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Effect of nitrogen and phosphorus availability on the emergence, growth and over-wintering of *Rumex crispus* and *Rumex obtusifolius*

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Abstract

Rumex crispus and *R. obtusifolius* are known to be nitrophilous but it is not known whether either or both species require a high N supply at all developmental stages. Furthermore, it is not clear whether both species require a high P supply, attain flowering in the seeding year, or have similar levels of winter resistance. The effect of nutrient availability on the emergence, growth and over-wintering of both *Rumex* species was investigated in a pot experiment (ten N, P and K fertilizer treatments) in Prague, Czech Republic. In both species, emergence of seedlings was negatively affected by very high N, but positively affected by increased P availability in the soil. No effect of K supply on the emergence, or subsequent growth, was recorded. High flowering in the seeding season and high winter mortality of *R. obtusifolius* contrasted with no flowering and no mortality of *R. crispus*. Over-wintering was not markedly affected by N, P or K supply. Both *Rumex* species are sensitive to a very high N supply in early developmental stages but tend to require a high N supply from the fully developed rosette-stage onwards. In addition to high N requirements during stem growth, flowering and seed ripening, both species also require a high P supply. At least some Central European populations of *R. crispus*, in contrast to *R. obtusifolius*, do not flower in the seeding year. In Central Europe, the frequently reported high field winter mortality of *R. obtusifolius* can be caused by its low frost resistance.

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Introduction

Rumex crispus L. (curled dock) and *R. obtusifolius* L. (broad-leaved dock) are perennial species native to temperate Europe (Cavers and Harper, 1964) and nowadays are cosmopolitan and are troublesome weeds worldwide, especially on arable land and in temperate grasslands (Jeangros and Nösberger, 1990; Hopkins and Johnson, 2002; Gebhardt *et al.*, 2006; Zaller, 2006; van Evert *et al.*, 2009; Stilmant *et al.*, 2010). For farmers in temperate regions, the fear of infestation of pastures by *R. crispus* and *R. obtusifolius* is one of the major obstacles preventing the switch from conventional to organic farming (Zaller, 2004). Both *Rumex* species are detrimental for livestock production as they decrease forage quality and have adverse animal health effects, causing serious digestive problems if eaten in high quantities (Holm *et al.*, 1977; Hejduk and Doležal, 2004).

Large numbers of viable and germinable seeds, which last in the soil for many years, are produced by both *Rumex* species; up to 60 000 seeds per plant per year have been reported (Cavers and Harper, 1964). In addition to generative reproduction, both *Rumex* species are able to regenerate from fragmented roots. High reproduction and regenerative capacity allows *R. crispus* and *R. obtusifolius* to be highly successful weeds (Honěk and Martinková, 2004; Šilc and Čarni, 2007), and their control without herbicides is extremely difficult (Pino *et al.*, 1998; Hopkins and Johnson, 2002; Strnad *et al.*, 2010).

Although the ecology of both species has received much research attention (Hatcher *et al.*, 1995, 1997a,b; Benvenuti *et al.*, 2001; Honěk and Martinková, 2002), the timing of the first flowering and seed production after the establishment of seedlings still remains unclear. According to Cavers and Harper (1964),

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flowering and seed set occasionally occur in the seedling year, but usually not until the second year after germination. According to Akeroyd and Briggs (1983), the flowering of *R. crispus* occurs from the second season after seedling establishment, and the same finding was also reported for *R. obtusifolius* (Hongo, 1989b). Unlike in Britain and the rest of Europe, plants of *R. crispus* in most North American populations are reported to require over-wintering before flowering can occur (Hume and Cavers, 1983; Bond *et al.*, 2007).

Germination under natural conditions in Western Europe can occur throughout the growing season, but occurs mostly during spring and autumn because of a loss of dormancy at low temperatures (Roberts and Totterdell, 1981; van Assche and Vanlerberghe, 1989). Seeds of *R. obtusifolius* germinate more slowly than *R. crispus*, but early development of seedlings occurs more quickly in *R. crispus* (Cavers and Harper, 1964, 1979).

Both *Rumex* species are known to be nitrophilous (Novak and Slamka, 2003; Hejduk and Doležal, 2004), although there are doubts as to whether or not both *Rumex* species are nitrophilous in all developmental stages (Zaller, 2004). According to Klimeš (1996), low concentrations of nutrients have a stimulating effect on the germination of *R. obtusifolius*, whereas high concentrations slow down germination and decrease the proportion of germinating seeds. A low concentration of nitrates (0·01 mol L^{-1}) was found to stimulate the germination of *R. obtusifolius*, whereas a high concentration (0·1 mol L^{-1}) reduced its germination (Milberg, 1997). Although the requirement for high nitrogen (N) in mature plants of *R. obtusifolius* is generally known (Jeangros and Nösberger, 1990), little attention has been paid to the nutrient requirements of young plants or to the phosphorus (P) and potassium (K) nutrition of mature plants (Humphreys *et al.*, 1999).

