Journal für Kulturpflanzen, 68 (8). S. 232–240, 2016, ISSN 1867-0911, DOI: 10.5073/JfK.2016.08.03 Verlag Eugen Ulmer KG, Stuttgart

Originalarbeit

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Effects of biochar on dry matter production and competitive ability of *Rumex obtusifolius* L.

Auswirkungen der Biokohle auf die Trockenmasseproduktion und Wettbewerbsfähigkeit des Stumpfblättrigen Ampfers (*Rumex obtusifolius* L.)

Abstract

Rumex obtusifolius L. (broad-leaved dock) is one of the most troublesome weeds in intensively managed grassland. This study investigated the potential of biochar (BC), produced from woody green waste residues, to support its control. For this purpose, a pot experiment was conducted out of doors in Austria. It was expected that *R. obtusifolius* could be controlled by reducing available N content in the soil. *R. obtusifolius* and two grass species, *Lolium multiflorum* and *Dactylis glomerata*, were grown from seeds in monocultures, respectively. Moreover, *R. obtusifolius* was grown in mixtures with *L. multiflorum*. Due to a pure BC addition to soil (3% by wt), the concentrations of N, S, Ca and Mg in the shoot biomass decreased relative to the control in all three species, suggesting a dilution effect. The K concentration, however, increased only in *R. obtusifolius*, indicating its high absorption capacity for K. In *R. obtusifolius*, K rather than N was the most growth-limiting nutrient element. The K level in soil appears to be important in controlling its distribution. To prevent *Rumex* infestation and/or to reduce existing infestations, a high soil K supply should be avoided. The average shoot dry weight of all three species was significantly higher when BC was applied (by 247%, 65% and 108%, in *R. obtusifolius, L. multiflorum* and *D. glomerata*, respectively), presumably because of a better K supply in soil. *R. obtusifolius* responded to interspecific competition with *L. multiflorum* by a density-dependent reduction of its shoot growth. BC did not decrease the competitive ability of *Rumex* in mixtures with *Lolium*. It is concluded that the addition of woody green waste BC to soil is no successful strategy for controlling *R. obtusifolius* in grassland. However, the results of this study can serve as a basis for preventive measures to *Rumex* control.

Key words: Pot experiment, grassland soil, nutrient requirement, interspecific competition, weed control

Zusammenfassung

Der Stumpfblättrige Ampfer (*Rumex obtusifolius* L.) ist ein gefürchtetes Unkraut im intensiv bewirtschafteten Grünland. In dieser Studie wurde untersucht, ob die Biokohle durch eine Verminderung des pflanzenverfügbaren N-Gehaltes im Boden für die Ampfer-Regulierung eingesetzt werden kann. Dazu wurde ein Gefäßversuch im Freien durchgeführt. Der Stumpfblättrige Ampfer und zwei Gräser, Italienisches Raygras (*Lolium multiflorum*) und Wiesen-Knaulgras (*Dactylis glomerata*), wuchsen in Reinkultur. *R. obtusifolius* wurde auch in Mischungen mit *L. multiflorum* angesät. Die Zufuhr von Biokohle zum Boden bewirkte eine Verminderung der Konzentration an N, S, Ca und Mg in der oberirdischen Phytomasse bei allen Arten. Dies dürfte auf einen Verdünnungseffekt zurückzuführen sein. Die K-Konzentration nahm nur beim Stumpfblättrigen Ampfer im Vergleich zur Kontrolle zu. Der höhere K-Gehalt im Boden infolge Biokohle-Zufuhr dürfte dafür verantwortlich sein. Beim Stumpfblättrigen

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Accepted
15 July 2016

Ampfer war K und nicht N das wachstumslimitierende Nährelement. Ein hoher pflanzenverfügbarer K-Gehalt im Boden dürfte die Massenvermehrung des Stumpfblättrigen Ampfers im Grünland deutlich fördern. Durch die Zufuhr von Biokohle und dem daraus resultierenden höheren K-Gehalt im Boden hat das durchschnittliche Spross-Trockengewicht beim Stumpfblättrigen Ampfer um 247%, beim Italienischen Raygras um 65% und beim Wiesen-Knaulgras um 108% im Vergleich zur Kontrolle zugenommen. Durch interspezifische Konkurrenz mit *L. multiflorum* wurde *R. obtusifolius* im Sprosswachstum deutlich gehemmt. Die Biokohle hat die Wettbewerbsfähigkeit des Stumpfblättrigen Ampfers nicht vermindert und kann daher auch nicht zur Ampfer-Regulierung eingesetzt werden. Die vorliegenden Untersuchungsergebnisse können als Grundlage für vorbeugende Maßnahmen zur Ampfer-Regulierung dienen.

