Reduced crop sowing density improves performance of rare arable weed species more effectively than reduced fertilisation

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Summary

Characteristic arable weed species of dryland cereal fields have undergone significant declines due to agricultural intensification to the point that some of them are considered rare. Crop edges host higher abundances of arable weed species and thus may act as a refuge for the conservation of these rare arable species. Using mesocosms, we experimentally tested how conditions at field edges (i.e., lower sowing densities and less intensive fertiliser applications) operate on the growth (biomass and height) and reproduction (reproductive biomass and flower onset) of six rare arable species.

We found that rare arable species achieved lower biomass when growing with wheat compared with growing alone, and biomass of most of species was lower under high wheat sowing density than under low sowing density. In contrast, fertiliser application affected only two of the six arable species tested, especially when they were growing alone. Although the time to flowering was not affected by the conditions tested, reproductive biomass showed the same trends as overall biomass. These results indicate that conservation of rare arable species must primarily consider reduction in crop competition to increase their biomass and reproductive ability.

Keywords

Crop-weed competition, fertilisation, plant biomass and height, reproductive response, rare arable weed species, sowing density

Introduction

Arable farming systems sustain an important part of the global biodiversity that has been neglected in favour of crop production (Tscharntke *et al.*, 2005). The elimination of weed species from arable farming systems has guided agricultural management of the last decades with the goal of improving crop yields. However, only few of the many arable weed species thriving in dryland arable fields actually cause crop yield losses (Albrecht, 2003). Instead, the arable species that are less damaging to crop production have suffered the most from agricultural intensification and have experienced drastic declines (José-María *et al.*, 2010; Meyer *et al.*, 2013; Chamorro, Masalles & Sans, 2016). Some of these species are highly adapted to arable systems, representing the specialist end of the species-generalist continuum of species in the arable weed flora (Fried, Petit & Reboud, 2010). These species are known as characteristic arable species and have undergone such drastic declines over the last decades that some of them can be currently considered rare (José-María *et al.*, 2010; Rotchés-Ribalta *et al.*, 2015a).

Crop edges are the most outer few meters of the crop, adjacent to the field margins or boundaries, as defined by Marshall & Moonen (2002). Crop edges generally have higher levels of arable weed species diversity than field cores (Fried et al. 2009; José-María et al. 2010); thus buffering the decline of arable species diversity. Crop edges are particularly important for the conservation of rare weed species characteristic of dry land cereal fields, such as *Euphorbia falcata* L., *Galium tricornutum* Dandy, *Hypecoum pendulum* L., *Kickxia spuria* (L.) Dumort., *Scandix pecten-veneris* L. or *Viola tricolor* L. subsp. *arvensis* (murray) Gaud., that reach their maximum abundance in the crop edge (Fried *et al.*, 2009; José-María *et al.*, 2010). It is argued that, at crop edges, the periodic agricultural management practices characteristic of arable farming systems (e.g., soil cultivation, fertilisation and herbicide and insecticide spraying) are carried out at lower intensity than in the centre of fields, with an estimated effect of management 55 % lower in the edge than in the centre of fields (José-María *et al.*, 2010), thereby providing suitable conditions for rare arable species to survive. This is why field edges may act as refuges for the conservation of rare arable weed species (Fried *et al.*, 2009).

At field edges, crop sowing often occurs less homogeneously than at the field centres because of the difficulty of machine access at the edges, reducing the pressure exerted by crop competition, allowing higher light penetration and benefiting the occurrence of arable weeds (Fried *et al.*, 2009). Additionally, farming operations such as herbicide application and fertilisation are performed less successfully at field margins (Marshall & Moonen, 2002), which also favours the persistence of arable weed species (Petit *et al.*, 2011). In fact, these conditions at crop edges (lower sowing density and lower external inputs such as fertilisers and herbicides) may benefit arable species by altering the competitive relationships between crops and arable species. Alterations may act either directly by reducing the number of competitors and thus increasing light availability (Yasin *et al.*, 2019), or indirectly through the different responses of arable species and crops to nitrogen availability and radiation (Tuor & Froud-Williams, 2002; Kaur, Kaur & Chauhan, 2018). However, not much information is available regarding the quantification of intensity of practices conducted at field edges in comparison to the field centres.