Similarly, the winter resistance of both species has received little research attention up to now. In a study performed in a cool-winter region of Central Europe, winter mortality of *R. obtusifolius* prevailed over summer mortality, and half of the plants died within the first 4 years of the field experiment and only 4% survived more than 8 years under a no-cutting management (Martinkova *et al.*, 2009). In the same region, high mortality of mature *R. obtusifolius* plants on unmanaged semi-natural grassland was recorded (Pavlů *et al.*, 2008a,b). High winter mortality of *R. obtusifolius* and *R. crispus* (approximately 50% mortality in the seeding year) was recorded in the cool winter season in Hokkaido, Japan (Hongo, 1989a). In the grassland experiment by Hongo (1989b) in the same region, 98% of transplanted seedlings of *R. obtusifolius* died in the third and fourth years, whereas the mortality of *R. crispus* was gradual and 17% of transplanted plants survived for 5 years. Differences in winter resistance may explain the differences in the world distribution of both these species, as *R. crispus*, in contrast to *R. obtusifolius*, can occur in northern and continental regions with severe winter frosts (Cavers and Harper, 1964). Although winter resistance may be a factor contributing to the different world distributions of the two species, differences in winter resistance between *R. cripus* and *R. obtusifolius* have not been investigated experimentally.

The aim of this study was to answer following questions: (i) is there any effect of high N, P and K availability on the emergence of *R. crispus* and *R. obtusifolius*? (ii) How is the performance (in terms of number of leaves, plant height and number of stems) of these two *Rumex* species affected by different N, P and K availabilities? (iii) How is winter survival different between the two species and how is it affected by different N, P and K availabilities?

Materials and methods

Experimental design

In May 2008 and in May 2009, a factorial pot experiment was established in the open-air vegetation hall of the Crop Research Institute in Prague-Ruzyně (Czech Republic, 50°5′N; 14°18′E) with natural rain, temperature and light conditions. The investigated factors were species (two levels: *Rumex crispus* and *R. obtusifolius*) and nutrient availability (ten levels: Control, N_1, N_2, P_1, P_2, K, N_1P_1, N_1P_1K, N_2P_1K, N_2P_2K; see Table 1 for details) providing a total of 20 treatments. Each treatment was replicated five times (thus, 100 pots in total). The pots were fertilized twice per vegetation season, on 12 May and 20 July, using the following fertilizers dissolved in

Table 1 Fertilizer treatments and amount of nutrients applied in one dressing. Numbers given in brackets correspond to the total seasonal amount of applied nutrients (two dressings together).

Treatment abbreviation	N (kg ha^{-1})	P(kg ha^{-1})	K(kg ha^{-1})
Cont	–	–	–
N_1	150 (300)	–	–
N_2	300 (600)	–	–
P_1	–	40 (80)	–
P_2	–	80 (160)	–
K	–	–	100 (200)
N_1P_1	150 (300)	40 (80)	–
N_1P_1K	150 (300)	40 (80)	100 (200)
N_2P_1K	300 (600)	40 (80)	100 (200)
N_2P_2K	300 (600)	80 (160)	100 (200)

water: ammonium nitrate with lime (NH_4NO_3 + $CaCO_3$, 27·5% N, 10% Ca), superphosphate ($Ca(H_2PO_4)2$ + $CaSO_4$, containing 8·5% P, 20% Ca, 10% S) and potassium chloride (KCl, 50% K, 47% Cl). The position of individual pots was changed at weekly intervals to avoid any pseudoreplication and edge effects.

The pot volume was 30 L, and the pot surface area was 1963 cm^2 (pot diameter 50 cm). Clay soil with the following chemical properties was used: N_{total} = 919 mg kg^{-1}, $K_{MehlichIII}$ 160 mg kg^{-1} (good K availability) (Madaras and Lipavský, 2009), $P_{MehlichIII}$ 16 mg kg^{-1} (low P availability) (Kulhánek *et al.*, 2007), $Mg_{MehlichIII}$ 373 mg kg^{-1} (high Mg availability), $Ca_{MehlichIII\ 10\ 501\ mg\ kg^{-1}}$ (very high Ca availability) and $CaCl_2$ pH 7·96. Potassium-rich soil was used to avoid any risk of K limitation on growth, as the emphasis was placed on N and P nutrition in this study. To ensure that growth was not limited by K, treatments with K applications (K, N_1P_1K and N_2P_2K) were used.

