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Performance and Mortality of *Rumex obtusifolius* and *R. crispus* in Managed Grasslands are Affected by Nutrient Availability

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Abstract The reasons for the greater incidence of *Rumex obtusifolius* in grasslands compared with *R. crispus* have never been investigated. In a small-plot field experiment in which seedlings of *R. obtusifolius* and *R. crispus* were transplanted into a sward dominated by *Dactylis glomerata*, the growth and survival of seedlings were monitored over three years under control and P, N, NP and NPK fertilizer treatments. The highest plants of *R. obtusifolius* and *R. crispus* were generally recorded in the N, NP and NPK treatments and the lowest in the control and P treatment. The maximum recorded heights of *R. obtusifolius* were 100 cm and of *R. crispus* 80 cm. The number of leaves per plant, weight of individual plants, cover and fertility were generally higher for *R. obtusifolius* than for *R. crispus*. 30% to 80% of transplanted *R. obtusifolius* plants flowered in the first (seeding) year and this contrasted with no flowering of transplanted *R. crispus* plants. After cutting, substantially better regrowth of *R. obtusifolius* was recorded compared to that of *R. crispus* and surviving *R. crispus* plants tended to show a gradual reduction in leaf number. The mortality of *R. obtusifolius* over three years ranged from 0% in the NPK treatment to 13% in the control, with an average of 8% over all treatments. The mortality of *R. crispus* ranged from 19% in the control to 94% in the NPK treatment with an average of 64% over all

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treatments. We concluded that *R. obtusifolius* is better adapted to growing in highly productive temperate grasslands than *R. crispus* because of its perennial character, larger plant size and higher fertility.

Keywords Curled and broad-leaved docks · Fertilizer experiment · Nitrogen · Phosphorus and potassium · Survival · Weed ecology

Introduction

Rumex obtusifolius L. subsp. *obtusifolius* (broad-leaved dock, hereafter referred to as *R. obtusifolius*) is one of the most problematic weed taxa in permanent temperate grasslands (Cavers and Harper 1964; Van Evert et al. 2009; Gilgen et al. 2010; Strnad et al. 2010). *R. obtusifolius* was reported by Grime et al. (1988) as a polycarpic perennial species that does not usually flower until the second year. However, flowering of 100% of plants in the seeding year was recorded by Křišťálová et al. (2011) under optimal growth conditions in Central Europe. In grasslands, *R. obtusifolius* can survive different cutting frequencies for many years although frequent cutting can decrease the size of individual plants (Zaller 2006; Stilmant et al. 2010). *R. obtusifolius* can therefore rarely be eradicated from grasslands by frequent cutting as generally believed by many farmers. In Central Europe, high mortality of *R. obtusifolius* was recorded in unmanaged grasslands and in those cut late in the season (Pavlů et al. 2008; Martínková et al. 2009), and therefore no management seems to be more effective for the control of *R. obtusifolius* than frequent cutting.

One of the factors enabling the spread of *R. obtusifolius* into grasslands is the high nutrient availability in such habitats, because *R. obtusifolius* is considered to be nitrophilous (Zaller 2004a). The competitive ability of *R. obtusifolius* in grass-dominated swards increases substantially under high nitrogen (N), phosphorus (P) and potassium (K) availability in the soil (Haggar 1980; Niggli et al. 1993; Hatcher et al. 1997; Humphreys et al. 1999; Hopkins and Johnson 2002).

Rumex crispus L. (curled dock) is one of the most problematic weed species worldwide, especially on arable land (Pye and Andersson 2009). Although the effects of nutrient availability on the growth of *R. crispus* have received considerably less attention than in the case of *R. obtusifolius*, it is generally believed that both species have similarly high nutrient requirements (Jursík et al. 2008). *R. crispus* was reported by Grime et al. (1988) as a short-lived perennial or, more rarely, as an annual species that is able to flower in its seeding year. Nevertheless, no flowering was recorded in the seeding year by Hongo (1989) on Hokkaido, by Hume and Cavers (1983) in North America or by Křišťálová et al. (2011) in Central Europe. *R. crispus* often dies after flowering and tends to disappear from permanent grassland if new seedlings fail to establish (Bond et al. 2007; Křišťálová 2010). Perennation of *R. crispus* can be encouraged by cutting before flowering although *R. crispus* is generally much more negatively affected by severe defoliation than *R. obtusifolius* (Bentley and Whittaker 1979; Hongo 1989). Perennation of *R. crispus* on arable land can be achieved by its regeneration from fragmented underground organs (Hongo 1988; Pye 2008).