Some agro-environmental schemes are already promoting the protection of crop edges and margins with the goal of preserving the associated biodiversity (e.g., conservation headlands). Some of these schemes include uncropped options either cultivated annually or not, and restrictions on insecticide, herbicide or fertiliser applications (Walker *et al.*, 2007). However, little is known about how the specific conditions of field edges operate to preserve the diversity of arable weed species. Therefore, acquiring this knowledge is fundamental to fine-tune the practices that should be promoted in agro-environmental schemes focused on conserving the diversity of rare arable species to ensure success (Wagner *et al.*, 2017). As these practices may act by altering crop-weed competitive relationships, we considered it appropriate to assess the effects of crop competition on rare arable species under the conditions that are found at the field edges (namely, lower sowing density and less fertilisation) in comparison to the conditions at the field centres (namely, higher sowing density and higher fertilisation). To this end, we conducted an experiment with mesocosms under controlled conditions and assessed the effects of crop sowing density and fertilisation on the growth and reproduction of some arable species that are considered rare in Mediterranean dryland arable fields (Rotchés-Ribalta *et al.*, 2015b; a). Specifically, we aimed to determine the effects of cereal crop competition when sown at different densities under different doses of fertilisation on the growth and reproduction of six rare arable weed species.

Materials and Methods

Experimental design

A mesocosm experiment was conducted in 2011 (from the 3rd of January until the 26th of May) in the experimental fields of the Faculty of Biology, University of Barcelona, Spain. The mean daily temperature during the experiment was 14.7ºC ranging from 5.5ºC to 26.1ºC. The mean daily humidity was 69.8 % and ranged from 31.3 % to 97.7 %. Low-density polyethylene bags of 26 cm diameter and 35 cm height were used as pots, each containing 18 L of soil. Holes were drilled into the bottom of the bags to allow water drainage. The soil was a mixture of white peat, coconut fibre and composted pine bark, with perlite and a basic balanced fertiliser (NPK 14-16-18) (Burés®, Sant Boi de Llobregat, Barcelona, Spain). Once the soil was placed in the bags, it was watered thoroughly to reduce to minimum the level of available nutrients (i.e., nitrate-N and ammonium-N) [35.39 (± 5.79) mg N/kg of soil].

The experimental setup consisted of two different doses of fertiliser and three densities of wheat to simulate the conditions at crop edges and field centres. NPK 14-13-16 fertiliser was added to the soil at two different doses equivalent to 87.0 kg N ha^{-1} as the high fertilisation dose, (F+), and 43.5 kg N ha^{-1} as the low fertilisation dose, (F-). We applied 45.4 g of fertiliser per mesocosm for the high dose consisting of 18 g of Osmocote, 14 g of 15-15-15, 8.2 g of $SO_4(NH_4)_2$, 5.2 g of PO_4HK_2 and 30 g of $CaCO_3$. Half of this dose was used for the low fertilisation treatment. Winter wheat (*Triticum aestivum* L. cv. Montcada) was sown at two different densities apart from the controls (no wheat): high (400 seeds m^{-2}, being 20 seeds per mesocosm) and low (200 seeds m^{-2}, 10 seeds per mesocosm) density. The wheat was sown in two parallel rows spaced apart 12.5 cm, corresponding to the standard distance between cereal rows in the field.

The weed species tested (*Agrostemma githago* L., *Centaurea cyanus* L., *Lithospermum arvense* L., *Neslia paniculata* (L.) Desv. subsp. *thracica* (Velen.) Bornm., *Papaver hybridum* L. and *Vaccaria hispanica* (Mill.) Rauschert) are characteristic of communities from the phytosociological order *Secalietalia cerealis* Br.-Bl. 1976 and are currently found at very low frequencies in Mediterranean arable fields, so they can be considered rare arable weeds (Rotchés-Ribalta *et al.*, 2015a; b).