At the study site, the long-term mean annual temperature was 8·2°C (ranging from 6·4 to 9·7°C), and the mean annual precipitation was 422 mm (ranging from 255 to 701 mm; Prague-Ruzyně meteorological station, 1955–2007). The mean temperature from June to September 2008 and 2009 (main vegetation season) was 17·6 and 17·9°C, respectively, and from December to March 2008/2009 and 2009/2010 (winter season), it was 2·4 and 0°C respectively. During the winter season 2008/2009, the lowest measured temperature (−13·2°C) was recorded on 3 January 2009, and during the winter season 2009/2010, the lowest temperature (−19·8 °C) was recorded on 27 January 2010.

Seedling emergence

Seeds of *R. obtusifolius* subsp. *obtusifolius* (hereafter referred to as *R. obtusifolius*) and *R. crispu*s were collected during autumn 2007 and 2008 from a region near Prague city in central Czech Republic. 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 selected randomly at each site, taking care not to favour tall or small plants. The seeds were stored at room temperature, in paper bags in the dark. Germination was tested under laboratory conditions in a day/night light regime at 20°C. Germination was performed in four Petri dishes, each with fifty seeds for each species before seeding. Germination was 95% for both species. Twenty visually undamaged and fully ripened seeds of *R. obtusifolius* and *R. crispus* were sown into each pot with pre-fertilized soil on 19 May 2008 and the following year on 18 May 2009. The depth of sowing was 1–2 cm, and the pots were watered if necessary to maintain optimal moisture conditions for plant growth. The cumulative number of seedlings was recorded up to 26 June, in both 2008 and 2009, and no emergence of other seedlings was recorded after this date.

Plant performance

Three of the most developed plants were left in each pot after 26 June 2008 and 2009. The following data were collected at weekly intervals: (i) number of leaves per plant; (ii) number of leaves per main stem; (iii) length of the longest leaf; (iv) height of the plant; and (v) number of stems per plant.

Over-wintering

The plants were not cut during the vegetation season or in the autumn. The pots were not protected by any covering or insulation from frost, and they were exposed to normal weather conditions during the winter. The number of plants that survived the winter was counted on the 1 April 2009 and 10 April 2010.

Data analysis

All analysis was performed using STATISTICA 8.0 software (Statsoft, Tulsa, OK, USA). Emergence and winter survival data were evaluated by factorial ANOVA for species and treatment effects and their interactions. After obtaining significant results, multiple comparisons using Tukey's HSD test were applied to identify significant differences between treatments for each species. The number of stems per main stem, number of leaves per plant, length of longest leaf, number of stems or growing points and plant height data were evaluated using a mixed ANOVA model for species, treatment and time effects and time and treatment interactions.

As the results from both seasons, 2008/2009 and 2009/2010, were highly comparable, only the data from the first season have been included in the results section, and they are summarized in graphs.

Results

Emergence

When analysed by factorial ANOVA, it was found that emergence was significantly affected by species ($F = 16{\cdot}9$, $P < 0{\cdot}001$) and treatment ($F = 19{\cdot}4$, $P < 0{\cdot}001$), but not by their interaction ($F = 1{\cdot}2$, $P = 0{\cdot}32$). The mean emergence over all levels of nutrient availability was 39% and 49% for *R. obtusifolius* and *R. crispus* respectively. In both species, emergence was lowest in all treatments with N_2 applications (N_2, N_2P_1 K and N_2P_2K), and these treatments were significantly different from the P_1 and P_2 treatments (Figure 1).

Plant performance

Number of leaves per main stem

The number of leaves per main stem was significantly affected by species ($F = 1064$, $P < 0{\cdot}001$), treatment ($F = 29$, $P < 0{\cdot}001$), time ($F = 68$, $P < 0{\cdot}001$) and all of their interactions. In the case of *R. obtusifolius*, the greatest number of leaves (6·4) was recorded for the N_2P_1K treatment on 1 August. For the N_1P_1, N_1P_1K and N_2P_2K treatments, the greatest number of leaves (from 4·5 to 6) was recorded on 1 August, but for the Control, N_1, N_2, P_2 and K treatments, the greatest number of leaves (from 0·8 to 4·3) was recorded on either 21 or 28 August (Figure 2a). No stems of *R. crispus* developed in any of the fertilizer treatments during the seeding season.