In this paper, we examined why *R. obtusifolius* is more successful in productive temperate grasslands than *R. crispus*. This issue was addressed in a transplantation experiment in which both related species were exposed to the same environmental conditions and the same plant traits were measured simultaneously. This approach enabled us to precisely quantify differences in life strategies between the related species and thus to identify key plant traits responsible for their different behavior in grasslands.

We established a grassland fertilizer experiment and transplanted seedlings of *R. obtusifolius* and *R. crispus* into the existing sward with different N, P and K availability. The aim of this study was to answer the following questions: *i*) How are the plant height, number of leaves per plant, weight of individual plants, their cover, fertility and the mortality of *R. obtusifolius* and *R. crispus* affected by fertilizer treatment? *ii*) How does the behavior of *R. obtusifolius* and *R. crispus* differ in permanent cut grassland?

Material and Methods

Study Site

The fertilizer experiment was set up near the village of Mšec, 45 km northwest of Prague (50°12′24″ N; 13°51′40″ E) at an altitude 490 m a.s.l. The study site was a flat intensively used species-poor meadow with mean annual precipitation of 550 mm and mean annual temperature of 8°C. The study site's soil type was Pararendzina (syn. Calcic Leptosols) developed on mesozoic Ca-rich sediments. The pH (H_2O) in the upper 10 cm soil layer before the start of the experiment was 6.4, the concentration of plant-available (Mehlich III) P was 152 mg/kg, of K 267 mg/kg, of Ca 1688 mg/kg and Mg 171 mg/kg. Total (Kjeldahl) N content was 2,300 mg/kg. *Dactylis glomerata* (visually estimated cover of 45%), *Festuca arundinacea* (12%), *Phleum pratense* (9%) and *Taraxacum* sp. (8%) were the dominant species before establishment of the experiment. The meadow had been regularly cut two or three times per year and occasionally fertilized with farmyard manure before establishment of the experiment.

Experimental Design

The experiment was established in summer 2007 on a meadow in which *R. obtusifolius* was growing. A completely randomized block design was used with the unfertilized control and P, N, NP and NPK fertilizer treatments replicated four times (20 monitoring plots altogether, see Fig. **S1** in Electronic Supplementary Material). The area of each individual monitoring plot was 4 m × 3 m. The application rates for N and in each dressing were 150 kg N/ha, for P 40 kg P/ha and for K 100 kg K/ha. The first fertilizer application was performed on the 19th August 2007. In 2008, 2009 and 2010 fertilizers were applied at the beginning of March and then after the first cut in June. High application rates of N, P and K were used as both *Rumex* species are considered to require a high nutrient supply (Zaller 2004a; Křišťálová et al. 2011). Naturally occurring plants of *R. obtusifolius* were dug out to 5 cm below the ground eight times during the vegetation seasons 2007–2009 to test the effectiveness of mechanical weeding, but such weeding was not successful (see Strnad et al. 2010 for details). Over three years, the cover of naturally occurring *R. obtusifolius* plants decreased only slightly from 7.5% to 4.5% and the effectiveness of weeding was not significantly affected by fertilizer treatment. A meadow containing naturally occurring *R. obtusifolius* plants was selected to ensure that the environmental conditions were suitable for this species.

The experimental plots were cut twice each year – at the beginning of June and in August. The stubble height in each cut was 5 cm. In June 2008, after the first cut, four seedlings of *R. obtusifolius* and four of *R. crispus* were transplanted into each individual monitoring plot and marked with a plastic stick (see Fig. **S1** in Electronic Supplementary Material). These seedlings were grown from seeds of *R. obtusifolius* and *R. crispu*s collected during autumn 2007 from a region near Prague in central Czech Republic. The same seeds were used in the pot fertilizer experiment carried out by Křišťálová et al. (2011) to ensure that the results of the pot experiment and this field experiment were directly comparable. The collection sites were mainly roadside ditches or abandoned fields. Seed material was collected from a group of plants at three localities. Five plants were randomly selected at each site, taking care not to favor tall or small plants. Seeds were sown in late March 2008 in a greenhouse and small seedlings with the first true leaf were transferred into individual pots in April and then planted in open-air conditions. Seedlings with three true leaves were transplanted into experimental plots. All transplanted seedlings were watered with the same amount of water during the first two weeks after transplantation to prevent desiccation.