The seeds used were collected from arable fields in the central depression of Catalonia, NE Spain. For each species, we collected seeds from individuals that grew more than 20 m away from each other to ensure high genetic variability of the resulting seed samples. The seeds were air-dried and stored at a room temperature in paper bags until sowing.

Sowing took place on the 3rd of January directly in the potted soil. Wheat seeds were sown at 1.5 cm depth at the different densities using a template with two lines separated by 12.5 cm. Arable weed seeds were also sown directly in the soil of the bags. Different numbers of seeds, depending on the germination success of each species, were sown at the centre of the soil surface. Some seeds were sown in separate containers using the same soil mixture to replace possible failures. Only one seedling was kept in each mesocosm.

All mesocosms were placed on a grid on the ground outdoors, subject to environmental conditions, but they were watered regularly. Mesocosms were distributed in eight blocks, corresponding to eight replicates. Within each block, two sub-blocks were placed according to fertilisation, within which three sub-sub-blocks were placed for wheat sowing density to minimise interference from surrounding mesocosms. Therefore, the experimental design consisted of 288 mesocosms (three wheat densities, two fertilisation rates, six different weed species and eight replicates).

Data collection

The height of focal weed plants in each mesocosm was measured four different times during the experiment, measured from the soil surface to the top end. The phenology of arable species, assessed as either vegetative or flowering, was also recorded regularly during the experiment up to twelve times.

At the end of the experiment, nearly 21 weeks after sowing, and when the wheat was already ripe and dry, we harvested the rare weed plants. The aboveground biomass was bagged separately by species for the rare weeds, dried at approximately 60ºC for at least 5 days, and weighed. The reproductive fraction (seeds, fruits and flowers, if still present) and the vegetative fraction of the arable species biomass were weighed separately.

Using the biomass of the weed plants growing alone and with wheat, we calculated the relative competitive intensity (RCI) index (Weigelt & Jolliffe, 2003) for each arable species growing under the same experimental conditions in each block. The RCI was computed as $(P_{alone} - P_{mixture})/P_{alone}$ where P is the performance (biomass in this case) of a weed plant growing alone in a mesocosm (P_{alone}) or one growing with wheat ($P_{mixture}$).

Statistical analyses

- *Effects of fertilisation and wheat density on weed biomass and height*. Mixed-effects models fitted by REML were used to assess the effects of fertilisation and wheat density, as well as their interactions, on weed performance as characterised by the total aboveground biomass. Plant biomass was log-transformed to achieve normality and homoscedasticity of the residuals. When the homoscedasticity requirement was not met after transformation, the models included a heteroscedastic error structure. Wheat density factors were entered as orthogonal contrasts, which allowed testing of the effects of growing with crop competition vs. growing without crop competition, and also the effects of growing with the low-density vs. the high-density cases of wheat. The same models were conducted for the reproductive biomass (seed, fruit and flower biomass) as well to obtain the effects of fertilisation amounts and wheat density on reproductive investment of the different weed species.

The same model was run for each rare arable weed species to assess the effects of fertilisation and of wheat competition on plant height. As there were different times of height measurements throughout the experiment, the sampling date was included in the models through a polynomial trend, considering linear, quadratic and cubic functions. This allowed modelling of the temporal trends on the growth of characteristic arable species as well as possible without relying on a priori growth models and enabled the detection of differences on growth rates among treatments. The random effects structure was set to account for the repeated measures on the same plant individuals (plant individuals within block). Height was log-transformed to achieve normality and homoscedasticity of the residuals. When the homoscedasticity requirement was not met after transformation, the models included a heteroscedastic error structure.

- *Effects of fertilisation and wheat density on the time to flowering*. The effects of the variables considered (namely, wheat sowing density and fertiliser dose) and their interaction on the time to flowering of each characteristic arable species was assessed using Cox proportional hazards mixed-effects models. The wheat density factor was also entered as an orthogonal contrast as in the previous models.

- *Effects of fertilisation and wheat density on weed competitiveness*. To assess the effects of fertilisation and the effects of the different densities of sowing wheat, as well as their interaction, on the competitive ability of weeds, we conducted linear mixed-effects models on the RCI for each species.

