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Future challenge for endangered arable weed species facing global warming: Low temperature optima and narrow moisture requirements

A. Theresa Rühl [a],*, R. Lutz Eckstein [a], Annette Otte [a], Tobias W. Donath [b]

[a] *Institute of Landscape Ecology and Resource Management, Division of Landscape Ecology and Landscape Planning, Justus Liebig University Giessen, 35392 Giessen, Germany*
[b] *Department of Landscape Ecology, Institute for Natural Resource Conservation, Christian-Albrechts-University Kiel, 24118 Kiel, Germany*

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ABSTRACT

As a result of the intensification of agriculture in Central Europe, many arable weed species have declined. Global climate change may further challenge the adaptability of arable weeds since plants may be more often subjected to higher temperatures and lower soil moisture during the germination period.

A climate chamber experiment analysed the response of four familial pairs of common and endangered arable weeds from Germany. To this end we used a large range of temperatures and water potentials to assess specific traits defining their germination requirements. Using a simple response surface approach, we predicted germination response under three climate change scenarios.

Results supported our expectation that endangered species, owing to their narrow germination requirements, may be more negatively affected by global warming than common species. Endangered species germinated significantly less than the common arable weeds, except at very low temperatures (3 °C and 5 °C). The preference of endangered arable weed species for low germination temperatures was confirmed by their low optimal germination temperature (15.8 °C ± 0.4). In contrast, common species germinated at significant higher temperatures (optimal temperature 18.4 °C ± 0.2), had a significantly wider range of germination temperature (endangered: 24 °C ± 3.5, common: 31 °C ± 0.5) and were also more flexible towards changes in water potential.

Calculations based on response surfaces for three climate change scenarios indicated that endangered arable weed species may benefit less from climate warming than common species.

1. Introduction

With about 25% of the land area being used as crop fields, Central Europe is characterised by arable landscapes (Eurostat, 2014), which are important for biodiversity. However, as a result of agricultural intensification, populations of arable weeds have declined dramatically during the last century (Sieben and Otte, 1992; Storkey et al., 2011; Meyer et al., 2013; Simmering et al., 2013). Arable weeds are very closely connected to agricultural management. Long-term co-evolution with the crops turned them into specialists for arable sites, closely adapted to the associated land use practices (Otte et al., 2006). Since recent land use changes strongly affected environmental conditions on crop fields, many arable weeds currently have an extremely high extinction risk and weeds are one of the most endangered species groups in Europe (Meyer et al., 2013).

However, not all plant species are affected equally. In fact, a shift in the spectrum of species has been observed. Spring germinating species which are herbicide susceptible and less nitrophilous have decreased recently, while competitive, nitrophilous and autumn germinating species have benefitted from agricultural intensification (Hawes, 2010). Competitive weeds that expand their distribution range efficiently use the good nutrient and water supply on arable fields despite a high density of the crop stands (Otte et al., 2006). Today, these few generalists are common in agricultural landscapes. At the same time many arable weeds are endangered or even threatened by extinction because of unfavourable environmental conditions (Storkey et al., 2011).

With respect to abiotic conditions, climate scenarios predict an increase of annual mean temperatures by 1.5–4 °C by the end of 21th century (IPCC, 2013) and an increased frequency of extreme meteorological conditions (Walck et al., 2011). As a consequence, plants may be more often subjected to high temperatures and low soil moisture during the growing season in spring and summer

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* Corresponding author at: Institute of Landscape Ecology and Resource Management, Division of Landscape Ecology and Landscape Planning, Justus Liebig University Giessen, Heinrich-Buff-Ring 26-32, 35392 Giessen, Germany. Tel.: +49 641 9937177; fax: +49 641 9937169.

E-mail address: theresa.ruehl@umwelt.uni-giessen.de (A.T. Rühl).

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(Knapp et al., 2008). Therefore, global climate change may present a further threat to the survival of arable weeds (Thuiller, 2005; Dreesen et al., 2012).

Germination is a crucial stage especially for annual species. As temperature and water availability control germination of seeds (Baskin and Baskin, 2001), changes in these factors may have major impacts on the establishment and survival of plant populations (Hedhly et al., 2008; Walck et al., 2011). Temperature is an important local trigger allowing seedlings to emerge when the most favourable environmental conditions prevail (Cochrane et al., 2011). Consequently, due to an expansion of the growing season (Menzel et al., 2006) some species may be able to germinate at an earlier date in the year. However, despite matching temperature, these seedlings may encounter unfavourable conditions with respect to diurnal temperature fluctuations or water availability because they germinated in the "wrong" season (Cochrane et al., 2011; Mondoni et al., 2012). Additionally, higher temperatures combined with less precipitation may prevent germination and seedling emergence completely.