Number of leaves per plant

The number of leaves per plant was significantly affected by species ($F = 25{\cdot}1$, $P < 0{\cdot}001$), treatment ($F = 106{\cdot}4$, $P < 0{\cdot}001$), time ($F = 63{\cdot}8$, $P < 0{\cdot}001$) and all of their interactions. In the first sampling dates (seedlings stage), the number of leaves in both species was greater in P_1 and P_2 than in other treatments (Figure 2c, d). On the other hand, the number of leaves was greatest in all treatments with N applications on the last sampling date. Generally, the greatest number of leaves was recorded in all treatments with N_1P_1 or N_1P_1K applications in the period from 24 July to 21 August. In the case of *R. obtusifolius,* the absolutely greatest number of leaves (20 per plant) was recorded for the N_2P_1K treatment on 1 August. In the case of *R. crispus,* the absolutely greatest number of leaves (24 per plant) was recorded for the N_1P_1 treatment on the 1 August. The number of leaves was significantly and positively affected by the number of growing points (*Rumex obtusifolius*: $y = 2{\cdot}0393 + 2{\cdot}4171x$; $R^2 = 0{\cdot}703$, $P < 0{\cdot}001$; *Rumex crispus*: $y = 0{\cdot}07 + 0{\cdot}4x$; $R^2 = 0{\cdot}95$, $P < 0{\cdot}001$) and by plant height (*Rumex obtusifolius*: $y = 30{\cdot}6 + 1{\cdot}6x$; $R^2 = 0{\cdot}15$, $P = 0{\cdot}006$; *Rumex crispus*: $y = 2{\cdot}38 + 0{\cdot}22x$; $R^2 = 0{\cdot}79$, $P < 0{\cdot}001$).

Length of the longest leaf

The length of the longest leaf was significantly affected by species ($F = 15{\cdot}1$, $P < 0{\cdot}001$), treatment ($F = 23$, $P < 0{\cdot}001$), time ($F = 82{\cdot}9$, $P < 0{\cdot}001$) and all of their interactions. In the seedling stage, the length of the longest leaf was greatest for the P_2, P_1 and N_1P_1K treatments (Figure 3a, b) in both species. On the other hand, leaves of *R. obtusifolius* were longest for N_2 and N_1 treatments, but the leaves of *R. crispus* were longest for the N_2P_2K, N_1P_1, N_2 P_1K and N_1P_1K treatments on the last sampling date. In the case of *R. obtusifolius,* the absolutely longest leaves (33 cm) were recorded on 1 August, but in the case of *R. crispus,* the absolutely longest leaves (34 cm) were recorded for treatment N_2P_2K on 4 September.

Number of stems or growing points

The number of stems or growing points was significantly affected by species ($F = 122$, $P < 0{\cdot}001$), treatment ($F = 189{\cdot}5$, $P < 0{\cdot}001$), time ($F = 162{\cdot}5$, $P < 0{\cdot}001$) and all of their interactions. In the seedling stage, the number of growing points was highest for P_2 treatment in both species (Figure 4a, b). On the

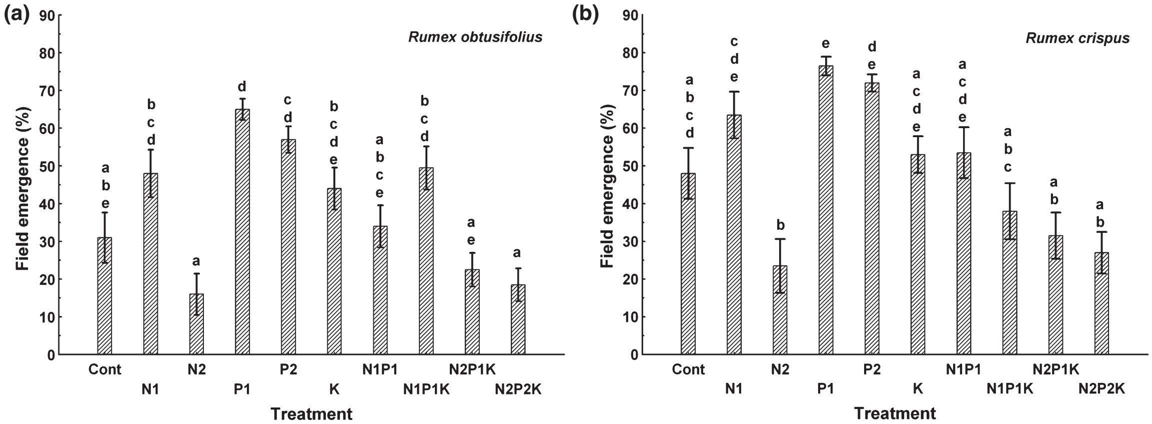

Figure 1 Effect of treatments on the emergence of *Rumex obtusifolius* (a) and *R. crispus* (b). Error bars represent standard errors of the means (SE). Treatment abbreviations are given in Table 1. Using Tukey's post-hoc test, treatments with the same letter were not significantly different at the 0.05 probability value.