Stichwörter: Gefäßversuch, Grünlandboden, Nährstoffbedarf, interspezifischer Wettbewerb, Unkrautregulierung

Introduction

Rumex obtusifolius L. (broad-leaved dock) is a common weed of intensively managed grassland in Austria (BOHNER, 2001) and in many other countries (CAVERS and HARPER, 1964). It is a deep-rooted, broad-leaved, medium-sized perennial herb with a life-span of more than five years. *R. obtusifolius* is capable of producing large quantities of seed annually, which remain viable in the soil for many years. This weed species has a high capacity for regrowth following defoliation. Reproduction takes place mostly by seeds but mature plants also propagate vegetatively (CAVERS and HARPER, 1964). *R. obtusifolius* occurs almost exclusively in nutrient-rich habitats. It is a nitrophilous plant species (ELLENBERG et al., 2001) with a high absorption capacity for NO_3 and K (BOHNER, 2001). Therefore, long-term excessive application of manure or nitrogenous fertiliser favours broad-leaved dock infestation in grassland (NIGGLI et al., 1993). Under nutrient-rich soil conditions, *R. obtusifolius* is a very strong competitor and spreads rapidly, especially if there are many gaps in the grass sward (ZALLER, 2004). This fast-growing plant species can seriously reduce grass biomass and forage quality (OSWALD and HAGGAR, 1983). Hence, *R. obtusifolius* is considered to be one of the most troublesome weeds in intensively managed grassland (JEANGROS and NÖSBERGER, 1990) and its control is therefore desirable. Once it has become established, however, broad-leaved dock is very difficult to control. Several mechanical, biological and chemical control methods against *R. obtusifolius* have already been recommended (ZALLER, 2004). However, mechanical weed control is time-consuming and therefore restricted to small areas or to grassland where *Rumex* infestation is not serious. Moreover, elimination of established *Rumex* plants without supplemental measures is frequently only a short-term control. Prevention of flowering and thus seed production by early mowing is not effective in controlling *Rumex* populations because of the large number of dormant seeds in the soil seed bank. On the contrary, since *R. obtusifolius* has a higher capacity for regrowth following defoliation than the competing grasses, early and frequent mowing usually favours *R. obtusifolius* within the plant community. Up to now, limited success has been achieved via biological methods. Nevertheless, biological *Rumex* control can be successful if combined with other control methods (MÜLLER, 2015). The efficacy of biological control methods might be greater when *Rumex* plants are already stressed by environmental conditions (WHITTAKER, 1982). Numerous investigations have been made on the control of *R. obtusifolius* by herbicides. The application of herbicides, however, is effective only for a short time (NIGGLI et al., 1993). Obviously, there is still a high demand for sustainable control measures against *R. obtusifolius* in grassland.

We hypothesised that the use of biochar (BC) could be an alternative to conventional control methods against *R. obtusifolius*. Up to now, this possibility has received scant attention, although several studies have shown that the addition of BC alone to soil can have detrimental effects on plant growth (e.g., GUNDALE and DELUCA, 2007). The addition of BC to grassland soil may reduce plant growth of *R. obtusifolius* through selective alteration of decisive soil properties, leading to a decreased competitive ability and finally to a disappearance from the plant community. One reason for an inhibited plant growth can be attributed to a deceleration of soil organic N cycling due to pure BC addition, which may cause N deficiency in plants, thereby decreasing plant growth (PROMMER et al., 2014). There are several studies indicating that a pure addition of plant-derived BC might decrease soil N availability to plants, at least for a short time (e.g., BARGMANN et al., 2014). TAGHIZADEH-TOOSI et al. (2011) reported lower NO_3-N concentrations in a pasture soil in New Zealand when BC, produced from Monterey pine (*Pinus radiata* D.Don), was incorporated to a depth of 10 cm at a rate of 30 t ha^{-1}. Based on the results of these studies, we hypothesised that the addition of BC to grassland soil could be a successful measure for controlling the nitrophilous broad-leaved dock. We expected a decreased N availability in the soil when BC with high C:N ratio was applied without supplemental fertilizer addition, inducing N deficiency in *R. obtusifolius* and thus reducing its competitive ability in the plant community. To examine this hypothesis, a pot experiment was designed.

The spread of *R. obtusifolius* also depends on the capacity of seedlings to survive and establish in competition with neighbouring plant species (CAVERS and HARPER, 1964). VAN DE VOORDE et al. (2014) showed in a grassland field experiment in the Netherlands that BC addition to soil can affect plant competition. Therefore, we tested the response of *R. obtusifolius* to BC addition not only in monoculture but also in two-component mixtures. Since *R. obtusifolius* should be replaced by valuable forage grasses, also the response of particular grass species to

BC addition was tested. The objectives of this study were to determine (1) whether the addition of BC to grassland soil has an effect on seed germination, dry matter production and nutritional status of *R. obtusifolius* and selected grass species and (2) whether BC addition also influences the competitive ability of *R. obtusifolius* in mixtures with a highly competitive forage grass.

