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Key management practices to reduce the risk of the occurrence of *Rumex obtusifolius* in productive grasslands

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Abstract

Rumex obtusifolius (broad-leaved dock) is a problematic weed that reduces yield and nutritional value of forage in grasslands of temperate regions worldwide. We conducted an on-farm study to identify management practices and environmental factors that influence the risk of the occurrence of *R. obtusifolius* in high densities in permanent, productive grasslands used for forage production. Following a common protocol, a paired case–control design was implemented in Switzerland (CH), Slovenia (SI), and United Kingdom (UK) to compare parcels with high densities of *R. obtusifolius* (cases, ≥1 plant m^{-2}) with nearby parcels free of or with very low densities of the species (controls, ≤4 plants 100 m^{-2}). A total of 40, 20, and 18 pairs were recorded in CH, SI, and UK respectively. Parameters measured included data about management practices and history, vegetation cover and composition, and soil nutrients and texture. Across countries, increased vegetation cover reduced the relative risk of *R. obtusifolius* occurrence. By contrast, increased soil phosphorus and potassium and high soil bulk density raised the relative risk. These effects were consistent across countries, as no interactions between country and any of the factors were observed. The two indicator species for case parcels, *Plantago major* and *Poa annua*, were typical species of disturbed areas and fertile soils, while indicators for control parcels were characteristic of grasslands under medium to high management intensity (e.g., *Festuca rubra*, *Cynosorus cristatus*, *Anthoxantum odoratum*). We conclude that the risk for grassland infestation with *R. obtusifolius* can be significantly affected by management practices. Prevention measures should target phosphorus and potassium fertilisation to the forage plants' requirements, minimise soil compaction, and maintain dense swards.

KEYWORDS
indicator species, integrated weed management, soil bulk density, soil K content, soil P content, vegetation cover

1 | INTRODUCTION

Rumex obtusifolius L. (broad-leaved dock) is a problematic weed that decreases both the yield and nutritional value of forage in sown and permanent grasslands of temperate regions worldwide (Zaller, 2004). The plant is native to Europe and has been introduced into many other parts of the world (Cavers & Harper, 1964). *Rumex obtusifolius* prefers fertile sites (Ellenberg & Leuschner, 2010), and following Cavers and Harper (1964), the species is common at waste and disturbed grounds, but it has also been associated with poor management of grasslands, such as the excessive application of organic or mineral nitrogen fertilisers (Zaller, 2004).

Rumex obtusifolius has several characteristics that can explain its success in colonising forage grassland (Zaller, 2004). The species shows both vegetative and generative propagation. Mature plants produce up to 60 000 seeds in a single year (Cavers & Harper, 1964; Zaller, 2004), and seeds can remain viable for more than 20 years (Tsuyuzaki & Goto, 2001). Where *R. obtusifolius* is abundant, it can form large, persistent soil seed banks (Suter et al., 2023) from which the species can potentially recruit many years into the future. The root system of *R. obtusifolius* with its fleshy taproots allows for clonal growth and is able to re-grow from fragments left in the soil after digging and pulling out mature plants (Pino et al., 1995). In addition, the taproots serve to store carbohydrates, which increases the re-grow potential after cutting (Pino et al., 1995). Finally, *R. obtusifolius* is not suitable forage for cattle due to its oxalic acid compounds (Bohner, 2001) and is often not grazed by livestock, allowing the plant to produce seeds and complete its life cycle. Thus, in improved grassland systems used for livestock production, *R. obtusifolius* is reported as one of the main problem weed species (Grossrieder & Keary, 2004; Hatcher et al., 2008).

Several direct methods are used to control *R. obtusifolius* in grasslands. Herbicides are often applied in conventional farming; however, it has been shown that herbicides need repeated treatment to control *R. obtusifolius*, with often moderate and generally short-term effectiveness (O'Donovan et al., 2021). In organic farming, cutting of flowering organs and pulling/digging out the entire plant are common. When repeatedly applied, manual weeding of the root system down to 15 cm depth is considered an effective method (Hujerova et al., 2016); the procedure, however, is laborious and time-consuming. In situations of very high *R. obtusifolius* abundance (>5–8 small to big plants m^{-2}), complete sward destruction by ploughing followed by reseeding seems to be the most adequate solution (Ringselle et al., 2019), although this measure comes, amongst others, with substantial soil carbon losses (Reinsch et al., 2018). In short, all of these methods have either limited efficacy and/or are laborious and expensive. It is therefore reasonable to take a more preventative approach, limiting the recruitment opportunities for *R. obtusifolius* to avoid large populations becoming established. To achieve this, knowing the risk factors that make grassland prone to infestation with *R. obtusifolius* is key.

