transgenerational phenotypic plasticity may be adaptive, improving plant fitness (Mosseau and Fox 1998, Van Zandt and Mopper 2004, Galloway 2005, Molinier et al. 2006, Galloway and Etterson 2007, Sultan et al. 2009).

The main aim of this study was to compare the performance of the offspring of mothers from eight different environments (resulting from the combination of the three global change drivers: habitat fragmentation, changes in habitat quality and water availability) of the endemic gypsophile *Centaurea hyssopifolia* (Asteraceae). In a previous field study, mother plants were selected in natural habitats that differed in the level of habitat fragmentation (large and small fragments) and habitat quality (high and poor), and were submitted to experimental manipulation of water availability for two years (Matesanz et al. 2009). In this study, Matesanz et al. (2009) found complex and non-additive effects of these three drivers on plant survival, phenology and reproductive effort; so transgenerational effects of global change are expected in this species. We performed a common garden experiment using the offspring of these mother plants to test the following hypothesis: 1) germination, seedling survival and growth are lower in seedlings from mother plants from the most unfavourable environments and 2) the maternal environment influences seedling's physiological plasticity to water stress and their ability to survive to drought.

45 Methods

Study species

Centaurea hyssopifolia is a perennial shrub, endemic to gypsum outcrops of semiarid central Spain (Luzuriaga et al. 2006). It constitutes one of the dominant species of the dwarf shrub plant communities of the Iberian gypsum habitats, which are considered among the most threatened habitats in the Mediterranean Basin. Human activities have strongly fragmented gypsum shrub communities, including *C. hyssopifolia* populations. Flowering plants produce 2–550 capitula with an average of 2.75 (range 0–11) viable seeds per capitulum (Matesanz unpubl.). Flowering period extends from mid May to mid July and seeds ripen from early June to later July. It is a self-incompatible species with generalist entomophilous pollination (Luzuriaga et al. 2006).

Seed origin and experimental design

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0 with gypsum soil collected from the study area. Soil was
 1 collected from a relatively small area to avoid heterogeneity
 2 in the substrate, and it was thoroughly mixed and sieved
 3 afterwards. A total of 5394 seeds were sown (2–9 per cavity
 4 and 80–300 per mother plant, depending on seed availability).
 5 Seeds were monitored twice a week during September 2006,
 6 and every two weeks during October and November. They were
 7 considered to have germinated as soon as cotyledons emerged
 8 above the soil. During this period, trays were periodically
 9 watered to ensure permanent humidity, and temperature in the
 10 experiment was controlled to match the optimum reported for
 11 this species (Escudero et al. 1997). Final germination percentage
 12 and number of days required for germination of 50% of the total
 13 number of germinated seeds (t_{50}) were calculated for each
 14 mother plant. In the situations where several seeds germinated
 15 in the same cavity, extra seedlings were clipped immediately
 16 and the first one to emerge was kept. These clipped seedlings
 17 were not included in the survival analyses but they were
 18 considered for germination analyses. Seedling survival rate was
 19 evaluated since seedling emergence to the beginning of the
 20 water stress experiment.

21 On 5 December 2006, a total of 360 (25–53 per maternal
 22 environment) surviving healthy seedlings were transplanted
 23 into randomly arranged pots (500 ml each) filled with the
 24 same type of soil used for the germination trays. During
 25 this period, pots were watered twice a week to keep them
 26 moist. On 12 March 2007, number of leaves and major and
 27 minor diameter of the rosette were recorded for each
 28 seedling. Diameters were measured using a digital calliper
 29 with an accuracy of 0.01 mm. Rosette area was calculated
 30 as the area of an ellipse. These measurements were repeated
 31 after two months in early May.

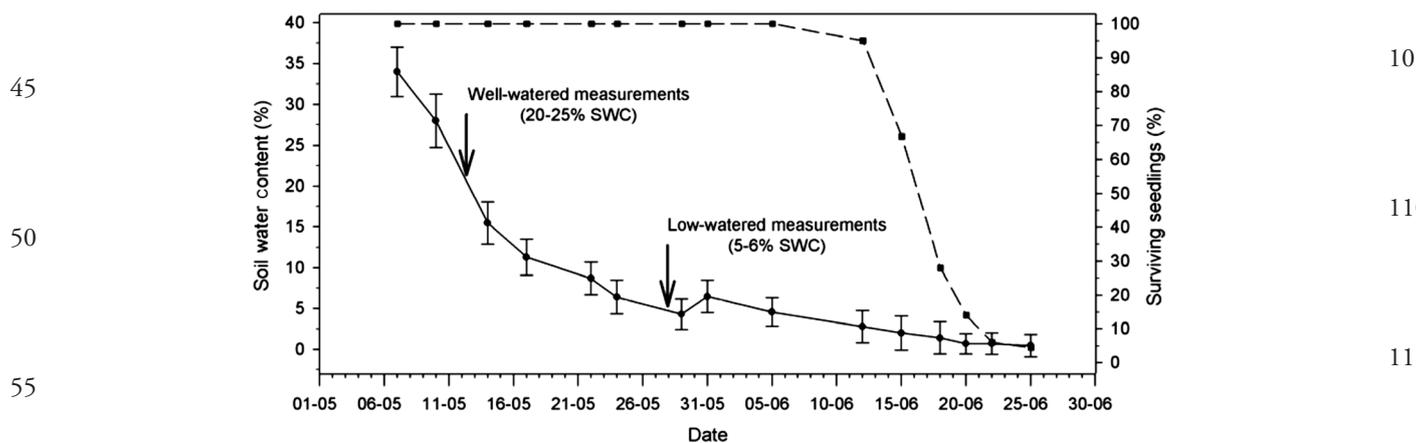
32 Water stress experiment and physiological 33 measurements

34 An experiment simulating Mediterranean summer drought
 35 was carried out in May–June 2007 to evaluate the effect of
 36 the maternal environment on seedling performance and
 37 plasticity in response to stressful conditions mimicking field
 38 conditions. We determined the survival curve along the

39 drought experiment and measured maximal photochemical
 40 efficiency of photosystem II (Fv/Fm), maximum net photo-
 41 synthetic rate (Amax) and instantaneous water use efficiency
 42 (iWUE) at two different soil water content. Volumetric soil
 43 water content (SWC) was determined for a random subsam-
 44 ple of 40 pots twice each week. Probes comprised of two
 45 parallel stainless steel rods, 5 cm in length. Separation
 46 between their axes was also 5 cm. In order to obtain
 47 optimal measurements, the probes were inserted in the
 48 pots before the seedling transplant to avoid interferences
 49 with plant growth and to ensure the maximum contact
 50 between the rods and the soil (Topp and Davis 1985). Also,
 51 all pots were weighted twice a week to determine water
 52 loss. Water stress was slowly imposed adjusting soil water
 53 content of the pots by replacing part of the transpired
 54 water (Fig. 1). Measurements were taken before watering
 55 to obtain an estimate of maximum stress between two
 56 watering events.