All statistical analyses were carried out with R 3.0.3 (R Core Team, 2016) with the package nlme (Pinheiro *et al.*, 2013) for linear mixed-effects models with a Gaussian error distribution and with the package coxme (Therneau, 2012) for the Cox proportional hazards mixed effects models. All models included the experimental sub-sub-blocks, nested to sub-blocks, nested to blocks as random-effect factors.

Results

Effects of fertilisation and wheat density on weed biomass and height

Total aboveground biomass of all tested arable species was reduced when grown with wheat, as compared to when grown in the absence of wheat, with an average reduction in biomass of about 96 % (Figure 1 and Table 1). Wheat sowing density was negatively correlated with growth of four out of six tested arable weed species, growing less under high wheat sowing density than under low sowing density (Table 1). High inputs of fertilisers allowed more vigorous growth only for *L. arvense* and *P. hybridum*, especially when these species were growing alone, as shown by the significant interaction between sowing density and fertilisation (Table 1).

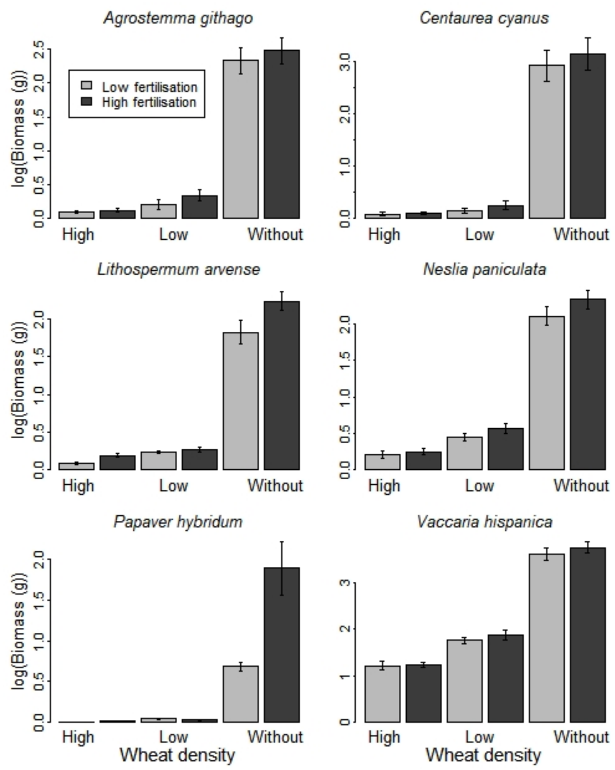

Figure 1. Mean (± SE) above ground biomass (logarithmic scale) of each characteristic arable species tested when growing in different situations of wheat competition: high sowing density, low sowing density and without wheat; and of fertilizer application.

*Table 1. Effects of fixed factors on arable species aboveground biomass (· P<0.1; *P<0.05; **P<0.01; and, ***P<0.001).*

	Agrostemma githago		*Centaurea cyanus*		*Lithospermim arvense*		*Neslia paniculata*		*Papaver hybridum*		*Vaccaria hispanica*	
	Estimated coefficient	±SE	Estimated coefficient	±SE	Estimated coefficient	±SE	Estimated coefficient	±SE	Estimated coefficient	±SE	Estimated coefficient	±SE
High fertilisation (vs. low fertilisation)	0.108	±0.103	0.064	±0.161	0.186	±0.071*	0.136	±0.071*	0.288	±0.100*	0.106	±0.071
Wheat density												
Wheat (vs. no wheat)	-0.687	±0.068***	-0.866	±0.111***	-0.526	±0.044***	-0.571	±0.036***	-0.217	±0.043***	-0.696	±0.036***
High density (vs. low density)	-0.042	±0.030	-0.022	±0.026	-0.078	±0.016***	-0.116	±0.062*	-0.016	±0.004**	-0.284	±0.062***
High fertilisation × wheat (vs. no wheat)	-0.031	±0.099	-0.021	±0.159	-0.128	±0.070*	-0.057	±0.050	-0.292	±0.100**	-0.032	±0.051
High fertilisation × high density (vs. low)	-0.060	±0.049	-0.044	±0.042	0.042	±0.024*	-0.037	±0.087	0.009	±0.006	-0.018	±0.088

Reproductive investment assessed in terms of reproductive biomass followed the same trends as the overall aboveground biomass; the presence of wheat, particularly at the high wheat sowing density, and high rates of fertilisation reduced the reproductive investment (Table A1 of Supplementary materials). Higher doses of fertilisers involved higher reproductive biomass levels for *L. arvense* and *P. hybridum* mainly when these species were growing alone.