Strategies that combine control with prevention measures are a central feature of integrated weed management (Schaffner et al., 2022). Prevention measures target at improved management practices, such as site-adapted fertiliser application and stocking rates, which indeed can be related to the occurrence of *R. obtusifolius* in grasslands (Zaller, 2004). Presumably because of scarce reliable evidence and high variability in the outcomes of such measures, Zaller (2004) emphasised the need for long-term research on 'management factors most often stated to be responsible for the development of *Rumex* infestations, such as high soil nitrogen (N) and potassium (K) levels, slurry and farmyard manure application, sward disturbance, cutting frequency, grazing management, and soil compaction'.

Previous experimental and observational studies have assessed the influence of fertilisation and cutting frequency on *R. obtusifolius*. The proportion of *R. obtusifolius* in forage and its dry matter and abundance in grass-dominated swards was often increased under high N, phosphorus (P), and K availability in the soil or due to fertiliser application (Harrington et al., 2014; Hopkins & Johnson, 2002; Humphreys et al., 1999; Niggli et al., 1993). This suggests that the competitive ability of *R. obtusifolius* increases under high fertilisation regimes. Regarding cutting, aboveground biomass of *R. obtusifolius* plants as well as their regrowth after cutting was negatively impacted by shorter cutting intervals, that is, by increasing the number of cuts per growing season, for example, from 1 to 3, or 4 to 6 cuts (Hopkins & Johnson, 2002; Niggli et al., 1993; Stilmant et al., 2010). Likewise, a reduction of root mass of *R. obtusifolius* and an associated decrease of starch content was observed when plants were subjected to higher defoliation frequencies (Humphreys et al., 1999; Stilmant et al., 2010). Thus, high mowing frequencies of grasslands should discourage *R. obtusifolius*, although none of the cutting treatments resulted in the elimination of the species within the 2 years of the experiments (Hopkins & Johnson, 2002; Niggli et al., 1993; Stilmant et al., 2010).

The studies on fertilisation and cutting (Hopkins & Johnson, 2002; Niggli et al., 1993) indicate that the two factors have opposite effects on growth of *R. obtusifolius*. Because in intensively managed grasslands, an increase of mowing and grazing frequencies often goes along with increased fertilisation, a higher land-use intensity in terms of these two parameters may result in inconsistent effects on *R. obtusifolius* (Hann et al., 2012). Promotion of *R. obtusifolius* can be expected where defoliation and fertilisation are imbalanced (low cutting frequency but high fertilisation or vice versa) or where a management leads to sward damage and patches of bare ground, for example, by machinery or intensive livestock trampling. Disturbed grasslands and bare ground should strongly favour *R. obtusifolius*, as the species has high germination rates when its seeds are exposed to light (Benvenuti et al., 2001; Totterdell & Roberts, 1980) and seedling growth is considerably favoured where competition from neighbouring plants is reduced (Jeangros & Nösberger, 1990).

Little is known about the effects of grazing on *R. obtusifolius* infestations in pasture systems. It could be argued that, where cleaning cuts are not made, a prolonged period of seed set could allow *R. obtusifolius* to produce large numbers of seeds that become a source of future infestations. Furthermore, soil disturbance from livestock trampling, particularly at resting sites, can create microsites that favour the emergence of weed seedlings (Eskelinen & Virtanen, 2005). Both factors may increase the risk of *R. obtusifolius* infestation in grazed grasslands compared to a mown system, where the biomass is evenly removed.

Parameters related to pedo-climatic conditions affecting *R. obtusifolius* have been examined to a lesser extent. In a study relating *Rumex* plant density and soil parameters, patches of *R. obtusifolius* in pastures were positively correlated to soil compaction at 9–15 cm depth, measured with a penetrometer (Harrington et al., 2014). In agreement, Landolt et al. (2010) reported that *R. obtusifolius* is an indicator for soils with weakly aerated, compacted soils. Given that soil compaction is closely related to soil bulk density (Drewry et al., 2008; Mayel et al., 2021), both findings suggest that *R. obtusifolius* should be favoured by compacted soils and/or comparably high soil bulk density.

In this paper, we addressed how the joint effects of management practices and environmental conditions influence the occurrence of *R. obtusifolius* in managed grasslands. Based on the species' growth characteristics reported from observational studies and its reaction to fertilisation and cutting in experiments, we hypothesise that (i) grasslands with high soil nutrient availability will favour the occurrence of *R. obtusifolius*, (ii) land-use intensity in terms of defoliation frequency and fertilisation should only weakly and inconsistently affect *R. obtusifolius*, (iii) dense swards will negatively impact *R. obtusifolius*, (iv) grazing may favour *R. obtusifolius* compared to mowing, and (v) grassland soils with increased soil compaction will favour *R. obtusifolius*.