57 Physiological measurements were carried out at two
 58 levels of soil water content: 1) well-watered conditions
 59 (20–25% SWC), and 2) low-watered conditions (5–6%
 60 SWC). It has been shown that effects of water stress on
 61 seedling performance of Mediterranean woody plants are
 62 noticeable for values of SWC below 10% (Valladares
 63 et al. 2005). Therefore, soil was slowly dried and SWC
 64 was maintained below this level during ten days before
 65 low-watered measurements (Fig. 1). Air temperature and
 66 available photosynthetic photon flux density (PPFD) were
 67 recorded every 5 min during the whole water stress
 68 experiment with a data logger. Mean daily temperature
 69 for this period was 25.3°C; mean maximum and minimum
 70 temperature were 39.3°C and 14.8°C respectively; and
 71 mean daily PPFD (400–700 nm) was 31.6 mol m² d⁻¹.
 72 These conditions were very similar to the conditions
 73 experienced by mother plants in the field (Matesanz
 74 unpubl.).

75 The maximal photochemical efficiency of photosystem
 76 II (Fv/Fm) in one fully expanded leaf was determined
 77 for all seedlings (nM360) with a portable pulse-modulated
 78 fluorometer. Measurements were taken from 8:00 to
 79 10:00 GMT in healthy leaves dark-adapted for 30 min
 80 with leaf clips provided by the manufacturer. Minimal
 81 (Fo) and maximal (Fm) fluorescence were measured, and
 82 these values were used to calculate Fv/Fm as Fv/Fm =
 83 (Fm – Fo) / Fm



84 Figure 1. Temporal dynamics of soil water content in the pots during the water stress experiment. The dashed line shows the percentage of
 85 surviving seedlings at each soil water content. The arrows denote two levels of soil water content (SWC) where the physiological measurements
 86 were done.

0 (Maxwell and Johnson 2000). Maximum net photosynthetic
rate (A_{max}) was measured in 80 randomly chosen seedlings
rate (ten per maternal environment) in one fully-expanded
leaf using a portable gas exchange system. The leaves were
exposed to an atmospheric CO_2 concentration of $400 \mu l$
5 l^{-1} (using the built-in CO_2 controller) and saturating light
($K1500 \mu mol m^{-2} s^{-1} PAR$). Seedlings' leaves were too nar-
row for the standard chamber, so the 'Arabidopsis-chamber'
was used. This chamber lacks an internal light source, and
measurements were taken using an external source of cold
10 light. Measurements were performed at $25-26^\circ C$ (i.e. growth
temperature) and relative humidity of $45-50\%$. Instanta-
neous water use efficiency ($iWUE$) was estimated as the ratio
between maximum photosynthetic rate and stomatal con-
ductance (Gulías et al. 2002).

15 Watering was decreased after low-watered measure-
ments to keep soil water content below 5% , so the effects of
maternal environment on seedling survival to drought could
be addressed. All pots were examined every day until seed-
ling death, and pot weight was then recorded to calculate
20 soil water content. We labelled as dead those seedlings pre-
sented no photosynthetically active leaves (i.e. green and
bendy leaves) and exhibited loss of flexibility in the stems.
No resprouting was observed after watering in a random
sample of seedlings previously labelled as dead, confirming
25 our estimation of mortality. SWC for each pot at seedling
death was estimated as: $SWCM(\text{soil weight} - \text{dry soil weight}) /$
soil weight, were soil weight $M_{pot} \text{ weight} - (\text{empty pot}$
weight + TDR probes weight). Soil was dried at ambient
temperature during two weeks to obtain the dry soil weight
30 measurement. We checked in a random soil sample dried in
an oven at $60^\circ C$ that SWC was negligible after this period.

Statistical analysis

35 Analyses were carried out using SAS 9.0 (SAS Inst.). The
effects of the three global change drivers (fragmentation,
habitat quality and mother plant water availability, and their
interactions) on germination percentage, germination rate
(t_{50}), survival rate and seedling growth of *C. hyssopifolia*
40 were explored fitting generalized linear mixed models using
the procedure GLIMMIX of SAS. We used the restricted
maximum-likelihood method (REML) and type III sum of
squares. Global change drivers were included in our models
as fixed effects (one degree of freedom per treatment) and
45 mother plant identity (nested within fragmentation \downarrow habi-
tat quality \downarrow water availability interaction) as a random fac-
tor. GLMMs allow the analysis of response variables that are
generally non-normally distributed, such as percentages, by
adjusting adequate function responses and are appropriate
50 because they allow for a distinction between fixed and ran-
dom effects in the models (see Littell et al. 1996 and Bolker
et al. 2008 for further details). Germination and final sur-
vival rate were modelled as binomial distributions with a
logit link function, and t_{50} , number of leaves per seedling
55 and seedling rosette size were modelled using a normal dis-
tribution with an identity link function. Effect of the mother
plant identity was tested using Wald Z-statistic test, which
is appropriate for large samples (Littell et al. 1996). Post-hoc
tests were performed using the LSMEANS option of the
60 GLIMMIX procedure.

Survival curves of seedlings of different treatments were
61 estimated by means of the Kaplan–Meier product-limit
method and compared using non-parametric logrank test
(Pyke and Thompson 1986). This statistical analysis was
performed using STATISTICA 6.0 (Statsoft). 65

Effects of global change drivers on physiological
measurements in the water stress experiment were explored
separately for each level of seedlings' water availability (well
watered and low-watered conditions) due to the complex-
70 ity of the model. Differences in F_v/F_m , A_{max} and $iWUE$
values among factors were explored by means of GLMMs
including mother plant identity as a random factor following
the same approach as used for previously described GLMMs.
We assumed a binomial error distribution with a logit link
75 function in F_v/F_m variable response and a normal error dis-
tribution with an identity link function in A_{max} and $iWUE$
variables.