Data Collection

Plant height, the number of leaves per plant, the proportion of fertile plants and the proportion of unassigned plants were recorded 12 times during three vegetation seasons. Unassigned plants were 1) living plants but without any green leaves and 2) dead plants. The term “unassigned plants” was used because it was impossible to distinguish between living plants with no leaves and dead plants on some occasions. On the last sampling date, the number of unassigned plants corresponded to mortality as no regeneration of stems was recorded lately. The weight of dry matter above-ground biomass per plant cut 5 cm above ground level was determined four times and the cover of four transplanted plants in each experimental plot was visually estimated five times during the study period. The weight of individual plants and estimation of their cover was recorded directly before cutting.

Data Analysis

Repeated measures ANOVA was used to evaluate all data. One-way ANOVA followed by a post-hoc comparison using the Tukey HSD test were then applied to identify significant differences among treatments. The blocks were treated as a random factor. All analyses were performed using the STATISTICA 8.0 software (StatSoft, Tulsa, USA).

Results

According to the repeated measures ANOVA, the effect of time on all characteristics of *R. obtusifolius* and *R. crispus* was significant (Table **1**). In the case of *R.*

Table 1 Results of repeated measures ANOVA analyses calculated separately for *Rumex obtusifolius* and *R. crispus* characteristics

Tested variable	Effect	*R. obtusifolius*				*R. crispus*			
		d.f.	d.f.s	*F*-value	*P*-value	d.f.	d.f.s	*F*-value	*P*-value
Plant height	time	11	40	78.4	**<0.001**	11	35	43.9	**<0.001**
	treatment	4	9	20.3	**<0.001**	4	20	8.4	**<0.001**
	treatment × time	42	90	1.5	0.066	42	91	3.4	**<0.001**
Number of leaves per plant	time	11	36	25.4	**<0.001**	11	32	4.3	**0.001**
	treatment	4	8	18.2	**<0.001**	4	17	3.1	**0.044**
	treatment × time	42	95	2.6	**<0.001**	42	85	1.8	**0.012**
Weight of plant	time	3	9	19.4	**<0.001**	3	13	11.1	**0.001**
	treatment	4	10	12.2	**0.001**	4	8	1.8	0.216
	treatment × time	12	27	7.6	**<0.001**	12	15	1.5	0.238
Cover of transplanted plants	time	4	12	39.1	**<0.001**	4	12	10.9	**0.001**
	treatment	4	12	8.2	**0.002**	4	12	4.5	**0.019**
	treatment × time	16	48	2.5	**0.008**	16	48	2.0	**0.034**
Proportion of fertile plants	time	11	35	41.0	**<0.001**	11	80	96.9	**<0.001**
	treatment	4	8	14.7	**0.001**	4	18	2.2	0.117
	treatment × time	42	86	1.6	**0.039**	42	76	2.2	**0.002**
Proportion of unassigned plants	time	11	35	6.1	**<0.001**	11	38	30.2	**<0.001**
	treatment	4	8	1.0	0.452	4	16	0.8	0.564
	treatment × time	42	86	1.5	0.052	42	88	1.5	0.054

Significant results are printed in bold. Investigated treatments were control and application of P, N, NP and NPK. d.f. – degrees of freedom, d.f.s – residual degrees of freedom.

obtusifolius, the effect of treatment on all measured characteristics was significant, with the exception of the proportion of unassigned plants. The effect of the interaction of treatment and time was significant for number of leaves per plant, plant weight, cover of transplanted plants and proportion of fertile plants. In the case of *R. crispus*, treatment had a significant effect on plant height, number of leaves per plant and on cover of transplanted plants. The effect of the interaction of treatment and time was significant for plant height, number of leaves per plant, cover of transplanted plants and the proportion of fertile plants.