Centaurea cyanus and *P. hybridum* were significantly shorter when grown with wheat than when grown alone (Figure 2 and Table A2 of Supplementary materials). In contrast, *L. arvense* attained marginally greater plant height when grown with wheat than when grown alone, but height was greater at the lower wheat sowing density than at the higher sowing density, as for *P. hybridum*. Growth of both *N. paniculata* and *V. hispanica* was unaffected by wheat competition (Table A2 of Supplementary materials).

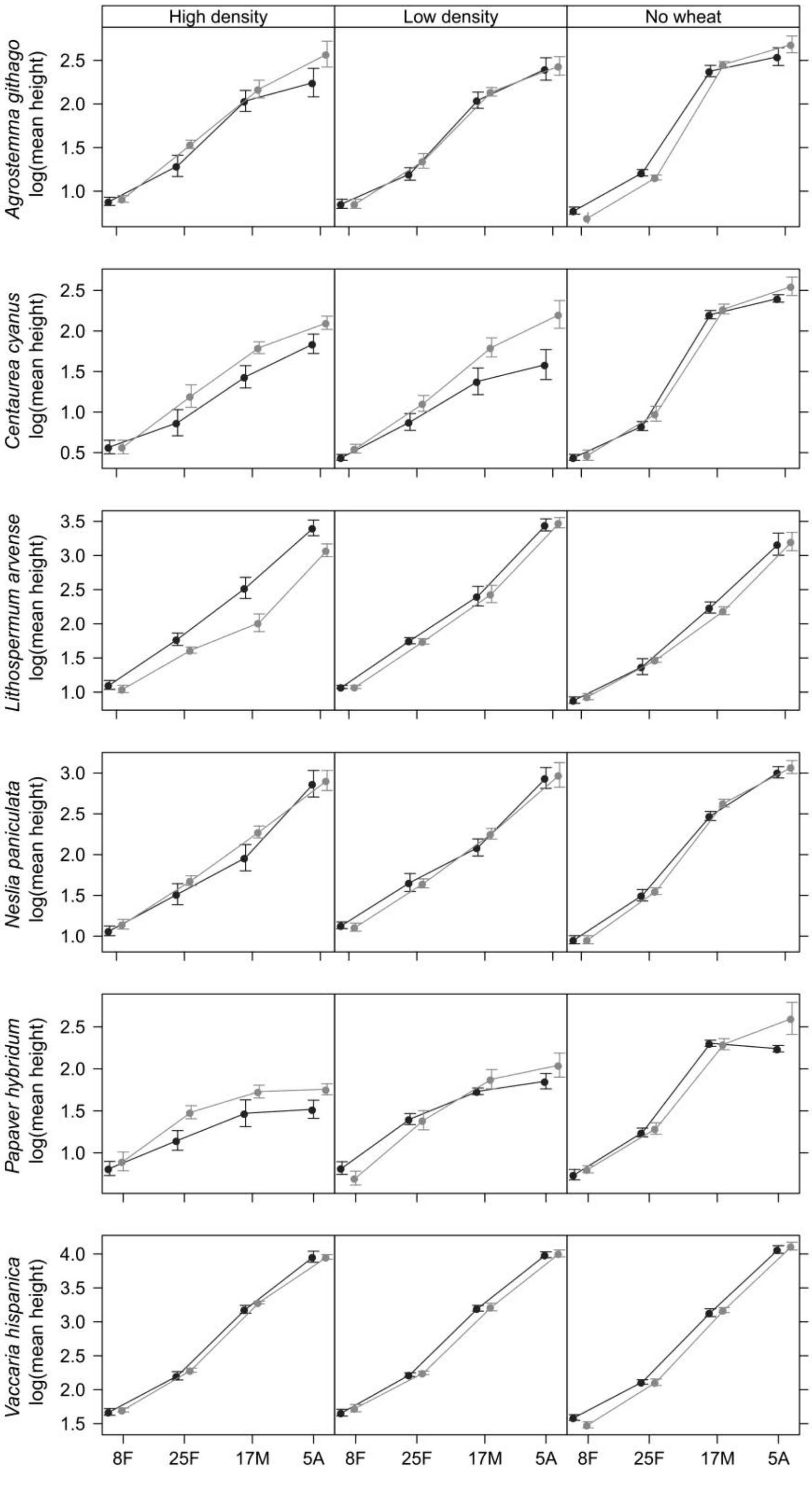

Figure 2. Mean (± SE) height of each characteristic arable species for each sampling date (8 February, 25 February, 17 March and 5 April) when growing in different situations of wheat competition: high sowing density, low sowing density and without wheat; and of fertiliser application: low dose of fertiliser (light grey) and high dose of fertiliser (dark grey)

Some of the arable weed species grew taller under high fertiliser inputs (Figure 2 and Table A2 of Supplementary materials). *Centaurea cyanus*, *N. paniculata* and *P. hybridum* were able to grow taller when fertilisation was high, independently of wheat competition. *Agrostemma githago* and *V. hispanica*, by contrast, were affected neither by the fertilisation nor by the wheat density.

The growth of all rare arable weed species tested, except for *L. arvense*, took place faster when they grew alone, as indicated by the significant interaction between the temporal trends and the competition from growing with wheat (Table A2 of Supplementary materials). *Agrostemma githago*, *C. cyanus* and *P. hybridum* were able to grow faster under the high fertiliser rates.

Effects of fertilisation and wheat density on the time to flowering