To test treatment effect (water conditions) and treatment
 \downarrow maternal environment interaction effect we used additional
repeated measures analyses performed by means GLIMMIX
80 procedure of SAS. Maternal environment (resulting from
the combination of the three global change drivers: habitat
fragmentation, changes in habitat quality, and water avail-
ability) was in this case a factor with eight different levels
corresponding to each maternal environment. Individual
85 seedling (for F_v/F_m), and individual mother plant (for
 A_{max} and $iWUE$) were considered as random factors (sub-
ject), and treatment (within-subject), and maternal environ-
ment (among-subject) were considered fixed factors. Finally,
effects of global change factors on drought seedling tolerance
90 (i.e. SWC in the day of seedling death) were explored fol-
lowing the same approach as used for previous GLMMs. We
assumed binomial distributions with a logit link function in
this case. 95

Results

Germination and survival under well-watered conditions

100 Germination percentages were in general low. Mean germi-
nation percentage of plants from each maternal environment
ranged from 13% to 21% . We found a positive maternal
effect of water availability on germination, with lower ger-
105 mination percentages of the seeds from non-watered mother
plants (Table 1, Fig. 2a). Likewise, we found a significant
three-way interaction (fragmentation \downarrow habitat quality \downarrow
water availability) on this trait, with lower values of germina-
110 tion of the seeds from the least favourable maternal environ-
ment, i.e. non-watered plants from small fragments of poor
habitat quality (Table 1, Fig. 2a). In addition, fragmentation
also had a significant and negative effect on the number of
days required for germination of 50% of the total germinated
115 seeds (t_{50}). Seeds of plants from large fragments germinated
faster than those from small fragments (Table 1, Fig. 2b).

Percentage of surviving seedlings from each environment
ranged between 32% and 60% (Appendix 1). We found a
significant and negative effect of fragment size on final sur-
vival rate (Table 1): seedlings of mothers from large frag-
ments had higher final survival. Moreover, Kaplan–Meier analysis
121

0 Table 1. Results for the fixed effects of generalized linear mixed models (GLMMs) used to test the effects of global change factors (fragmentation, habitat quality and water availability, and their interactions) on germination percentage, time at which 50% of seeds germinated (t_{50}) and final survival rate. Germination and survival were modelled using binomial distributions, and t_{50} with normal distribution. $p < 0.05$ are in bold. $n = 39$ mother plants.

5 Source of variation	Germination			t_{50}			Survival		
	F	DF	p	F	DF	p	F	DF	p
Fragmentation (F)	0.62	1	0.433	4.22	1	0.043	4.18	1	0.041
Habitat quality (Q)	0.55	1	0.459	0.22	1	0.642	0.28	1	0.596
Water availability (W)	8.10	1	0.005	0.93	1	0.336	0.05	1	0.816
10 F × Q	0.54	1	0.4639	0.18	1	0.674	0.11	1	0.735
F × W	0.77	1	0.3824	1.27	1	0.262	2.07	1	0.151
Q × W	0.53	1	0.469	0.45	1	0.502	0.04	1	0.837
F × Q × W	0.12	1	0.043	0.57	1	0.450	2.72	1	0.099

15 revealed significant differences in the survival function of seedlings of different mother plants, with those from large fragments having a slower rate of mortality than those from small fragments (log rank $M = 2.54$, $p = 0.010$, Fig. 3).

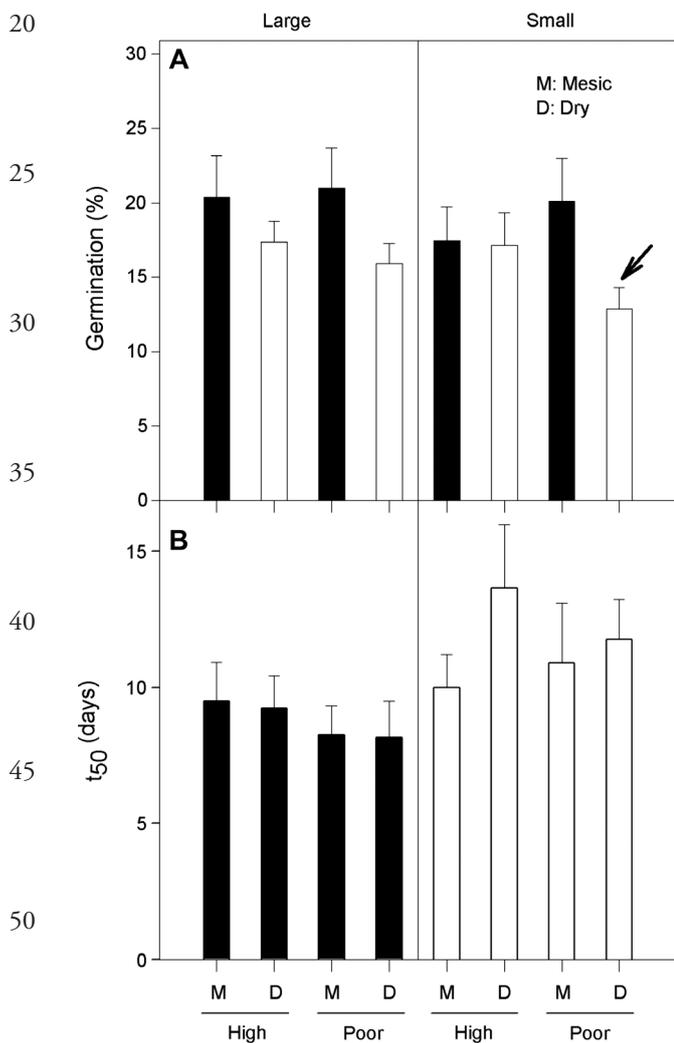
Mother plant identity did not have any significant effect on these variables ($Z < 1.20$, $p > 0.11$).