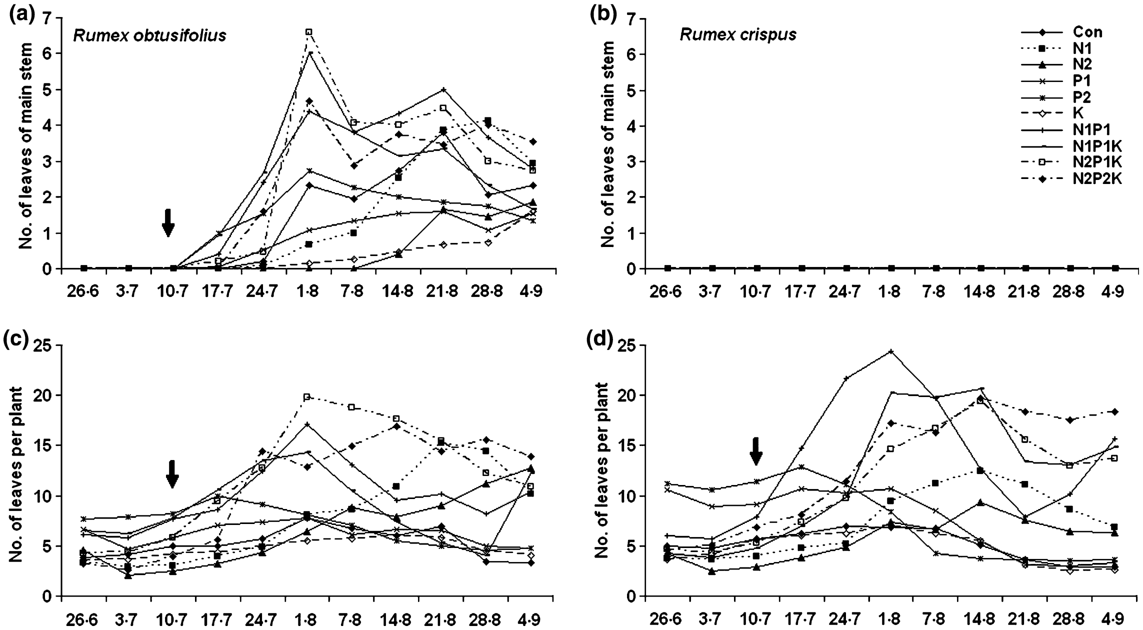

Figure 2 Effect of treatments on the number of leaves on the main stem of *Rumex obtusifolius* (a) and *R. crispus* (b) and the number of leaves on whole plants of *R. obtusifolius* (c) and *R. crispus* (d). Treatment abbreviations are given in Table 1. Arrows indicate the beginning of the stem phase.

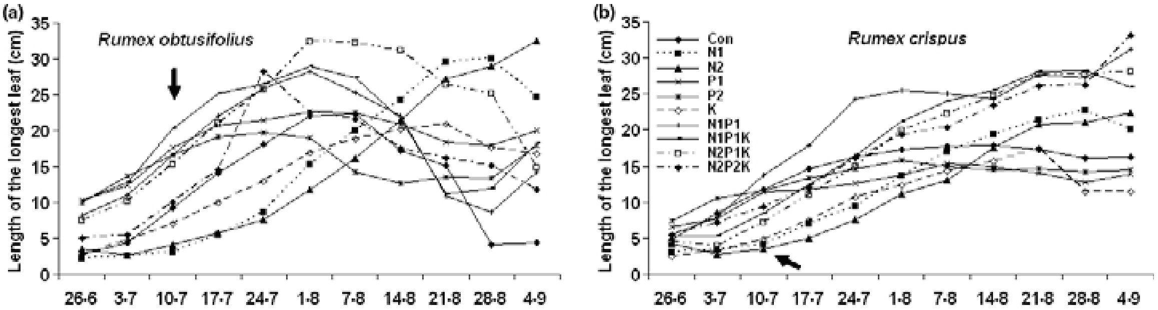

Figure 3 Effect of treatments on the length of leaves of *Rumex obtusifolius* (a) and *R. crispus* (b). Treatment abbreviations are given in Table 1. Arrows indicate the beginning of the stem phase.

other hand, the number of stems of *R. obtusifolius* was greatest for N_2P_1K and N_1P_1K treatments, and the number of growing points of *R. crispus* was greatest for the N_2P_2K and N_1P_1K treatments on the last sampling date. The greatest number of stems (4·9) and growing points (7·5) was recorded on the last sampling date, 4 September.