According to one-way ANOVA, the heights of *R. obtusifolius* and *R. crispus* were significantly affected by treatment in 11 and 9 measurements respectively out of the 12 performed (Fig. 1a,b). In most cases, the tallest plants of both species were recorded in the N, NP and NPK treatments and the shortest in the control and P treatments. The maximum recorded heights of *R. obtusifolius* were 100 cm and *R. crispus* 80 cm.

The number of leaves per plant of *R. obtusifolius* was significantly affected by treatment in 11 and of *R. crispus* in 7 measurements out of the 12 performed (Fig. 2a,b). In most cases, the number of leaves was higher when N was added,

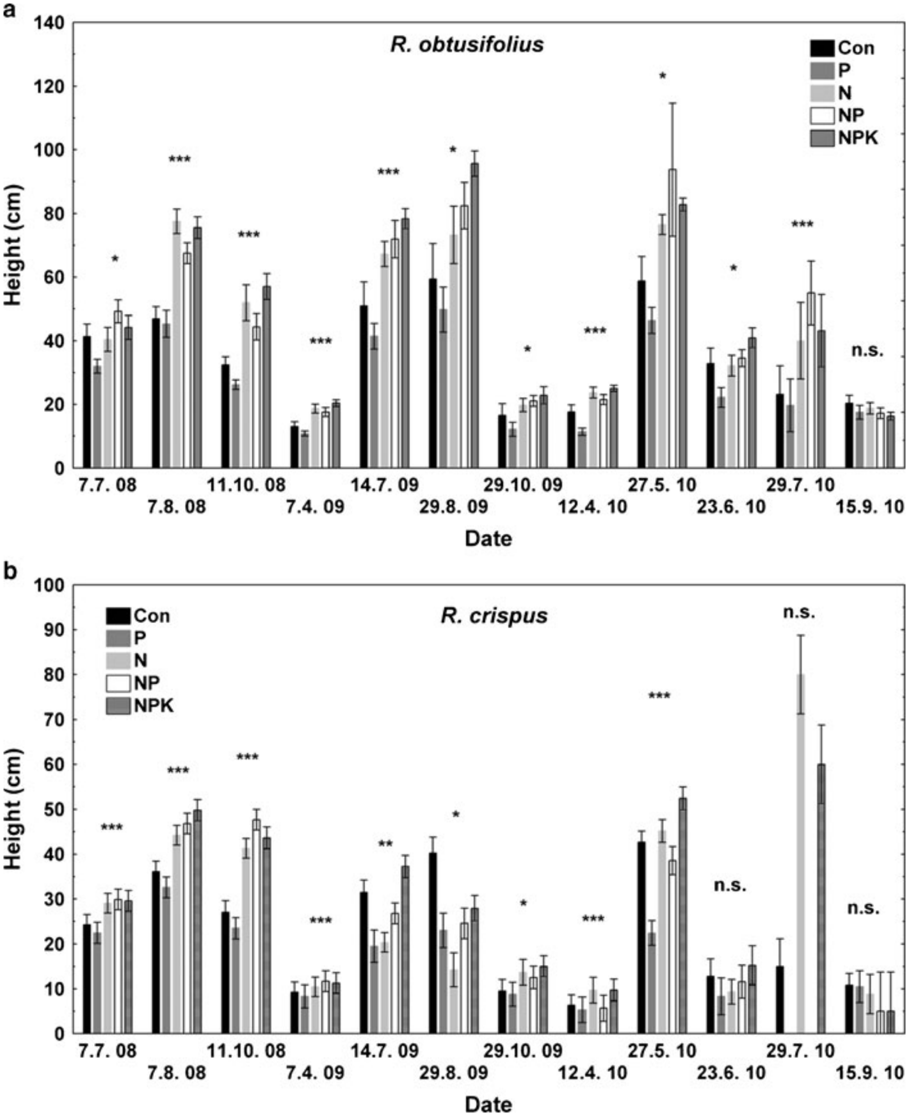

Fig. 1 Height of **a** *Rumex obtusifolius* and **b** *R. crispus* in investigated treatments over the study period from 2008 to 2010. Error bars represent standard error of the mean (s.e.). According to one-way ANOVA, the effect of treatment on each sampling date was not significant (n.s.), or significant at 0.05 (*), 0.01 (**) or 0.001 (***) probability level

compared to the control and P treatment. The numbers of leaves per plant were generally higher in *R. obtusifolius* than *R. crispus*. The maximum number of leaves per plant was 24 for *R. obtusifolius* and 11 for *R. crispus*. With the exception of the last two measurements when the leaves were heavily damaged by the beetle *Gastrophysa viridula*, the number of leaves per plant of *R. obtusifolius* gradually increased during the study. This trend contrasted sharply with the abrupt decrease recorded for *R. crispus* between April and July 2009 and with not much change afterwards.