Materials and methods

Experimental site and experimental design

The pot experiment was carried out at the Agricultural Research and Education Centre Raumberg-Gumpenstein in Styria, Austria. At the experimental site (47°29'N, 14°05'E; 700 m altitude), climate is relatively cool and humid, with a mean annual air temperature of +7.0°C and a mean annual precipitation of 1014 mm, of which 69% falls during the vegetation period (April-October). Mean monthly air temperature varies from −3.1°C in January to +16.5°C in July.

The pot experiment was performed under natural light and climatic conditions out of doors. We used Mitscherlich pots with a surface diameter of 20 cm and a height of 21 cm. Each pot contained 5 kg of field-moist soil. The pots were arranged on benches in a completely randomised design and periodically rotated as to position to reduce variability in light intensity. The soil used for this study was taken from the A and B horizon of a carbonate-free Cambisol with loamy sand texture. This soil type represents a typical grassland soil in Austria. Soil material from both horizons was blended and sifted through a 12.7 mm mesh sieve, representing the BC-free grassland soil. The BC-amended soil was prepared by thoroughly mixing the grassland soil with milled BC (particle size of < 2 mm). BC was added once only at a dose of 30 g kg^{-1} soil, equating to a field application rate of approximately 30 t ha^{-1} if calculated for an incorporation depth of 10 cm and a soil bulk density of 1.0 g cm^{-3}. In comparison to other BC studies, this means a moderately high rate of BC addition to soil. BC was produced at the thermal power station Dürnrohr in Lower Austria from woody green waste residues through pyrolysis at a temperature of 525°C. We have chosen woody green waste BC because of its relatively wide C:N ratio of 58:1 and moderately high ash content of 15 wt% on a dry weight basis. Some additional basic properties of the BC used in this study are presented in Table 1. Half of the pots was filled with the BC-free grassland soil, representing the control treatment (soil without BC), and the other half was filled with the BC-amended soil, representing the BC treatment (soil with BC).

Among grass species, *Lolium multiflorum* Lam. (Italian ryegrass) and *Dactylis glomerata* L. (cocksfoot) were selected for study because under suitable site conditions they are competitive, fast- and tall-growing, high-yielding forage grasses. Moreover, both species benefit from a high soil nutrient supply and consequently they occur mainly on nutrient-rich soils, behaving in this respect similar to *R. obtusifolius*. *D. glomerata* was also selected because this grass species is common and widely distributed in grassland and is frequently included in seed mixtures of Austria. For the two-component mixture, *L. multiflorum* was chosen as competitor because it had been observed that this annual forage grass was able to compete much stronger with *R. obtusifolius* than other grass species (Niggli et al., 1993).

Seeds of *R. obtusifolius* were collected from a local meadow which was heavily infested with broad-leaved dock. Germination capacity of the seeds was 76% for *R. obtusifolius*, 92% for *L. multiflorum* (variety Aubade) and 88% for *D. glomerata* (variety Tandem). Seeds of all species were sown at the same time directly into the pots on 22 May 2012.

The pot experiment consisted of five treatments, each with and without BC addition, and five replicates for each treatment. In each treatment, the species were sown at equal seed numbers and they were arranged equidistantly, thus eliminating growth differences due to variations in plant density. To minimise edge effects, *Rumex* plants were always grown in the centre of each pot. In treatment (1), four individuals of *R. obtusifolius* were grown in monoculture at 8 cm spacing. This distance was chosen in order to avoid severe intraspecific competition. In treatment (2), four *Rumex* plants were surrounded by seventeen individuals of *L. multiflorum* at a distance of 4 cm. In treatment (3), four *Rumex* plants were surrounded by twenty-one individuals of *L. multiflorum* at a distance of 3 cm. In this treatment, most of the available space was used by the plants as soon as they became larger, leading to a greater interspecific competition compared to treatment (2). In treatments (4) and (5), twenty-five grasses of *L. multiflorum* and *D. glomerata*, respectively, were grown in monoculture in each pot at a distance of 3 cm between the individuals.