The time to flowering was not affected significantly by the factors of wheat competition and fertilisation doses (Table A3 of Supplementary materials). Only *C. cyanus* and, marginally, *A. githago*, began to flower later when growing with wheat. Fertilisation did not influence the flowering time of the weed species tested (Table A3 of Supplementary materials).

Effects of arable species on wheat growth

Fertilisation did not influence the ability of the arable species to compete with wheat (Table 2), except for *P. hybridum,* which showed higher competitive ability (lower RCI) at higher fertiliser doses. In contrast, all rare arable species tested, except *A. githago* and *C. cyanus*, showed a reduced ability (higher RCI) to compete with wheat when wheat was sown at high densities. As indicated by a significant interaction in the case of *P. hybridum*, this species was much less competitive when a high wheat sowing density was combined with low fertilisation (Table 2).

Table 2. Effects of fixed factors on arable plant species relative competition intensity, calculated as $(P_{alone} - P_{mixture})/P_{alone}$, where P is biomass (P<0.05; ** P<0.01; and, *** P<0.001).*

	Agrostemma githago		*Centaurea cyanus*		*Lithospermum arvense*		*Neslia paniculata*		*Papaver hybridum*		*Vaccaria hispanica*	
	Estimated Coefficient	±SE	Estimated Coefficient	±SE	Estimated Coefficient	±SE	Estimated Coefficient	±SE	Estimated Coefficient	±SE	Estimated Coefficient	±SE
High fertilisation (vs. low fertilisation)	-0.020	±0.011	0.000	±0.008	0.024	±0.015	-0.007	0.020	0.025	0.008*	0.017	0.022
High density (vs. low density)	0.008	±0.011	0.003	±0.003	0.043	±0.010***	0.047	0.014**	0.037	0.007***	0.083	0.020**
High fertilisation × High density (vs. low)	0.025	±0.016	-0.003	±0.005	-0.028	±0.014*	0.007	0.019	-0.030	0.009**	-0.011	0.028