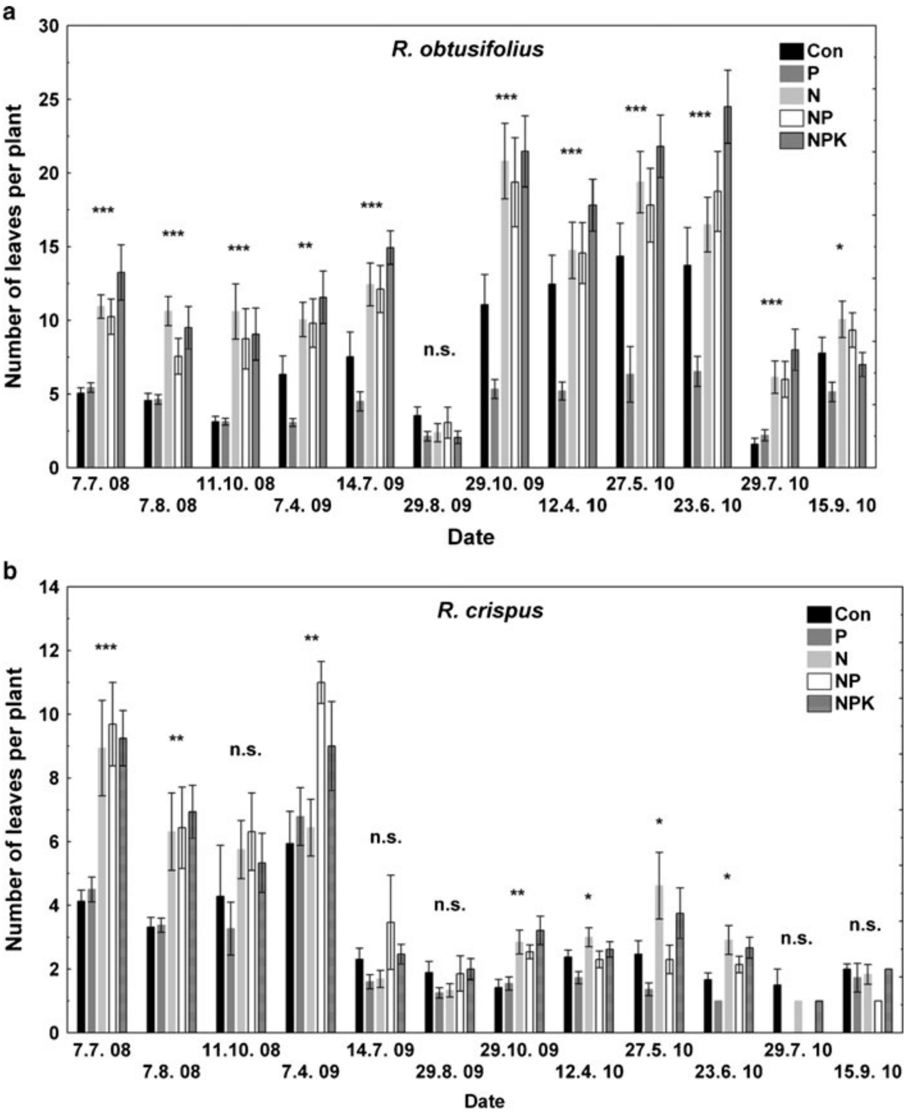

Fig. 2 Number of leaves per individual plant of **a** *Rumex obtusifolius* and **b** *R. crispus* in investigated treatments over the study period from 2008 to 2010. Error bars represent standard error of the mean (s.e.). According to one-way ANOVA, the effect of treatment on each sampling date was not significant (n.s.), or significant at 0.05 (*), 0.01 (**) or 0.001 (***) probability level

The number of leaves per plant corresponded well with the weight of dry matter aboveground biomass per plant, which was substantially higher for *R. obtusifolius* than for *R. crispus* (see Fig. **S2** in Electronic Supplementary Material). In two of the four measurements performed, treatment significantly affected the weight of *R. obtusifolius* plants. In one of the four measurements performed, treatment significantly affected *R. crispus* plants. In significant cases, the weight of plants was higher when N was added in comparison to the control and P treatment.