The pot experiment was performed for twelve weeks from 22 May 2012 to 20 August 2012. Since we did not observe strong root accumulation at the bottom of the pots, we assume that throughout the duration of our

Table 1. Some properties of woody green waste BC used in this pot experiment

Parameter	Value
$T_{pyrolysis}$ [°C]	525
pH	8.9 ± 0.06
EC [mS cm^{-1}]	1.58 ± 0.02
ash content [w.-%]	15.20
C [w.-%]	67.14 ± 1.3
N [w.-%]	1.15 ± 0.03
C:N	58.18 ± 0.73
CEC [$mmol_c$ kg^{-1}]	93.0 ± 1.91

EC = electrical conductivity, CEC = cation exchange capacity experiment there was no root-restriction stress due to the small pot volume. All plants were harvested when some sprouts of *R. obtusifolius* started to become infested with plant parasites (fungi). At that time, *Rumex* plants were at the end of the elongation phase and grasses were in the stage of stem elongation. Throughout the duration of our experiment, weather conditions were relatively warm and humid, with a mean air temperature of +17.8°C (maximum and minimum: +33.5°C and +2.4°C, respectively) and a precipitation sum of 497 mm. The plants were well supplied with water. Only during dry periods the pots were additionally watered with tap water. There was no limitation of plant growth due to shortage or surplus of water. No fertiliser was applied to the pots and appearing weeds were immediately removed by hand.

Plant and soil analyses, seed germination

Shoot dry weight and mineral element concentrations in the shoot biomass were chosen as the best measures of plant response to BC addition. Therefore, at the end of the experiment in all pots the above-ground biomass was harvested by clipping each plant at the soil surface. In order to get sufficient plant material, a composite sample without replications had to be used for plant analyses of each treatment. Plant samples were dried for 48 hours at 50°C. After grinding, plant material was again dried for 4 hours at 105°C. C, N and S concentrations in the plant tissue were determined using a CNS elemental analyser. Concentrations of P, Ca, Mg and K were measured by ICP-OES after digestion with hydrochloric acid. Seed germination was evaluated 14 days after sowing. Germination rate was calculated from the number of plants emerged divided by the number of seeds sown. Competitive ability of *R. obtusifolius* was determined by comparing its shoot biomass in two different mixtures with that in monoculture at harvest. At the end of the experiment, a composite soil sample both from the BC-amended and from the BC-free pots was taken for chemical analyses in order to assess changes in soil properties. Soil samples were air-dried and passed through a 2-mm sieve. Soil analyses (total C, N and S, pH, electrical conductivity (EC), calcium-acetate-lactate (CAL)-extractable P and K content, water-soluble P content) were carried out according to the ÖNORM methods (Austrian Standards Institute).

Statistical analyses

To evaluate the significance of treatment differences, Kruskal-Wallis test followed by Mann-Whitney test and a two-way analysis of variance (ANOVA) with Tukey´s post-hoc test were used. Statistical calculations were made both on log-transformed and non-transformed data, but the results were quite similar. Therefore, only values based on non-transformed data are presented here. All results were stated as statistically significant if $p < 0.05$ and highly significant if $p < 0.001$. Statistical data analyses were performed with SPSS (Version 20).

Results

Soil chemical properties

The grassland soil used in this pot experiment was characterised by a very low CAL-extractable P and K content and a wide C:N ratio (Table 2), indicating a nutrient-poor soil. The total soil C concentration was also very low, which can be attributed to the blending of the A with the B horizon. A single BC addition at an application rate of 30 g kg^{-1} soil caused an increase in total soil C concentration by 109% compared to the control. Simultaneously, also the soil EC and CAL-extractable K content increased by 45% and 871%, respectively. In contrast, total soil N and S concentration remained more or less unaffected, leading to a marked widening of the C:N and C:S ratio in the BC-treated soil. The pH value and water-soluble P content were not influenced by BC addition and the CAL-extractable P content increased only slightly.

Mineral element concentrations and ratios in the shoot biomass

As a result of BC addition to soil, the concentrations of N, S, Ca and Mg in the shoot biomass decreased relative to the control, both in *R. obtusifolius* and in the two grass species (Table 3). In contrast, the K concentration increased only in *R. obtusifolius* by 11% compared to the control. The P concentration slightly increased in the grass species but remained unaffected in *R. obtusifolius*. The addition of BC to soil resulted in a widening of the C:N ratio in the shoot biomass of all three species (Table 4). In *R. obtusifolius*, the N:S, N:P, N:Ca, N:Mg and

Table 2. Chemical properties of the soil in BC-amended and BC-free pots

Treatment	C_{tot}	N_{tot}	S_{tot}	C:N	C:S	pH $CaCl_2$	EC	P_{CAL}	K_{CAL}	P_{H2O}
		%					µS cm^{-1}		mg kg^{-1}	
Soil without biochar	1.27	0.11	0.02	12	64	7.1	80	5	17	4
Soil with biochar	2.65	0.12	0.02	22	133	7.1	116	7	165	4

EC = electrical conductivity, P_{CAL} and K_{CAL} = CAL-extractable phosphorus and potassium content,
P_{H2O} = water-soluble phosphorus content

Table 3. Mineral element concentrations in the above-ground biomass of various grassland species grown in monoculture with and without BC addition after twelve weeks of growth