Seedling growth

There was a marginally significant and positive effect of mother plant water availability on rosette size in March measurements (FM4.12, DFM1, $p = 0.052$). Seedlings from watered mother plants had significantly higher area than non-watered ones at this time (mean \pm SE: 24.06 ± 0.67 and 22.70 ± 0.61 cm², respectively). However, no significant effects of global change drivers or their interactions were found on the number of leaves per seedling ($F < 0.44$, DFM1, $p > 0.510$ in all cases) or on rosette size ($F < 2.65$, DFM1, $p > 0.113$ in all cases) in May measurements. Mother plant identity did not have any significant effect on these variables ($Z < 1.05$, $p > 0.14$).

Seedling performance and survival under water stress

We did not find any significant effect of global change drivers on maximal photochemical efficiency (Fv/Fm) in either well-watered or low-watered conditions (Table 2). Repeated measures analysis showed that Fv/Fm values were significantly



55 Figure 2. Mean values of (a) germination percentage and, (b) number of days required for germination of 50% of the total seed number, for the eight different maternal environments with different fragment size (small and large), habitat quality (high and poor), and water conditions (well- and low-watered). Different colours in the bars indicate significant differences at the 5% level for the main effects.

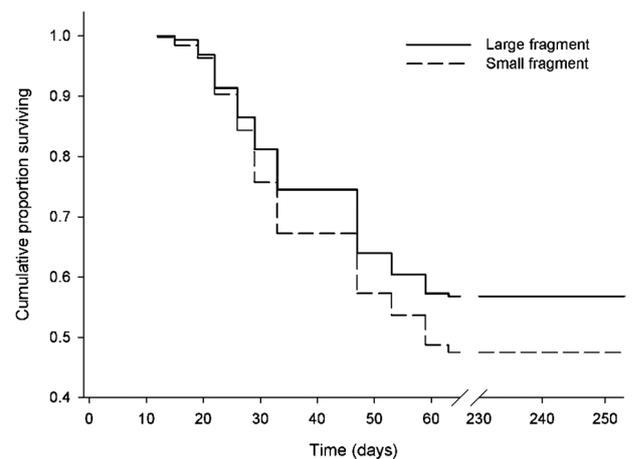


Figure 3. Kaplan-Meier survivorship curves for seedlings of mother plants from large and small fragments. Curves differed significantly at the 5% level in the log-rank test. Figure shows survival curves only for small versus large fragments because only fragmentation had an effect on final survival rate.

0 Table 2. Results for the fixed effects of generalized linear mixed models (GLMMs) used to test the effects of global change factors (fragmentation, habitat quality and water availability, and their interactions) on seedling performance under well-watered and low-watered conditions in the water stress experiment. Analyses were based on a GLMM with binomial error and logit link for maximal photochemical efficiency (F_v/F_m), and with normal distributions and identity function link for maximum photosynthetic rate (A_{max}) and water use efficiency (iWUE). $p < 0.01$ are in bold. 61

Source of variation	F_v/F_m			A_{max}			iWUE		
	F	DF	P	F	DF	P	F	DF	P
a) Well-watered									
Fragmentation (F)	0.98	1	0.323	12.64	1	< 0.001	1.23	1	0.267
Habitat quality (Q)	0.66	1	0.416	3.58	1	0.058	0.37	1	0.542
Water availability (W)	0.18	1	0.669	0.35	1	0.556	1.00	1	0.317
F × Q	0.63	1	0.427	2.26	1	0.132	3.69	1	0.054
F × W	0.02	1	0.887	2.00	1	0.157	1.37	1	0.241
Q × W	1.41	1	0.236	4.77	1	0.028	0.84	1	0.358
F × Q × W	2.32	1	0.129	6.57	1	0.010	1.90	1	0.167
b) Low-watered									
Fragmentation (F)	0.01	1	0.924	1.09	1	0.297	0.96	1	0.329
Habitat quality (Q)	0.62	1	0.432	0.85	1	0.359	0.47	1	0.494
Water availability (W)	0.02	1	0.902	0.00	1	0.976	0.83	1	0.355
F × Q	0.53	1	0.467	1.23	1	0.205	2.48	1	0.120
F × W	0.45	1	0.502	1.11	1	0.297	0.40	1	0.531
Q × W	1.35	1	0.246	0.30	1	0.584	0.94	1	0.336
F × Q × W	4.89	1	0.066	0.81	1	0.326	0.71	1	0.401

25 lower under low-watered (FM3.27, DFM1, $p < 0.001$; mean \pm SE: 0.82 ± 0.04 and 0.68 ± 0.03 , respectively; Fig. 4), although they were still relatively high.

30 Maximum photosynthetic rate (A_{max}) was negatively affected by fragmentation under well-watered conditions. Likewise, we found a significant three-way interaction (fragmentation \downarrow habitat quality \downarrow water availability) under well-watered conditions, indicating higher values for seedlings from non-watered mother plants from large fragments of poor habitat quality (Table 2). Repeated measures analysis showed that A_{max} was also significantly lower under low-watered conditions (FM58.22, DFM1, $p < 0.001$; mean \pm SE: 9.27 ± 0.33 and 2.58 ± 0.31 for well-watered and low-watered conditions respectively; Fig. 4). In this case, we found a significant treatment \downarrow maternal interaction, where seedlings of watered mother plants from small fragments of poor habitat quality showed a lower A_{max} reduction (FM26.44, DFM7, $p < 0.001$).

45 Water use efficiency (iWUE) was significantly higher under water stress (FM19.57, DFM1, $p < 0.001$; mean \pm SE: 11.38 ± 1.33 and 30.04 ± 2.14 for well-watered and low-watered conditions respectively; Fig. 4) and no effect of global change drivers were found for this variable (Table 2).

50 Likewise, there was no significant effect of the global change factors ($F < 2.14$, DFM1, $p > 0.158$) or the mother plant identity (ZM 1.59, pM0.156) on seedling survival to drought (i.e. SWC in the day of the seedling death). Ninety-five percent of the seedlings survived until soil water content was as low as 3%, and they tolerated SWC values below 5% for many days (Fig. 1).

Discussion

60 Overall, we found a significant effect of the global change drivers on the offspring of *Centaurea hyssopifolia*. Specifi-

85 cally, we found an effect of fragmentation on germination rate and seedling performance, matching the patterns found for other fragmented populations of self-incompatible species (Menges 1991, Kolb 2005). Germination under controlled conditions of the seeds from small fragments was lower and slower, and seedling mortality was higher and occurred faster. Likewise, we found a positive effect of water availability experienced by mother plants on germination. Finally, we detected a significant three-way interaction of the three global change drivers on the germination percentage; i.e. it was lowest in the least favourable environment (non-watered mother plants from small fragments of poor habitat quality). This result highlights the importance of multifactor experiments, as non-additive synergistic effects among global change drivers have been shown to affect plant responses (Sala et al. 2000).