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Discussion

Effects of wheat crop competition on weeds' growth

Growth of the tested rare arable species was noticeably affected by wheat crop competition, in accordance with previous studies (Weiner, Griepentrog & Kristensen, 2001; Andreasen, Litz & Streibig, 2006). Although these species are adapted to the periodic cropping practices from arable farming systems, the competition exerted by the wheat crop seems to affect their growth to a great extent. Crop species can take up nutrients more rapidly and efficiently and can outcompete most arable species for light (Tang *et al.*, 2014), suggesting that the main factor limiting the growth of rare weed species individuals within fields is the lower light availability under the crop canopies (Yasin *et al.*, 2019), which are typically denser at the field centres (Dutoit *et al.*, 2001; Perronne *et al.*, 2014). The reduction in crop sowing density facilitated more vigorous growth of four out of six weeds in comparison with the standard crop production conditions, in agreement with previous studies (Wagner *et al.*, 2017). These facts emphasize that the lower crop establishment at the crop edges promote the success of some rare arable weed species (Perronne *et al.*, 2014; Wagner *et al.*, 2017). Therefore, conservation strategies aiming to promote the conservation of arable species at the field edges should incentivise the reduction of crop sowing density.

The effect of reduced fertilisation on the aboveground biomass of the rare arable species was not as noticeable as that of crop sowing density, as previously stated (Gaba *et al.*, 2018). Only *L. arvense* and *P. hybridum* responded significantly to the higher fertiliser applications. However, this positive effect from high fertiliser inputs took place only when the tested species were growing without wheat competition. These results are in accordance with other studies (Andreasen *et al.*, 2006; Tang *et al.*, 2014; Albrecht *et al.*, 2016) and reinforce the idea that interactions between crop and arable species depend on soil fertility (Kleijn & van der Voort, 1997; Kaur, Kaur & Chauhan, 2018). The rare arable species tested here are adapted to farming strategies with lower nutrient levels and, thus, seem to be much less efficient in terms of nutrient utilisation than wheat, which places them at a disadvantage in a community context when compared to wheat. Similar trends have been previously reported for other arable species such as *Apera spica-venti* (L.) P.Beauv., *Gnaphalium uliginosum* L., *Legousia speculum-veneris* (L.) Chaix, *Papaver argemone* L., etc. (Kleijn & van der Voort, 1997; Andreasen *et al.*, 2006; Epperlein *et al.*, 2014; Albrecht *et al.*, 2016; Rotchés-Ribalta *et al.*, 2016), although the opposite pattern has been also reported for more competitive weeds, which are able to outcompete crops for resources (Blackshaw, Molnar & Larney, 2005). The direction of our results thus highlights that many characteristic species of dry land cereal fields that are currently rare, at the low densities at which they are found, are unlikely to interfere with crop growth and production. Moreover, most of the arable weed species tested here did not respond to the dose of fertiliser when growing with wheat. This result indicates that these species are not nitrophilous, and indeed better adapted to less intensive farming practices with lower nutrient levels, and thus providing further support to the claims that they are not competitive with the crop (Epperlein *et al.*, 2014).

Although the competitive effect of the cereal crop on the arable species may also be mediated through reduced light availability (Yasin *et al.*, 2019), the response of the rare arable species in terms of height is highly variable. *Centaurea cyanus* and *P. hybridum* grew shorter when they were growing in competition with wheat and thus were not able to compete with the crop for light, but others did not significantly change their height in response to wheat competition. One of the species, *L. arvense*, was even able to grow taller when growing in competition with the cereal crop, highlighting its ability to modulate its growth to meet its light requirements (Kleijn & van der Voort, 1997). Three of the arable weed species tested in this study were able to grow significantly taller under lower wheat sowing densities than under higher wheat sowing densities, showing a better ability to compete for light under the sowing conditions at the field edges (Perronne *et al.*, 2014).

The effects of crop competition on the heights of the rare arable species took place by reducing their growth rate. In this sense, most of the arable species grew faster alone than with wheat. The same trend was observed for some species whose individuals grew faster under the lower sowing density in comparison with the plants growing under the higher sowing density. This situation indicates that at the edges of fields, where the sowing density is usually lower, and the competition exerted by the crop is less intense than in the field centre, the rare arable species are able to grow faster and gain better access to light than those plants grown in the field centre. Under these conditions, the rare arable species can grow more vigorously than in the field centres and can, thus, allocate more resources to reproduction (Weiner, 2004), which emphasises the importance of field edges as refuges for this set of species (Kleijn & van der Voort, 1997).