Plant species	Biochar addition	N	S	P	Ca	Mg	K
		g kg^{-1} dry matter					
R. obtusifolius	0%	40.0	2.8	2.4	10.4	7.0	32.6
	3 wt%	35.0	2.6	2.4	9.6	6.7	36.2
L. multiflorum	0%	39.9	4.4	3.2	7.5	3.6	30.5
	3 wt%	35.5	3.4	3.5	6.0	2.9	30.0
D. glomerata	0%	46.7	4.2	2.9	5.5	3.9	35.7
	3 wt%	35.4	3.2	3.2	5.1	3.5	34.8

Table 4. C:N ratio and ratio of nitrogen to other mineral nutrients in the above-ground biomass of various grassland species grown in monoculture with and without BC addition after twelve weeks of growth

Plant species	Biochar addition	C:N	N:S	N:P	N:Ca	N:Mg	N:K
R. obtusifolius	0%	10.5	14.3	16.7	3.8	5.7	1.2
	3 wt%	11.8	13.5	14.6	3.6	5.2	1.0
L. multiflorum	0%	11.0	9.1	12.5	5.3	11.1	1.3
	3 wt%	12.1	10.4	10.1	5.9	12.2	1.2
D. glomerata	0%	9.5	11.1	16.1	8.5	12.0	1.3
	3 wt%	12.6	11.1	11.1	6.9	10.1	1.0

N:K ratio decreased relative to the control. A similar result could be observed in *D. glomerata*. In *L. multiflorum*, however, the N:S, N:Ca and N:Mg ratio in the shoot biomass increased as compared with the control, whereas the N:P and N:K ratio decreased after the addition of BC to soil.

Seed germination, shoot growth and plant competition

The application of BC to soil had no significant effect on germination rate and date of emergence of the plant species investigated ($p > 0.05$). On average, across all treatments 80% of the *R. obtusifolius* seeds germinated both in the BC-amended and in the BC-free pots. *R. obtusifolius, L. multiflorum* and *D. glomerata* germinated 6, 6 and 12 days, respectively, after sowing. Consequently, date of emergence had no impact on the competition between *R. obtusifolius* and *L. multiflorum* and the shoot dry weight of the plant species investigated.

As a result of BC addition to soil, the above-ground biomass production increased significantly ($p < 0.05$) in *R. obtusifolius* and highly significant ($p < 0.001$) in both grass species as compared to the control (Table 5). The rise in average shoot dry weight was for *R. obtusifolius, L. multiflorum* and *D. glomerata* 247%, 65% and 108%, respectively. When grown in competition with *L. multiflorum*, the shoot dry weight per plant of *R. obtusifolius* significantly decreased both in the BC-free ($p = 0.006$) and in the BC-amended ($p = 0.011$) pots (Fig. 1 and 2). Consequently, the reduced dry matter production due to the interspecific competition with grasses was not eliminated by the addition of BC. Furthermore, it can be seen from Fig. 1 and 2 that with increasing number and proximity of *L. multiflorum* individuals the above-ground biomass of *R. obtusifolius* is decreasing, especially in the BC-free pots. In *R. obtusifolius,* the greatest shoot dry weight per plant was produced in BC-amended pots in the absence of *L. multiflorum*, whereas the lowest shoot biomass was obtained in BC-free pots at the highest density of competing *Lolium* individuals (Table 5).

Discussion

Soil chemical properties

The addition of BC to soil induced rapid and large changes in some soil chemical properties. Total C concentration, C:N and C:S ratio in soil increased approximately twofold, suggesting that BC has the potential to immediately enhance C content in humus-poor soils. As intended, after BC addition the C:N ratio in soil was fairly high (22:1). These findings are in agreement with those of other studies (e.g., CHAN et al., 2007), who also observed a rise in total soil C concentration and an enlargement of the C:N ratio in soil following BC addition. In our pot

Table 5. Above-ground biomass production of various grassland species after twelve weeks of growth at different treatments

Plant species	Treatment	Biochar addition	Shoot dry weight[a]	
			am	s
R. obtusifolius	without competitors (4:0)	0%	312	134
	with competitors (4:17)	0%	172	62
	with competitors (4:21)	0%	62	45
R. obtusifolius	without competitors (4:0)	3 wt%	1084	215
	with competitors (4:17)	3 wt%	319	298
	with competitors (4:21)	3 wt%	242	210
L. multiflorum	without competitors (25:0)	0%	3.4	0.7
L. multiflorum	without competitors (25:0)	3 wt%	5.6	0.9
D. glomerata	without competitors (25:0)	0%	2.4	0.6
D. glomerata	without competitors (25:0)	3 wt%	5.0	0.2

[a] *R. obtusifolius*: mg per plant (mean of four plants per pot), *L. multiflorum* and *D. glomerata*: g per pot, am = arithmetic mean of five replications, s = standard deviation