90 Negative effects of fragmentation on germination and survival may be due to several non-exclusive reasons: genetic deterioration, quality of the available pollen for plants, and other maternal environment effects related to habitat fragmentation. In small fragments, pollinators abundance and behaviour may be profoundly affected, decreasing the abundance and the quality of available pollen (Aizen et al. 2002, Duncan et al. 2004, Aguilar et al. 2006, Lopes and Buzzato 2007). In self-incompatible species, as in our study plant, this fact may lead to a decrease in the amount of potential mates, and to the increase of crosses among related congeners (biparental inbreeding), which in turn may increase homozygosity and other deleterious genetic effects linked to inbreeding. Furthermore, reductions in pollen competition and gametes selectivity, before and after fertilization, may reinforce these negative effects on seed viability, germination, and also on offspring fitness (Colling et al. 2004). Kolb (2005) discussed the role of genetic effects to explain the low seedling survival of *Phyteuma spicatum* in small and fragmented populations. Several authors have tried 121

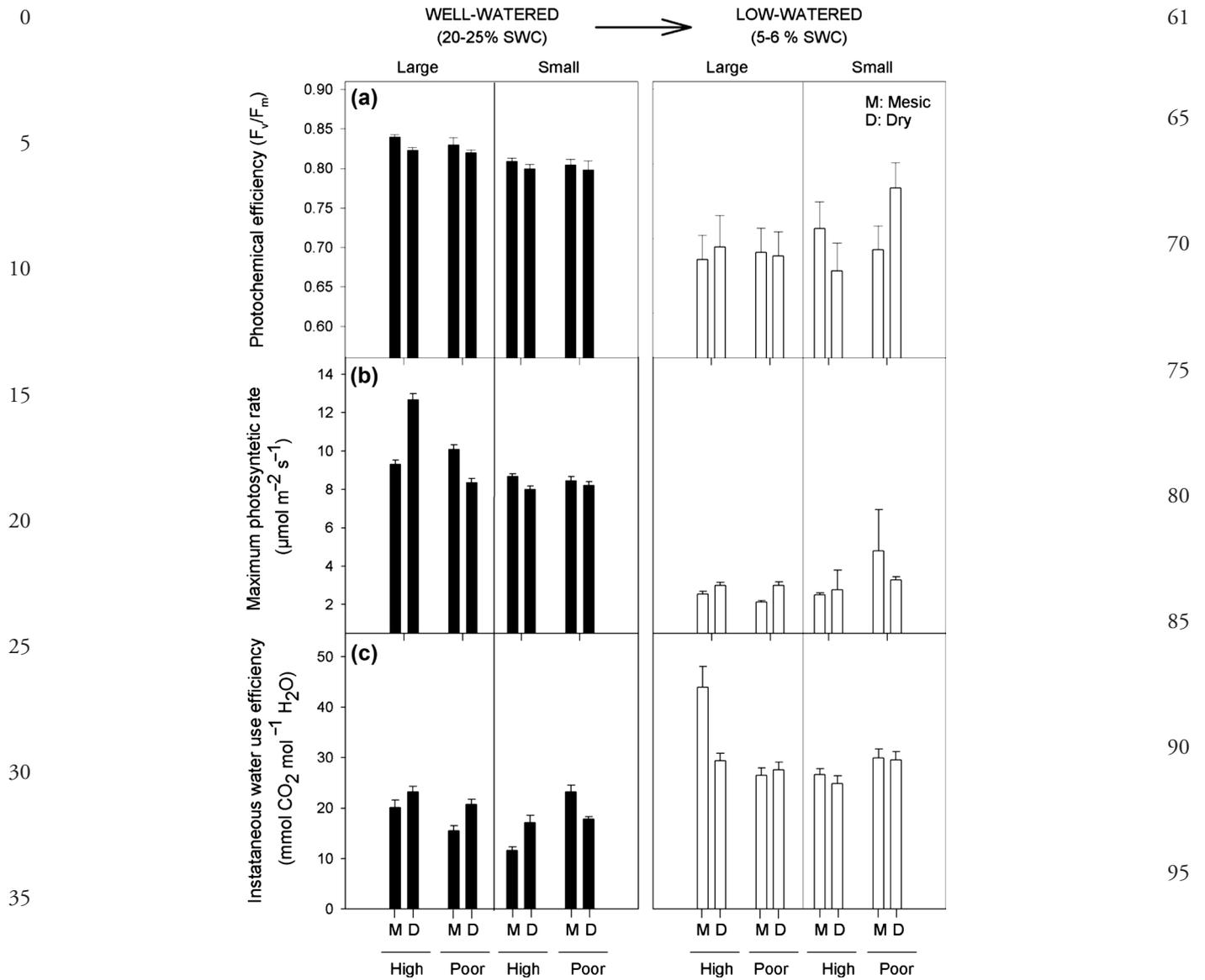


Figure 4. Mean values of (a) photochemical efficiency, (b) maximum photosynthetic rate and (c) water use efficiency of seedlings from the different maternal environments in well (left panels) and low-watered conditions (right panels). Different colours of the bars show significant differences between values in well- and low-watered conditions at the 5% significance level. Error bars represent one standard error of the mean.

to separate this so-called genetic effect from the maternal environment when describing transgenerational effects (Weiner et al. 1997). However, it is not possible to fully disentangle the genetic component of this response from the ecological component (maternal environment). In our study, some kind of genuine genetic effects may be responsible for the observed results. This is supported by previous findings of the same study population, where plants from small fragments had lower viable seed production and lower adult plant survival (Matesanz et al. 2009) which are traits frequently related to inbreeding (reviewed by Lienert 2004). An effect of fragmentation on subsequent life stages would support the genetic hypothesis to a greater extent (Roach and Wulff 1987). Despite our results do not show a significant effect of fragmentation on rosette size or number of leaves (as measures of plant growth), the effects of

inbreeding depression may arise under more stressful natural conditions (Ramsey and Vaughton 2000, Kolb 2005).