The cover of transplanted *R. obtusifolius* plants was substantially higher than that of *R. crispus* (see Fig. **S3** in Electronic Supplementary Material).

The cover of both species was significantly affected by treatment in three of the five measurements performed. In cases with a significant difference, the cover of both species was higher when N was added compared to the control and P treatment.

The proportion of fertile *R. obtusifolius* plants among living plants was substantially higher than the proportion of fertile *R. crispus* plants (see Fig. **S4** in Electronic Supplementary Material). Fertile plants of *R. obtusifolius* were recorded in seven out of 12 measurements and *R. crispus* in three out of 12 measurements. *R. obtusifolius* flowered in the seeding year, unlike *R. crispus*. The proportion of fertile plants was significantly affected by treatment on four occasions. On three of these, the proportion of fertile plants was highest in the NPK treatment and lowest in the P treatment.

The proportion of unassigned plants of *R. obtusifolius* was substantially lower than that of *R. crispus* (Fig. **3**a,b). For *R. obtusifolius*, the highest proportion of unassigned plants was recorded in the control and P treatment and the effect of treatment was significant in nine out of the ten measurements that included unassigned plants. A high proportion of unassigned *R. obtusifolius* plants was recorded on the 29th July 2010 after heavy grazing by the beetle *Gastrophysa viridula*. The proportion of unassigned plants of *R. crispus* gradually increased during the experiment. The highest proportion of unassigned plants was recorded when N was added. The mortality of *R. obtusifolius* over three years was substantially lower than that of *R. crispus* (Table **2**). The highest mortality of *R. obtusifolius* was recorded in the control and P treatment but the effect of treatment on mortality was on the border of significance. In the case of *R. crispus*, the highest mortality was recorded when N was added and the effect of treatment was significant.

Discussion

Rumex obtusifolius is substantially better adapted to growing in highly productive temperate grasslands than *R. crispus*. *R. obtusifolius* could produce taller plants with more leaves, plus higher biomass production per individual plant and higher cover than *R. crispus*. Seedlings of both species were produced at the same time and under the same growth conditions, and transplanted plants were the same size and had the same conditions for growth in the experimental grassland. Because for both species the developmental stage of transplanted plants and conditions for their growth was the same, these factors do not explain the differences in performance between *R. obtusifolius* and *R. crispus*. Further, despite substantially more frequent and severe attacks by the beetle *Gastrophysa viridula, R. obtusifolius* was able to grow better in the experimental grassland than *R. crispus*. *G. viridula* clearly preferred to graze on leaves of *R. obtusifolius* than on leaves of *R. crispus*, as previously demonstrated by Bentley and Whittaker (1979).

The minimal differences among N, NP and NPK treatments on the growth of both species can be explained by the N limitation of biomass production and the optimal P and K availability in the soil even in the absence of P and K application. N limitation without N application indicates that both species require a high N supply and can therefore be considered as nitrophilous. The concentrations of plant-available