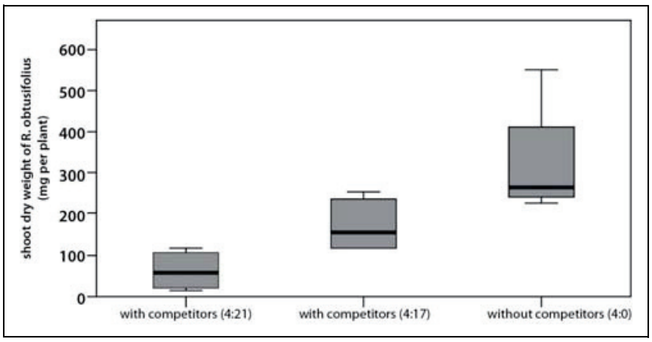

Fig. 1. Effect of *Lolium multiflorum* on above-ground biomass production of *Rumex obtusifolius* grown in pots without (on the left) and with (on the right) BC addition after twelve weeks of growth; note the difference in scale on the vertical axis (number in parentheses show the ratio of plant individuals "*R. obtusifolius*: *L. multiflorum*").

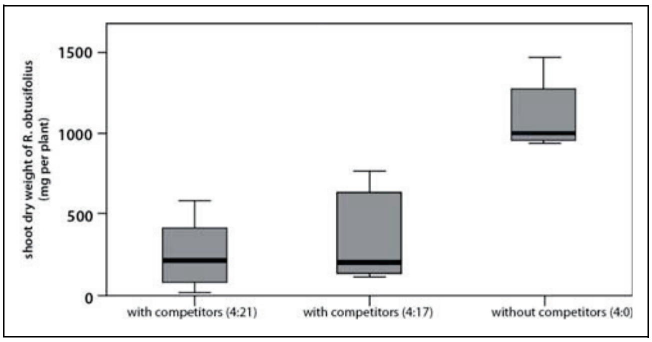

Fig. 2. Effect of *Lolium multiflorum* on above-ground biomass production of *Rumex obtusifolius* grown in pots without (on the left) and with (on the right) BC addition after twelve weeks of growth; note the difference in scale on the vertical axis (number in parentheses show the ratio of plant individuals "*R. obtusifolius*: *L. multiflorum*").

experiment, BC application considerably increased EC and CAL-extractable K content in soil, indicating a rapid release of soluble salts and potentially plant available K from the applied BC. Similar results were obtained in numerous other studies (e.g., Kloss et al., 2014). In the pot experiment presented here, BC application had no or only little effect on soil pH, total N and total S concentration, CAL-extractable and water-soluble P content in soil. Although CAL-extractable P content was very low, BC addition did not cause an appreciable increase in this P fraction. Similarly, Gaskin et al. (2010) found that the P and S content in soil were not affected by peanut hull and pine chip BC application. In contrast to our findings, several other studies (e.g., Kloss et al., 2014) reported an increase in potentially plant available P following BC addition to soil. Obviously, the different BC types vary considerably with respect to their readily soluble P content. The soil used in this pot trial had a pH of 7.1. Therefore it was not surprising, that in our experiment soil pH did not increase as a result of BC addition. The change in soil pH following the application of BC depends on several factors, including initial soil pH, soil buffer capacity, ash content and pH of the BC used. In acidic soils, however, a pH increase has been found in many other studies (e.g., Kloss et al., 2014) due to the liming effect of alkaline BC.

Seed germination

In our pot experiment, seed germination was not affected by BC addition. A similar result for grassland species was obtained by Van De Voorde et al. (2014).

Mineral element concentrations and ratios in the shoot biomass

In *L. multiflorum* and *D. glomerata*, the mineral element concentrations in the above-ground biomass at the time of sampling were within the normal ranges reported for field-grown plants (Lehmann et al., 1985) both in the BC-free and in the BC-amended pots. Only the P concentration was somewhat low, whereas the concentrations of Ca and Mg were rather high. In *R. obtusifolius*, the Ca and Mg concentration in the shoot biomass at the time of sampling was also elevated both in the BC treatment and in the control, indicating an enhanced level of plant available Ca and Mg in all pots. The concentrations of N, S and K were within the normal ranges reported for field-grown plants (Bohner, 2001). By contrast, the P concentration was very low both in the BC treatment and in the control, suggesting a reduced soil P supply and consequently an inhibited P uptake by the *Rumex* plants. This finding is corroborated by the soil analyses. The CAL-extractable P content was very low both in the BC-treated soil and in the control soil, indicating a poor capacity of the soils to supply plant available P.