Plant height

Plant height was significantly affected by species ($F = 197{\cdot}5$, $P < 0{\cdot}001$), treatment ($F = 79$, $P < 0{\cdot}001$), time ($F = 214$, $P < 0{\cdot}001$) and all of their interactions. In the seedling stage, the plant height of both species was not affected by treatment (Figure 4c, d). The growing points of both species started to become prolonged first in P_1 and P_2 treatments on 10 July, as the plant height was the highest of all treatments on this date. In both species, the highest plants were recorded for the N_1P_1, N_2 P_1K, N_1P_1K and N_2P_2K treatments on the final sampling date, 4 September. In the case of *R. obtusifolius*, the highest plants (66 cm) were recorded for N_1P_1 treatment on 4 September, and in the case of *R. crispus,* the highest plants (6·7 cm) were recorded for treatment N_2P_2K on the same sampling date.

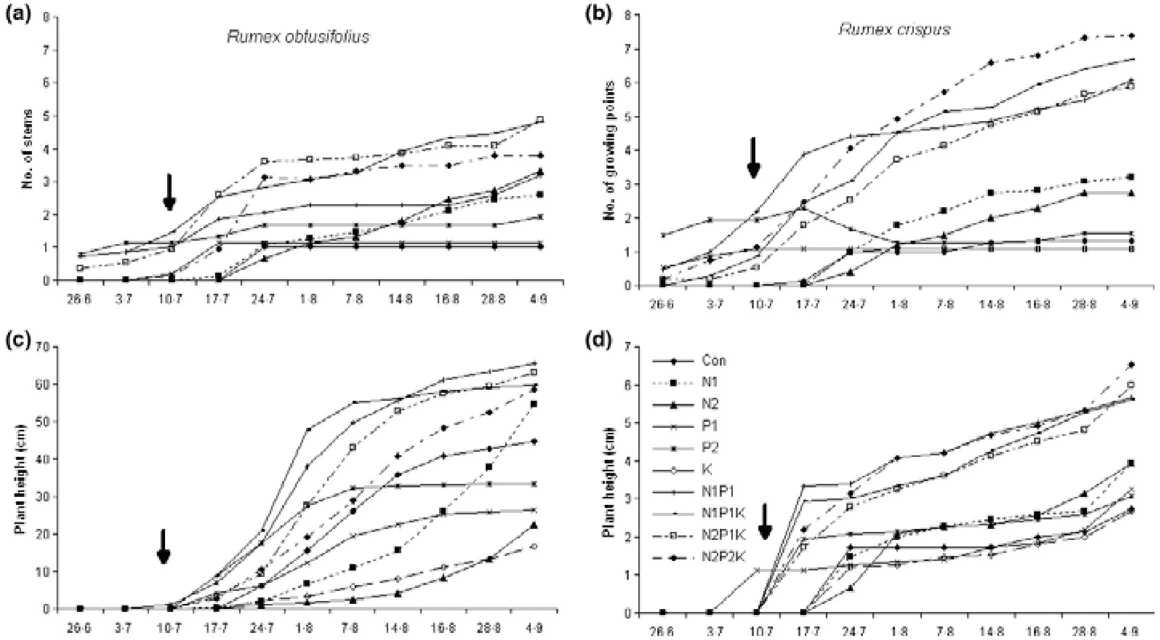

Figure 4 Effect of treatments on the number of stems of *Rumex obtusifolius* (a) on the number of growing points of *R. crispus* (b) and on the height of *R. obtusifolius* (c) and *R. crispus* (d). Treatment abbreviations are given in Table 1. Arrows indicate the beginning of the stem phase.

Over-wintering

Winter survival was significantly affected by species ($F = 1\ 009$, $P < 0{\cdot}001$), treatment ($F = 5$, $P < 0{\cdot}001$) and species and treatment interaction. Winter survival over all levels of nutrient availability was 18 and 100% for *R. obtusifolius* and *R. crispus* respectively (Figure 5a, b). Survival of *R. obtusifolius* was zero in the K treatment and was more than 30% in the N_1P_1 and N_2 P_1K treatments. No mortality was recorded for *R. crispus*.