Response of reproductive measures

The persistence of annual arable weed species relies on reproduction to replenish the soil seedbank and ensure future population recruitment. It is therefore important to evaluate the effect of crop competition and fertilisation on the reproductive ability of the rare arable species. Reproduction is dependent not only on plant growth but also on phenology, as decreased flowering or later flowering typically leads to lower reproductive investment, in line with Fried, Kazakou & Gaba (2012). In the current study, the time to flowering of most of the arable species tested was not affected either by growing with wheat or by the fertilisation rates. However, their reproductive biomass at harvest time was clearly negatively influenced by wheat competition as pointed out by Fried, Kazakou & Gaba

(2012). Chauvel et al. (2005) found that the reduction in light interception due to competition significantly decreased the reproductive ability of some arable species. Despite the flowering time was not affected, the final reproductive biomass of these rare arable species in response to wheat competition followed a similar pattern to that of aboveground biomass. Therefore, although reduced growth may not involve reduced survival, it likely involves reduced fertility (Weiner, 2004), which may negatively affect future establishment and, over several generations, cause a decline in population sizes (Goldberg & Miller, 1990).

The effects of fertilisation on the reproductive biomass of the rare arable species depended on the wheat sowing density. These results confirm the indirect effects of fertilisation not only on the growth of arable species but also on the reproductive yields and the consequent effects on populations of rare arable weed species (Tuor & Froud-Williams, 2002).

Competition effect of weed species on wheat

Apparently, the competitive effect of some arable weed species was reduced (higher RCI) when wheat was sown at full sowing density in comparison to the low sowing densities (Table 2), and only *P. hybridum* showed significantly higher competitive ability at higher doses of fertilisers. These results point out to a lack of potential detrimental effects of these rare arable species, at densities lower than crop, on crop production, as previously highlighted by Epperlein *et al.* (2014). However, further competition studies between crops and rare arable species should be conducted considering different sowing densities of both crop and weed species to determine the thresholds of rare arable species densities to be compatible with crop production.

Conclusions

Some measures aimed at preserving rare arable weed species have already been focused on field edges (e.g. conservation headlands in UK (Walker *et al.*, 2007; Wagner *et al.*, 2017)). However, such measures lack a more complete approach fine-tuning the different parameters (i.e., fertilisation, sowing density, herbicide application) that may affect rare arable species conservation and hence they are found to deliver relatively small benefits for arable plant diversity (Walker *et al.*, 2007).

Previous measures aiming to promote rare arable species already considered the periodic cultivation as well as a reduction or ban of external inputs (i.e., herbicides, insecticides and fertilisers) in crop edges. However, our experimental study suggests that reducing fertiliser application at the edges of the fields might not be an effective measure by itself to promote conservation of rare arable species, but it should be addressed along with other measures that reduce the competitive effects of the crop, such as reducing sowing density. Performance of periodic cropping practices (mainly soil management) but with no crop sowing or with a reduction of crop sowing densities, such as the "uncropped cultivated margins" in UK (Albrecht *et al.*, 2016), could be implemented at field edges to promote rare arable weed species performance. These practices should improve growth and reproduction of these species, which will likely have long-term beneficial effects on their populations. However, although these patterns are clear in the experimental conditions of the current study, further knowledge is needed about specific effects of crop sowing and nutrient inputs in the edges of fields at the actual field conditions to adjust the most appropriate management for the conservation of rare arable plants.

Besides, our experimental approach supports the potential compatibility between conservation of rare arable species, if maintained under appropriate thresholds, and crop production at the field edges, given the lack of differences in the competition ability of rare arable species in the different cropping conditions tested. However, further studies should be conducted regarding crop and rare arable species competition to fully understand the behaviour of the latter and crop production under the different cropping conditions.

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Conflicts of interest

The authors declare no conflicts of interest.

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