We also found that water shortage during mother plant growth exerted a negative effect on the germination of its seeds. The effect of water stress during mother plant life has been found to negatively affect germination in other plant species (Acosta and Kohashi 1989, Nielsen and Nelson 1998). Furthermore, in our case, water availability of mother plants had a positive effect on seedling growth, although it was only visible in the first measurement date. Transmission mechanisms can explain this genuine maternal environmental effect by: (1) affecting the quantity and quality of the resources supplied to the seeds (Weiner et al. 1997), (2) changing the structure and thickness of the seed coat (Lacey et al. 1997), (3) inducing abortion of seeds (Marshall and Ellstrand 1988) and (4) affecting the levels

0 of hormones, enzymes, etc during germination and early performance. Water stress during seed formation must have affected seed provisioning and enzymatic activity related to germination and initial development of the seedling, while subsequent stages of the offspring life can be expected to be less influenced (Roach and Wulff 1987).

5 The effect of water shortage on germination was boosted by the negative effect of both fragmentation and poor habitat quality. This finding concurs with Kolb (2005), who found that small-sized populations are more sensitive to unfavourable environmental conditions, and again highlights the importance of multifactor studies. This is particularly relevant for the Mediterranean region (Christensen et al. 2007) where more frequent and severe drought episodes are predicted to occur, leading to increased aridity. This, together with longer time for germination and an advanced mortality of seedlings from small fragments, may translate into lower water availability at the seedling stage, as seedlings would be smaller at the beginning of summer drought, which in turn can translate into higher mortality.

20 All the physiological variables were affected by water stress, but contrary to our expectations, seedlings' response did not differ in relation to their maternal environment. Although maximal photochemical efficiency (Fv/Fm) values are generally considered to be more sensitive to high temperature and light intensity than to water stress (Long et al. 1994, Llorens et al. 2003), we found decreases in Fv/Fm under the optimum values (0.83 according to Maxwell and Johnson 2000). Aragón et al. (2008) found that even small deviations in Fv/Fm values of a Mediterranean chamaephyte (*Helianthemum squamatum*) had strong consequences on plant fitness, and highlighted that the timing of stressful events may be even more important than the stress intensity. On the other hand, water use efficiency increased significantly under low-watered conditions, probably as a consequence of the reduction of stomatal conductance while maintaining similar photosynthetic rates, and concurs with other studies (Valladares et al. 2005, Liu et al. 2005). Valladares and Sánchez-Gómez (2006) identified a second stage where iWUE decreased pronouncedly as a response to prolonged and severe water stress, when SWC was around 7%. This is in contrast with our study, where seedlings showed an increase in iWUE under SWC of 5–6%. In this context, it is noteworthy that 95% of the plants survived until SWC was extremely low (3%), highlighting the capacity of this species to cope with water stress, and agreeing with results for other gypsum species (Aragón et al. 2007).

45 In conclusion, our results show that combinations of global change drivers can have effects not only on adult plant performance in natural conditions but also transgenerational effects on the plant offspring, as shown by the significant effect of the maternal environment on early fitness components and offspring performance under controlled conditions. These results suggest that detrimental effects of global change drivers can affect demographic trends not only by constraining the fertility rates of the population but also by conditioning the performance of future generations. Our findings also highlight the importance of human-mediated changes on population persistence, as they affected not only germination and seedling survival but also the capacity to exploit spring resource pulses, a typical feature of Mediterranean environments, and suggest that these effects are a

61 complex sum of both genetic and ecological factors. Despite the ability of seedlings to cope with water stress found for this species, our results show high vulnerability to the predicted climate change, as shown by its effects on germination. Finally, our study revealed the importance of including not only different global change drivers but also their assessing their effects on the performance of the descendants.

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80 References

- Acosta, G. and Kohashi, S. 1989. Effect of water stress on growth and yield of indeterminate dry-bean (*Phaseolus vulgaris*) cultivars.—*Field Crops Res.* – 20: 81–93.
- Ågren, J. 1996. Population size, pollinator limitation, and seed set in the self-incompatible herb *Lythrum Salicaria*. – *Ecology* 77: 1779–1790.
- Aguilar, R. et al. 2006. Plant reproductive susceptibility to habitat fragmentation: review and synthesis through a meta-analysis. – *Ecol. Lett.* 9: 968–980.
- Aizen, M. A. et al. 2002. Reproductive success in fragmented habitats: do compatibility systems and pollination specialization matter? – *J. Veg. Sci.* 13: 885–892.
- Alonso, B. and Valladares, F. 2008. International efforts on global change research.—In: Chuvieco E. (ed.), *Earth observation of global change: the role of satellite remote sensing in monitoring the global environment*. Springer, pp. 1–21.
- Aragón, C. F. et al. 2007. Environmental scales on the reproduction of a gypsophyte: a hierarchical approach. – *Ann. Bot.* 99: 519–527.
- Aragón, C. F. et al. 2008. Stress-induced dynamic adjustments of reproduction differentially affect fitness components of a semi-arid plant. – *J. Ecol.* 96: 222–229.
- Bezemer et al. 1998
- Bolker, B. et al. 2008. Generalized linear mixed models: a practical guide for ecology and evolution. – *Tree*. 1042: 1–9.
- Brys, R. et al. 2004. Reduced reproductive success in small populations of the self-incompatible *Primula vulgaris*. – *J. Ecol.* 92: 5–14.
- Chapin III, F. S. et al. 2001. Global biodiversity in a changing environment: scenarios for the 21st century.—Springer.
- Christensen, J. H. et al. 2007. Regional climate projections. Contribution of working group I to the 4th Assessment Rep. of the Intergovernmental Panel on Climate Change. Solomon S. et al. (eds). *Climate Change 2007: the physical science basis*.—Cambridge Univ. Press.
- Colling, G. et al. 2004. Effects of pollen quantity and quality on reproduction and offspring vigor in the rare plant *Scorzonera humilis* (Asteraceae). – *Am. J. Bot.* 91: 1774–1782.
- Donohue, K. 1999. Seed dispersal as a maternally influenced character: mechanism basis of maternal effects and selection on maternal characters in an annual plant. – *Am. Nat.* 154: 674–689.
- Donohue, K. and Schmitt, J. 1998. Maternal environmental effects on plants: adaptive plasticity?—In: Mosseau T. A. and Fox C. W. (eds), *Maternal effects as adaptations*. Oxford Univ. Press, pp. 137–158.