Discussion

Emergence

Emergence was negatively affected by very high N availability in both species, as the lowest rate of emergence was recorded in all the treatments with N_2 applications. However, it should be noted that emergence was only evaluated after the first application of nutrients (N_2 = 300 kg N ha^{-1}). This was attributed to a negative effect of high NH_4^+ and/or NO_3^- concentrations in the soil solution on seed germination. On the other hand, applications of lower N rates (N_1 = 150 kg N ha^{-1}) slightly stimulated germination. Negative effects of high NO_3^- concentrations on the germination of *R. obtusifolius*, and stimulating effects of low concentrations, were also recorded by Milberg (1997) and Klimeš (1996). Similarly, Mandák and Pyšek (2001) reported a negative effect of a high NO_3^- concentration on the germination of *Atriplex* species. No germination, in either *Rumex* species, was recorded in an experiment with NH_4NO_3 fertilizer applications in contrast to normal germination in an experiment with $Ca(H_2PO_4)_2$ fertilizer applications in a laboratory germination performed by Křišťálová (2010). On the other hand, there was a clear positive effect of P_1 and P_2 treatments on the emergence of both species. This is consistent with the conclusion by Jenkins and Ali (1999) that P is an essential nutrient which is especially important in the promotion of early plant growth. Emergence was not affected by K applications because the clay soil was able to supply the seedlings with an adequate amount of K even without K application. The same results, i.e. a negative effect of a very high N supply and a positive effect of P supply on the emergence of both species, were also recorded in the second experimental year (data not shown here).

Although both species are generally believed to be nitrophilous (Milberg, 1997; Zaller, 2004), they suffer from the effects of very high N availability during seed germination and seedling emergence, in contrast to mature plants. The negative effect of a very high N application rate on the seedling emergence of both *Rumex* species seems to be a possible practical measure that might be used for decreasing *Rumex* seedling

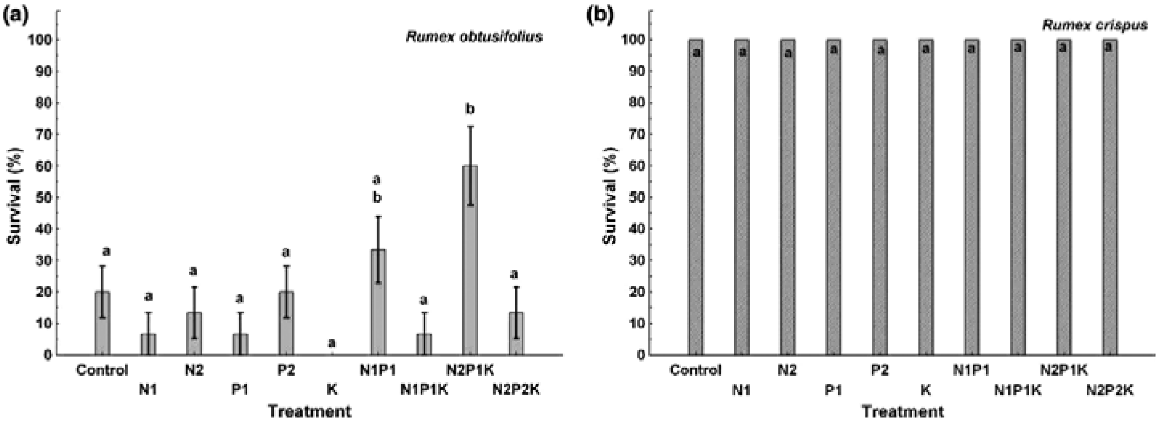

Figure 5 Effect of treatments on the over-wintering of *Rumex obtusifolius* (a) and *R. crispus* (b). Error bars represent standard errors of the means (SE). Treatment abbreviations are given in Table 1. Using Tukey's post-hoc test, treatments with the same letter were not significantly different at the 0.05 probability value.

emergence in locally disturbed patches after the removal of established *Rumex* plants in permanent grasslands, but this requires further investigation.

Plant performance

Three distinct life phases were recognized in the lifespan of *R. obtusifolius*: (i) a phase of germination and seedling emergence, (ii) a phase of rosettes and (iii) a phase of stem growth, flowering and seed ripening. Different effects of fertilizer treatments were recorded in each phase of plant growth. The germination, emergence and stabilization of seedlings took 3 weeks. Rosette growth was recorded from 19 May until 10 July, during which the supply of P appeared to play the main role. Seedlings of both species developed fastest in P_1 and P_2 in all treatments and had the greatest number of leaves during this phase. A further negative effect of a very high N supply on both species was recorded, as leaf growth during the rosette phase was depressed in all treatments with a N_2 supply (Figure 2). This clearly demonstrates a high P demand of *Rumex* plants in early development, but lower adaptation to a very high N supply.

The maturation, flowering and seeding period was recorded from 19 May until 4 September. Nitrogen, applied together with K and P, strongly increased plant performance (plant height, number of stems, number of leaves and length of the longest leaf) during the phase of stem growth, flowering and seed ripening. A delay of plant development was recorded for N_1 and N_2 treatments, probably due to P limitation in these treatments as the plants may have required time to increase their root systems to be sufficiently well developed to acquire enough P from the scarce amount in the soil. This indicates that a plant-available concentration of Mehlich III P of 16 mg kg^{-1} was not sufficient for the optimal growth of both species. In addition to P limitation in the N treatments, high N availability prolonged the vegetation season and seed ripening, and this effect of high N supply is in accordance with the results of Vos and Biemond (1992).