The application of BC to soil changed mineral element concentrations in the shoot biomass of the species investigated. The decrease in concentrations of N, S, Ca and Mg both in *R. obtusifolius* and in the two grass species was probably caused by the enhanced shoot growth resulting from BC addition, suggesting a dilution effect. In fact, adding BC to soil increased mineral element contents in the shoot biomass as compared to the control (data not shown). This indicates that plants have an increased mineral nutrient requirement, especially for N, after BC addition to soil due to an enhanced shoot growth.

The plant species examined differed greatly in their response to BC addition. The P concentration in the shoot biomass slightly increased in the grass species but not in *R. obtusifolius*. Surprisingly, shoot P concentration was lower in *R. obtusifolius* than in the two grass species both in the BC-amended and in the BC-free pots. This indicates that *R. obtusifolius* has a lower absorption capacity for P when growing in P-deficient soil than *L. multiflorum* or *D. glomerata*. Obviously, under conditions of low soil P supply the two grass species are more efficient at acquiring P than *R. obtusifolius*, presumably due to their comparatively greater root density (Kullmann, 1957), leading to a better exploitation of available P in the soil. The K concentration in the shoot biomass, however, increased only in *R. obtusifolius* relative to the control, whereas it remained more or less unaffected in the grass species. This indicates that broad-leaved dock has a greater absorption capacity for K when growing in K-rich soil than grasses. A high K absorption capacity is an important adaption of *R. obtusifolius* to soils with high plant available K supply. Moreover, our results suggest that *R. obtusifolius* has a very high K requirement to maintain vigorous growth, thus confirming previous findings obtained under field conditions (Bohner, 2001). A similar result from field trials has also been reported by Humphreys et al. (1999), who showed that *R. obtusifolius* benefits greatly from a high K supply in the soil. The marked increase of the CAL-extractable K content in the BC-treated soil and the concomitant enhanced K uptake by the plants are indications that appreciable amounts of plant available K were introduced into the pots by BC application. Obviously, woody green waste BC is an important source of rapidly plant available K, and acts therefore as a K fertiliser immediately after its application to K-deficient soil. This result is in agreement with Schimmelpfennig et al. (2015), who found in a grassland field experiment in Germany greater K concentrations in the plant biomass from BC-amended plots compared to control plots. In *R. obtusifolius*, BC addition caused an increase in the C:N ratio and simultaneously a decrease in the ratio of N to other mineral nutrient elements in the shoot biomass, indicating a deficient supply of plant available N in the BC-treated soil compared to the control soil. Obviously, soil N supply could not meet the enhanced plant requirement for N. The deficient soil N supply after BC addition did not inhibit shoot growth of *R. obtusifolius*. Apparently, under the specific conditions of our pot experiment N was not the growth-limiting nutrient in soil, but rather K supply controlled *Rumex* growth, as indicated by the considerable increase in shoot growth in response to an addition of K by BC application. Our data provide evidence that N shortage has a relatively small effect on shoot growth of *R. obtusifolius* as long as K is the growth-limiting nutrient element. However, at high levels of plant available K in soil N may become the major factor limiting growth of *R. obtusifolius* (Jeangros and Nösberger, 1990). An increase in K concentration and a concomitant decrease in N concentration due to BC addition were also observed in *Chenopodium quinoa* Willd. (Kammann et al., 2011) and in *Trifolium pratense* L. (Oram et al., 2014).

Shoot growth

In general, established *R. obtusifolius* plants appeared healthy and grew well in all pots until harvest, indicating suitable environmental conditions for satisfactory plant growth. There were no visible symptoms of nutrient deficiency throughout the duration of the experiment. However, only one dock plant produced an inflorescence. In general, *R. obtusifolius* does not flower in its seedling year; flowering and seed production usually occur in the second year of growth (Cavers and Harper, 1964). Since there was no BC-induced germination inhibition and all germinated plants survived to harvest, the effects of BC addition on *Rumex* growth can be assessed by means of its above-ground biomass production.

The significantly higher shoot biomass of all plant species examined in the BC treatment compared to the control demonstrates the potential of woody green waste BC to increase above-ground biomass production of particular grassland species when growing on nutrient-poor soils at least in the year of BC application. The addition of BC to soil enhanced shoot dry weight of *R. obtusifolius* in monoculture by a factor of 4 and in mixtures with *L. multiflorum* by a factor of 2 as compared to the control.

In contrast, adding BC to soil increased the shoot dry weight of grasses in monoculture only by a factor of 2 relative to the control. Thus, BC promoted the shoot growth of *R. obtusifolius* more than that of the grasses, indicating a species-specific fertilizer effect of applied BC. This is consistent with the findings of SCHIMMELPFENNIG et al. (2015), who showed in a grassland field experiment that BC favours growth of forbs over grasses. In general, species from nutrient-rich habitats are characterised by a high growth rate on fertile soils, they strongly respond to an increased soil nutrient supply and they have high nutrient requirements (CHAPIN et al., 1986). Therefore, *R. obtusifolius* can be considered as an indicator species of high soil fertility.