- 0 Duncan, D. H. et al. 2004. Plant isolation reduces outcross pollen receipt in a partially self-compatible herb. – *J. Ecol.* 92: 977–985.
- Eliason, S. A. and Allen, E. B. 1997. Exotic grass competition in suppressing native shrubland re-establishment. – *Restor. Ecol.* 5: 245–255.
- 5 Escudero, A. et al. 1997. Germination of gypsophytes and gypsogvags in semiarid central Spain. – *J. Arid Environ.* 36: 487–497.
- Etterson, J. R. and Galloway, L. F. 2002. The influence of light on paternal plants in *Campanula americana* (Campanulaceae): pollen characteristics and offspring traits. – *Am. J. Bot.* 89: 1899–1906.
- 10 Foley, J. A. et al. 2005. Global consequences of land use. – *Science* 309: 570–574.
- Galloway, L. F. 2001. Parental environmental effects on life history characters and plasticities in *Mimulus guttatus*. – *Evolution.* 49: 1095–1107.
- 15 Galloway, L. F. 2005. Maternal effects provide phenotypic adaptation to local environmental conditions. – *New Phytol.* 166: 93–100.
- Galloway L. F. and Etterson J. R. 2007. Transgenerational plasticity is adaptive in the wild. – *Science* 318: 1134–1136.
- 20 Gulías, J. et al. 2002. Photosynthetic responses to water deficit in six Mediterranean sclerophyll species: possible factors explaining the declining distribution of *Rhamnus ludovici-salvatoris*, an endemic Balearic species. – *Tree Physiol.* 22: 687–697.
- [AQ4] Gutterman, Y. 1993. Seed germination in desert plants.–Springer.
- Harrington, G. N. 1991. Effects of soil moisture on shrub seedling survival in a semi-arid grassland. – *Ecology* 72: 1138–1149.
- 25 Huxman et al. 2001
- Kéry, M. et al. 2000. Reduced fecundity and offspring performance in small populations of the declining grassland plants *Primula veris* and *Gentiana lutea*. – *J. Ecol.* 88: 17–30.
- 30 Kolb A. 2005. Reduced reproductive success and offspring survival in fragmented populations of the forest herb *Phyteuma spicatum*. – *J. Ecol.* 93: 1226–1237.
- Kosmas, C. et al. 2002. The effect of land use on soil erosion and land degradation under Mediterranean conditions.–In: Geeson N. A. et al. (eds), *Mediterranean desertification: a mosaic of processes and responses*, Wiley, pp. 57–70.
- 35 Lacey, E. P. 1996. Parental effects in *Plantago lanceolata* L.: a grow chamber experiment to examine pre- and postzygotic temperature effects. – *Evolution* 50: 865–878.
- Lacey, E. P. 1998. What is an adaptive environmentally induced parental effect?–In: Mosseau T. A. and Fox C. W. (eds), *Maternal effects as adaptations*. Oxford Univ. Press, pp. 54–66.
- 40 Lacey, E. P. et al. 1997. Parental effects on seed mass: seed coat but not embryo/endosperm effects. – *Am. J. Bot.* 84: 1617–1620.
- Lau, J. A. et al. 2008. Transgenerational effects of global environmental change: long-term CO₂ and nitrogen treatments influence offspring growth response to elevate CO₂. – *Oecologia* 158: 141–150.
- 45 Lavorel, S. et al. 1998. Mediterranean terrestrial ecosystems: research priorities on global change effects. – *Global Ecol. Biogeogr. Lett.* 7: 157–166.
- 50 Lienert, J. 2004. Habitat fragmentation effects on fitness of plant populations—a review. – *J. Nat. Conserv.* 12: 53–72.
- Littell, R. C. et al. 1996. SAS system for mixed models.–SAS Inst.
- Liu, F. L. et al. 2005. ABA regulated stomatal control and photosynthetic water use efficiency of potato (*Solanum tuberosum* L.) during progressive soil drying. – *Plant Sci.* 168: 831–836.
- 55 Llorens, L. et al. 2003. Diurnal and seasonal variations in photosynthetic performance and water relations of two-occurring Mediterranean shrubs, *Erica multiflora* and *Globularia alpinum*. – *Physiol. Plant* 118: 84–95.
- Long, S. P. et al. 1994. Photoinhibition of photosynthesis in nature. – *Annu. Rev. Plant Mol. Biol.* 45: 633–662.
- Lopes, L. E. and Buzato, S. 2007. Variation in pollinator assemblages in a fragmented landscape and its effects on reproductive stages of a self-incompatible treelet, *Psychotria suterella* (Rubiaceae). – *Oecologia* 154: 305–314.
- Luzuriaga, A. L. et al. 2006. Environmental maternal effects on seed morphology and germination in *Sinapis arvensis* (Cruciferae). – *Weed Res.* 46: 163–174.
- 65 Marshall, D. L. and Ellstrand, N. C. 1988. Effective mate choice in wild radish: evidence for selective seed abortion and its mechanism. – *Am. Nat.* 131: 739–756.
- Matesanz, S. et al. 2009. Impact of three global change drivers on a Mediterranean shrub. – *Ecology* 90: 2609–2621.
- 70 Maxwell, K. and Johnson, G. N. 2000. Chlorophyll fluorescence: a practical guide. – *J. Exp. Bot.* 51: 659–668.
- Menges, E. S. 1991. Seed germination percentage increases with population size in fragmented prairie species. – *Conserv. Biol.* 5: 158–164.
- 75 Molinier, J. et al. 2006. Transgeneration memory of stress in plants. – *Nature* 442: 1046–1048.
- Mooney, H. A. et al. 2001. Mediterranean-climate ecosystems.–In: Chapin III, F. S. et al. (eds), *Global biodiversity in a changing environment: scenarios for the 21st century.*, pp. 157–195. Springer.
- 80 [AQ5] Mosseau, T. A. and Fox, C. W. 1998. *Maternal effects as adaptations*.–Oxford Univ. Press.
- Nielsen, D. C. and Nelson, N. O. 1998. Black bean sensitivity to water stress at various growth stages. – *Crop Sci.* 38: 422–427.
- Parmesan, C. and Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. – *Nature* 421: 37–42.
- 85 Peñuelas, J. and Filella, I. 2001. Phenology: responses to a warming world. – *Science* 294: 793–795.
- Pyke, D. and Thompson, J. 1986. Statistical analysis of survival and removal rate experiments. – *Ecology* 67: 240–245.
- 90 Ramsey, M. and Vaughton, G. 2000. Pollen quality limits seed set in *Buchardia umbellata* (Colchicaceae). – *Am. J. Bot.* 87: 845–852.
- Roach, D. A. and Wulff, R. D. 1987. Maternal effects in plants. – *Annu. Rev. Ecol. Syst.* 18: 209–235.
- Sala, O. E. et al. 2000. Global biodiversity scenarios for the year 2100. – *Science* 287: 1770–1774.
- 95 Shaver, G. S. et al. 2000. Global warming and terrestrial ecosystems: a conceptual framework for analysis. – *Bioscience* 50: 871–882.
- Sultan, S. E. et al. 2009. Contrasting patterns of transgenerational plasticity in ecologically distinct congeners. – *Ecology* 90: 1831–1839.
- 100 Topp, G. C. and Davis, J. L. 1985. Measurement of soil water content using time domain reflectometry (TDR): a field evaluation. – *Soil Sci. Soc. Am. J.* 49: 19–24.
- Valladares, F. and Sánchez-Gómez, D. 2006. Ecophysiological traits associated with drought in Mediterranean tree seedlings: individual responses versus interspecific trends in eleven species. – *Plant Biol.* 8: 688–697.
- 105 Valladares, F. et al. 2005. Photoinhibition and drought in Mediterranean woody saplings: scaling effects and interactions in sun and shade phenotypes. – *J. Exp. Bot.* 56: 483–494.
- 110 Van Zandt, P. A. and Mopper, S. 2004. The effects of maternal salinity and seed environment on germination and growth in *Iris hexagona*. – *Evol. Ecol. Res.* 6: 813–832.
- Weiner, J. et al. 1997. How important are environmental maternal effects in plants? A study with *Centaurea maculosa*. – *J. Ecol.* 85: 133–142.
- 115 Wulff, R. et al. 1994. Seed and seedling responses to maternal and offspring environments in *Plantago lanceolata*. – *Funct. Ecol.* 8: 763–769.
- Yates, C. J. et al. 2007. Seed production, germinability and seedling growth for a bird-pollinated shrub in fragments of kwongan in south-west Australia. – *Biol. Conserv.* 136: 306–314.
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Appendix 1. Mean values \pm SE of the study variables in the different maternal environments.