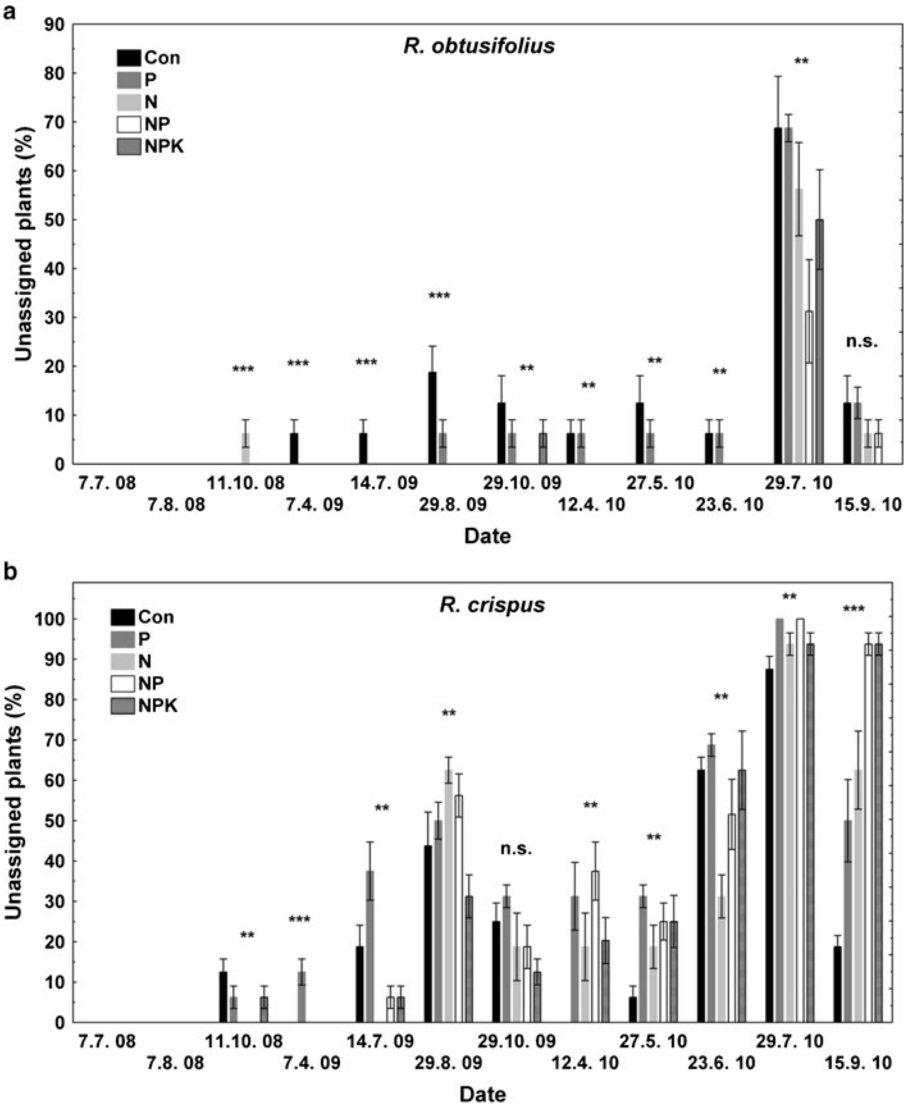

Fig. 3 Proportion of unassigned plants (living plants without any green leaves together with dead plants) out of total number of transplanted plants for **a** *Rumex obtusifolius* and **b** *R. crispus* in investigated treatments over the study period from 2008 to 2010. Error bars represent standard error of the mean (s.e.). According to one-way ANOVA, the effect of treatment on each sampling date was not significant (n.s.), or significant at 0.05 (*), 0.01 (**) or 0.001 (***) probability level

(Mehlich III) P were 152 mg/kg in the upper 10 cm soil layer and K 267 mg/kg. These values are considered to be optimal for crops with high P and K requirements (Hrevušová et al. 2009; Kulhánek et al. 2009; Černý et al. 2010; Šrek et al. 2010). The negative effect of P treatment on the growth of both species can be explained by the high P availability in the soil even in the absence of P application. In the P treatment, the growth of both species was the most severely limited by insufficient N

Table 2 Effect of treatment on proportion of unassigned plants (in %) over three seasons recorded on 15th September 2010

Treatment	*R. obtusifolius*		*R. crispus*	
d.f.	4		4	
d.f.s	8		8	
F-value	2.4		22.7	
P-value	0.059		<0.001	
Control	12.5[a]	±5.6	18.8[c]	±2.8
P	12.5[a]	±3.2	50.0[a]	±10.2
N	6.3[a]	±2.8	62.5[a]	±9.7
NP	6.3[a]	±2.8	93.8[b]	±2.8
NPK	0[a]	±0.0	93.8[b]	±2.8
Mean	7.5		63.8	

As no regeneration of unassigned plants was recorded in October 2010 and spring 2011, this proportion of unassigned plants corresponds to cumulative mortality of transplanted plants. *F*-value and *P*-value were obtained by one-way ANOVA, d.f. – degrees of freedom, d.f.s – residual degrees of freedom. Based on the Tukey HSD test, treatments with the same letter were not significantly different. ± values represent standard error of the mean (s.e.).

supply, with the biomass production and N concentration in the biomass of both species being lowest in the P treatment (unpubl. data of authors).