Although *R. obtusifolius* was recognized by Humphreys *et al.* (1999) as being highly K demanding, no response to K application was recorded in our study as no obvious differences in plant performance were recorded between N_1P_1 and N_1P_1K treatments. This indicates the ability of the clay soil that was used to supply an adequate amount of K for the growth of both species, even without K application. Evidently, a plant-available (Mehlich III) K concentration of 160 mg kg^{-1} was sufficient for the growth of both species. The results of our pot experiment are consistent with the conclusions by Kayser and Isselstein (2005) that K limitation in grassland is less likely on clay soils.

Stem production and the flowering of *R. obtusifolius* were recorded in the year of seeding, but there was no stem elongation or flowering of *R. crispus* in the year of seeding. The same result was recorded with genetically similar plants in the pot experiments on sandy soil as well as under field conditions on several soil types at different altitudes and in different years (Křišťálová, 2010). It seems that *R. crispus* requires a cold period and a sufficient amount of carbohydrates to induce stem growth and flowering. According to Cavers and Harper (1964), flowering and seed set can occasionally occur in the year of seeding, but not usually until the second year after germination. According to Hume and Cavers (1983) and Bond *et al.* (2007), plants of *R. crispus* in most North American populations require over-wintering before flowering can occur, unlike in the populations in Britain and the rest of Europe. The results of this study indicate that, at least in some populations of *R. crispus* in the Czech Republic, no flowering can occur in the year of seeding under all levels of nutrient availability. On the other hand, *R. obtusifolius* can flower in the year of seeding.

Over-wintering

According to Cavers and Harper (1964), both *R. crispus* and *R. obtusifolius* have a tendency to be monocarpic and to die after producing seeds. Monocarpic behaviour was supported by almost no over-wintering of *R. obtusifolius* after flowering in this study, but high over-wintering of the same genotype of *R. obtusifolius* was recorded in our field experiments in the same and other winter seasons (Křišťálová, 2010). Furthermore, there was no difference in over-wintering between sterile and fertile plants. It seems that the main reason for low over-wintering in the pot experiments was the low resistance of mature plants of *R. obtusifolius* to frost, as pots were exposed to winter conditions without any protection. On the other hand, *R. crispus* possessed substantially higher cold resistance as no winter mortality was recorded. Similar results were recorded after the next winter season (2009–2010) which had heavy and long-term frosts: 100% mortality of *R. obtusifolius* in contrast to no mortality of *R. crispus* in the pot experiments on clay and sandy soils (Křišťálová, 2010). The low frost resistance of *R. obtusifolius* probably explains why a high winter mortality of adult *R. obtusifolius* plants was recorded in field experiments by Hongo (1989a,b), Martinkova *et al.* (2009) and Pavlů *et al.* (2008a). Furthermore, the high mortality of *R. obtusifolius* after severe winters was recorded by many farmers in the Czech Republic. The substantially higher frost resistance in *R. crispus* than in *R. obtusifolius* revealed in this study may explain why *R. crispus* is common in regions with a continental climate and heavy winter frosts, whereas *R. obtusifolius* is more common in oceanic regions with less severe winters. In addition, *R. crispus*, in contrast to *R. obtusifolius*, is able to grow up to latitudes of 69°N and 65°N in Europe and North America respectively (Cavers and Harper, 1964). The over-wintering of *R. obtusifolius* was only marginally affected by N, P and K availability, and the over-wintering of *R. crispus* was not affected.

Conclusions

Seedling emergence of both *R. crispus* and *R. obtusifolius* was negatively affected by very high N availability but positively affected by increased P availability in the soil. Similarly, the seedlings were negatively affected by a very high N supply and developed fastest and had the greatest number of leaves in P treatments during the rosette phase. Both of these *Rumex* species are therefore sensitive to a very high N supply in early developmental stages, and they tend to tolerate a very high N supply from the phase of fully developed rosettes. In addition to high N requirements during the phase of stem growth, flowering and seed ripening, both species also require a high P supply. Similarly to most North American populations, at least some Central European populations of *R. crispus* do not flower in the seeding year, in contrast to *R. obtusifolius*. The high winter mortality of *R. obtusifolius* contrasted markedly with the absence of winter mortality in *R. crispus*, indicating that *R. crispus* possesses higher frost resistance. Over-wintering was only marginally affected by N, P and K availability.

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