	Large fragments						Small fragments					
	High habitat quality			Poor habitat quality			High habitat quality			Poor habitat quality		
	Mesic	Dry		Mesic	Dry		Mesic	Dry		Mesic	Dry	
Morphological traits												
Germination (%)	20.39 \pm 2.81	17.37 \pm 1.40		20.97 \pm 2.75	15.94 \pm 1.33		17.45 \pm 2.29	17.13 \pm 2.21		20.10 \pm 2.90	12.87 \pm 12.87	
T ₅₀ (days)	9.50 \pm 1.43	9.22 \pm 1.19		8.25 \pm 1.08	8.15 \pm 1.34		10.01 \pm 1.19	13.65 \pm 2.32		10.90 \pm 2.19	11.75 \pm 1.19	
Survival (%)	59.93 \pm 8.10	51.47 \pm 3.6		52.49 \pm 5.6	60.12 \pm 6.56		32.37 \pm 7.50	52.99 \pm 6.14		45.47 \pm 6.44	45.94 \pm 5.18	
No. leaves	16.96 \pm 0.39	15.11 \pm 0.49		16.17 \pm 0.47	16.33 \pm 0.42		16.31 \pm 0.58	16.14 \pm 0.43		15.32 \pm 0.44	16.68 \pm 0.51	
Size March (cm ²)	24.46 \pm 1.09	23.91 \pm 1.56		25.61 \pm 1.14	21.24 \pm 1.10		21.83 \pm 1.52	22.64 \pm 1.40		24.11 \pm 1.33	23.06 \pm 1.96	
Size May (cm ²)	42.90 \pm 0.09	42.23 \pm 1.66		40.52 \pm 0.80	45.48 \pm 1.10		41.03 \pm 0.70	43.20 \pm 1.20		42.15 \pm 1.07	42.02 \pm 1.06	
Physiological traits												
Well-watered												
F _v /F _m	0.84 \pm 0.003	0.82 \pm 0.003		0.83 \pm 0.008	0.82 \pm 0.004		0.81 \pm 0.004	0.79 \pm 0.005		0.80 \pm 0.007	0.78 \pm 0.010	
A _{max} (μmol m ⁻² s ⁻¹)	9.32 \pm 0.21	12.67 \pm 0.31		10.09 \pm 0.23	8.36 \pm 0.21		8.69 \pm 0.12	8.01 \pm 0.16		8.48 \pm 0.20	8.23 \pm 0.17	
iWUE (mmol CO ₂ mol ⁻¹ H ₂ O)	20.14 \pm 1.46	23.23 \pm 1.09		15.46 \pm 0.98	20.77 \pm 1.01		11.58 \pm 0.72	17.10 \pm 1.49		23.19 \pm 1.31	17.78 \pm 0.47	
Low-watered												
F _v /F _m	0.67 \pm 0.032	0.69 \pm 0.042		0.68 \pm 0.031	0.67 \pm 0.032		0.71 \pm 0.036	0.65 \pm 0.037		0.68 \pm 0.032	0.77 \pm 0.034	
A _{max} (μmol m ⁻² s ⁻¹)	2.13 \pm 0.15	2.59 \pm 1.68		1.68 \pm 0.08	2.60 \pm 0.17		2.08 \pm 0.11	2.35 \pm 1.05		4.43 \pm 2.23	2.88 \pm 0.18	
iWUE (mmol CO ₂ mol ⁻¹ H ₂ O)	44.74 \pm 4.16	29.94 \pm 1.51		26.91 \pm 1.55	27.51 \pm 1.54		27.01 \pm 1.18	25.33 \pm 1.54		30.47 \pm 1.79	30.13 \pm 1.64	

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