The Red List Status of arable species suggests that their adaptability towards recent changes in land use has reached its limit. This status may not only be caused by agricultural intensification but partly also by a growing mismatch between germination requirements and prevailing environmental conditions (Cochrane et al., 2011). If this is true, it is very likely that these species will be particularly sensitive to further changes in temperature or water availability due to global climate change. Endangered arable weeds showed significantly lower germination percentage in response to reduced water potential at two fluctuating temperatures and their germination occurred in a smaller time window (characterised by mean germination time and synchrony) as compared to common species (Rühl et al., unpublished). As drought and high temperatures are often co-occurring it is important to understand the impact and interaction of both stress factors on plants. Such information is essential to understand the response of endangered arable weed species to future changes in environmental conditions and for the development of successful conservation programs. Still, there is a dearth of studies that have addressed this topic.

The aims of this experimental study on arable weeds were (1) to compare germination of endangered and common arable weeds in response to a broad range of constant temperatures and water potentials, (2) to quantify the impact of different future climate scenarios on the germination success of endangered and common arable weeds and (3) to characterise and compare the germination syndrome of endangered and common arable weeds based on derived germination traits. To this end, we set up a multifactorial climate chamber experiment to study the impacts of temperature and water availability on germination of four familial pairs of common and endangered arable weed species.

2. Materials and methods

2.1. Study species

We chose four familial pairs of common and endangered arable weed species (Table 1) to ensure a phylogenetic balanced design and therefore a higher explanatory power of the results (Gitzendanner and Soltis, 2000). The Red List Status of these species referred to the Red List of threatened plant species in Germany (Ludwig and Schnittler, 1996). The seeds for the experiment were obtained from a commercial supplier of autochthonous seed material (Rieger and Hoffmann GmbH, Blaufeld-Raboldshausen, Germany).

2.2. Experimental design

To investigate the effects on germination, we used a factorial experimental design with *species* ($k = 8$) nested in *status* ($k = 2$; common vs. endangered), *water potential* ($k = 5$; 0, −0.3, −0.6, −0.9, −1.2 MPa) and *temperature* ($k = 8$; 3, 5, 10, 15, 20, 25, 30, 35 °C).

The water potentials were manipulated by using Mannitol (D-Mannitol, Euro OTC Pharma GmbH, Bönen, Germany). Water potentials of −0.3, −0.6, −0.9 and −1.2 MPa were prepared with Mannitol concentrations of 0.12, 0.24, 0.36 and 0.48 mol l^{-1} (according to Ludewig et al., 2014). As a control, distilled water was used for full water availability (0 MPa). For each treatment combination five replicates were set up, resulting in a total of 1600 experimental units.

In a Petri dish fifty seeds were placed on one layer of filter paper moistened with 3 mL of D-Mannitol solution or distilled water. To minimize evaporation, five Petri dishes were sealed together in a plastic bag. After 14 days of stratification at 3 °C in darkness in climate chambers (Rumed type 3401, Rubarth Apparate GmbH) the prepared Petri dishes were moved into climate chambers with constant temperatures of 3, 5, 10, 15, 20, 25, 30 and 35 °C with a 16-h day/8-h night cycle (Otte, 1996). Seeds were checked for germination twice a week. Germinated seeds were counted and removed at the time when the radicle was observable. After 5 weeks germination almost ceased and the experiment was finished.

2.3. Total germination

First we calculated for each experimental unit (i.e. Petri dish) the total germination (expressed as %), as the number of all germinated seeds divided by the initial number of seeds per Petri dish (50 seeds). Before analysis, total germination was arcsine-square-root-transformed to improve normal distribution and variance homogeneity (Quinn and Keough, 2002). With the transformed dataset a single factor variance analysis (ANOVA) with the factor family was carried out to account for potential phylogenetic effects ($F_{3,\,1596} = 25.2$, $p = <0.001$). All further calculations were performed with the residuals of this ANOVA. The effects of the single factors and the factor combinations of *species* (nested in *status*), *status*, *temperature* and *water potential* were assessed with a multi-factorial hierarchical ANOVA. Subsequently, significance of differences between treatments was assessed by employing a Tukey-HSD. To avoid zero inflation and missing data, the water potential −1.2 MPa was excluded from the statistical analysis. All statistical analyses were carried out using the programme STATISTICA (ver. 10.0, Statsoft Inc., Tulsa, OK, USA).

2.4. Germination traits

For a characterisation of the germination syndrome of common and endangered species we calculated for every level of the factor water potential the following traits (according to Olff et al., 1994; Hölzel and Otte, 2004; cf. Table 4) for each species: *Tmean* (°C), the mean temperature for germination, calculated as weighted average of total germination over all constant temperatures:

$$Tmean = \sum_{i=1} n_i t_i \bigg/ \sum_{i=1} n_i \tag{1}$$

where n_i is the total germination at temperature i and t_i is the constant temperature i in °C. *T_Gmax(final)* (%), the maximum total germination, was defined as the highest total germination in any of the constant temperatures at the end of the experiment. *T_Gmax(8d)* (%) was the maximum total germination after 8 days in the climate chamber. *Tmax(final)* (°C) was the temperature at which *T_Gmax(final)*