The unexpected considerable enhancement of shoot growth of all plant species examined in the BC-amended pots compared to the control can largely be attributed to an improved K supply to plants provided by the BC. It cannot be excluded, however, that the addition of BC to soil also positively influenced several other growth-controlling factors (e.g., supply of micronutrients), but they were not measured in our pot experiment. It is important to note that *Rumex* plants showed more morphological plasticity (shoot plasticity) in response to soil K enrichment than the grass species, leading to a greater competitive ability for light (shoot competitive ability). In general, a high degree of shoot plasticity is advantageous on fertile soils because it increases the shoot competitive ability of a plant under nutrient-rich conditions (GRIME et al., 1986).

Plant competition

In general, plants are more sensitive to environmental conditions in the juvenile stage of development than as established adults (ROBERTS and HUGHES, 1939). Therefore, the effects of BC addition on dry matter production and competitive ability of *R. obtusifolius* can be assessed, although plants were not grown to maturity. The aim of this pot experiment was not primarily to analyse the competition between plant populations, but rather to assess the competitive ability of *R. obtusifolius*. Therefore, in our competition treatments only the density of *L. multiflorum* was varied while that of *R. obtusifolius* was kept constant. Our data show that the number and distance of competing grasses play an important role in determining the shoot growth of *R. obtusifolius*. As the number of *Lolium* individuals increased and their distance to *Rumex* plants decreased, the shoot dry weight of *R. obtusifolius* declined both in the BC-free and in the BC-amended pots, suggesting that a density-dependent interspecific competition between these two species had occurred. We assume that intense root competition with the grasses for soil nutrients was primarily responsible for the reduced shoot growth of *R. obtusifolius*. However, it is important to note that *Rumex* plants did not disappear in the presence of *L. multiflorum* when both species were grown from seeds at equal time of seeding. In the treatment with the highest density of competing *Lolium* individuals, the shoot dry weight of *R. obtusifolius* was only 20% (BC-free soil) and 22% (BC-amended soil) of that in monoculture. The almost similar reduction in shoot growth indicates that the addition of BC to soil did not decrease competitive ability of *R. obtusifolius* in mixtures *with L. multiflorum*. Contrary to our hypothesis, this result suggests that the addition of woody green waste BC to soil is no successful strategy for controlling *R. obtusifolius* in grassland. Our findings agree with those of NIGGLI et al. (1993), who observed that under field conditions established *R. obtusifolius* plants cannot be controlled by competitive grass species or by variation in N fertilisation. Nevertheless, the results of this study have considerable practical importance to grassland management because our findings can serve as a basis for preventive measures to *Rumex* control.

Implications for grassland management

In K-deficient grassland soils, the application of BC, produced from woody green waste residues, may improve plant growth, especially the shoot growth of particular herbs.

R. obtusifolius seems to benefit from a high content of plant available K in soil more than grass species due to its ability to absorb large amounts of K. Under conditions of high soil K supply, *R. obtusifolius* has a competitive advantage over grasses mainly because of a comparatively greater above-ground biomass gain. Thus, in K-rich soils *Rumex* plants, once established, may suppress grasses from the plant community primarily through shading, provided that the supply of all other essential plant nutrients is adequate for a vigorous growth. Under the specific conditions of our pot experiment, K was the most growth-limiting nutrient element in *R. obtusifolius*. N, however, seems to be of minor importance as long as K is restricting its shoot growth. Thus, K availability in soil appears to be the key factor for *Rumex* infestation in grassland. Therefore, simply removing established *Rumex* plants, mechanically or chemically, may provide only temporary control, as long as soil K availability remains high. At an elevated soil K supply the ability of *R. obtusifolius* to dominate a plant stand is increased, especially if there are numerous gaps in the grass sward. Field observations and the evaluation of many vegetation surveys support this assumption. *R. obtusifolius* is usually absent from nutrient-poor grassland habitats despite gaps in the grass sward and seed input from the surrounding vegetation, emphasising the importance of soil nutrient status to broad-leaved dock infestation in grassland. To prevent *Rumex* infestation, a continued excessive application of manure or K fertiliser to grassland soils should be avoided. In seriously infested grassland, the reduction of annual K input in combination with biological control measures (MÜLLER, 2015) may reduce abundance of *R. obtusifolius* in the long term. A dense grass sward is also very important because it prevents the germination, establishment and spread of *R. obtusifolius*.

To our knowledge, this is the first report on the possible use of BC as a control measure against weeds in permanent grassland of temperate regions. However, the results of this study may be extrapolated to field conditions only with great caution. Therefore, long-term field trials and on-farm experiments at different sites using various BC types and application rates are needed to confirm our findings.

Acknowledgements

We thank Stefan Seirer for his kind support concerning statistical data analyses.

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