After cutting, *R. obtusifolius* showed substantially better recovery than *R. crispus*. This was clear from the gradual increase in plant size recorded for *R. obtusifolius* and the substantial decrease recorded for *R. crispus*. This is consistent with previously published results (Bentley and Whittaker 1979; Cideciyan and Malloch 1982; Hongo 1988), which showed that *R. obtusifolius* is substantially less negatively affected by defoliation than *R. crispus*. This is probably because *R. crispus* invests a higher proportion of assimilates into aboveground organs and generative reproduction than *R. obtusifolius,* which prefers to build up a large system of underground organs storing reserves (Hongo 1988; Zaller 2004b).

Of particular interest was that 30%–80% of *R. obtusifolius* plants flowered in the first (seeding) year, but that *R. crispus* did not flower at all in this period. Normal flowering of *R. obtusifolius* and the lack of flowering of *R. crispus* in the seeding year is consistent with the results of the pot experiment performed by Křišťálová et al. (2011) with the same genotypes of both species as those used in this field experiment. This contradicts the report by Grime et al. (1988), which concluded that *R. crispus* can flower in the seeding year and *R. obtusifolius* in the second year of growth. Like North American populations of *R. crispus* (Hume and Cavers 1983), at least some central European populations of *R. crispus* do not flower in the seeding year; this reproductive behavior is driven genetically, and not by nutrient availability as recorded in this study.

Mortality over three years was considerably lower in *R. obtusifolius* than in *R. crispus*. Mortality together with the proportion of fertile plants indicated that in cut grasslands in Central Europe *R. obtusifolius* is a perennial polycarpic species while *R.*

crispus is a biennial or short living perennial species. This conclusion should be extrapolated with caution to different climatic regions as Hongo (1989) recorded substantially higher mortality of *R. obtusifolius* compared to *R. crispus* over three years in newly sown grasslands cut twice per year in the cold winter season region of Hokkaido. Cold winter seasons can be detrimental for *R. obtusifolius*, but beneficial for *R. crispus*, as the two species differ in frost resistance, and furthermore, *R. crispus* is common in Nordic regions with cold winters (Cavers and Harper 1964; Křišťálová et al. 2011). Moreover, Hongo (1989) suggested that in cool winter regions *R. obtusifolius* has a life for only 3–4 years while *R. crispus* can live for many years. In the Czech Republic, substantially higher mortality of *R. obtusifolius* (50% over four years) was observed in comparison with our experiment in unmanaged swards (Martínková et al. 2009). It is highly probable that *R. obtusifolius* loses its competitive advantage over grasses and dies if grassland is left unmanaged.

The survival of some *R. crispus* plants for at least three years (perennation) was favored by cutting the grassland before seed production, because all plants that were cut when the seeds were fully ripe behaved strictly as monocarpic biennials in an experiment performed by Křišťálová (2010). Perennation of *R. crispus* enabled by the cutting of plants before seed production was also reported by other authors (Hongo 1989; Bond et al. 2007). In the control and P treatments, some plants probably survived longer because they did not flower during the first three seasons. Furthermore, the high mortality of *R. crispus* in treatments with N application indicates its lower competitive ability in highly productive swards. High mortality was exacerbated by the slow regeneration of *R. crispus* after cutting, meaning that regenerating plants were highly shaded by neighboring vegetation. It is possible that there were direct negative effects of N application on *R. crispus*, but no such effects were visually recorded. *R. crispus* evidently possesses lower competitive ability than *R. obtusifolius* under high nutrient availability in the sward. The higher mortality of *R. crispus* under higher nutrient availability and therefore the higher biomass production in the neighboring sward are consistent with the results reported by Hongo (1989).

Finally, we can conclude that *R. obtusifolius* is better adapted to growing in highly productive, regularly cut, temperate grasslands than *R. crispus* because of its perennial character, larger plant size and higher fertility.

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