To evaluate these hypotheses, we conducted an on-farm survey in Switzerland, Slovenia, and United Kingdom during 2019–2020 on intensively managed, permanent grasslands. Parcels with high density of *R. obtusifolius* were sampled and compared with nearby parcels that had very few or no *R. obtusifolius* plants at all. The management of both types of parcels as well as environmental factors were recorded. This allowed to identify factors that affect the risk of the occurrence of *R. obtusifolius* with the aim of improving strategies for the integrated weed management of the species.

2 | MATERIALS AND METHODS

2.1 | Study areas, sampling design, and management data

The survey was conducted in Switzerland (CH), Slovenia (SI), and United Kingdom (UK) following a common protocol. We focused on permanent, productive grasslands that were intensively managed for forage production for cattle and established for at least 5 years; the majority of parcels were managed as grasslands for more than 20 years. In CH, the sampling area covered the Midlands, the Jura region, and the northern Prealps (Figure 1A). In SI, the sampling area covered the central Osrednja/Jugovzhodna Slovenija regions and the Podravje/Pomurje regions in the northeast (Figure 1B), and in the UK, the area covered the southwest region, with farms predominately located in Devon but expanding into East Cornwall (Figure 1C).

Parcels of land (hereafter 'parcels') with high density of *R. obtusifolius* were identified with support of the agricultural advisory services. The sampling of parcels followed a paired case–control study (Agresti, 2002), a design that has successfully been used to evaluate the occurrence of two *Senecio* species in grasslands (Suter et al., 2007; Suter & Lüscher, 2008). At a location where *R. obtusifolius* occurred in high density (hereafter also 'occurrence of *R. obtusifolius*'), two parcels were selected: one with, on average, at least one *R. obtusifolius* plant m^{-2} (case) and a nearby parcel with, on average, a maximum of four *R. obtusifolius* plants per 100 m^2 (control). Case and control parcels were infested by or free of *R. obtusifolius* for at least 5 years; the majority of parcels had their respective infestation status (yes/no) for more than 10 years. The distance between pairs of parcels was generally less than 1 km (mostly <600 m, median: 330 m), but was occasionally larger if no matching control parcel was found nearby. This sampling design maximised similarity of environmental conditions regarding temperature and precipitation; additionally, slope and aspect of both parcels were chosen to be as similar as possible. In total, 80, 40, and 36 parcels were studied in CH, SI, and UK respectively, that is, 40, 20, and 18 pairs (Figure 1). Pairs of parcels were either conventionally or organically managed in CH (14 pairs organic) and UK (11 pairs organic), with two exceptions in CH where the case and control parcels were under either farming system. All parcels were conventionally managed in SI. Furthermore, in CH and SI all the animals on the grazed parcels were cattle, except for one parcel in SI that was grazed by horses, whereas in the UK 8 pairs of parcels were grazed by cattle and 10 pairs grazed by cattle and sheep. Finally, potential control parcels that had been treated with broadcast herbicides against *R. obtusifolius* within the last 5 years were excluded a priori (see Table 1 for further characteristics of the grasslands regarding altitude, parcel size, annual yield, and vegetation).

Data on the management of parcels were acquired by face-to-face interviews with the farmers. The type of management (mowing, mixed mowing-grazing, rotational grazing, continuous grazing) and the number of mowing and/or grazing events per year was recorded. A parcel was assigned to be of mixed management when it was mown at least once and otherwise grazed. The sum of mowing and grazing events resulted in the defoliation frequency (events $year^{-1}$). Information on grazing was used to calculate the grazing intensity as livestock unit days of grazing ha^{-1} $year^{-1}$. Grazing time was scaled per 24 h, meaning that if a parcel was grazed by, for example, 24 adult cows for 8 h day^{-1}, this resulted in 8 livestock units day^{-1}. The amount of plant-available N applied per year was calculated for the different forms of mineral and organic fertilisers, following standard tables of the three countries (AHDB, 2021; Mihelič et al., 2010; Richner et al., 2017). Data on plant-available N applied, mowing, and grazing intensity were used to calculate the quantitative, continuous index of land-use intensity (LUI) following Blüthgen et al. (2012) (see Supporting Information for more details on scaling LUI, and Figure S1 for the correlation between its components). Moreover, data about the parcel history was also collected from farmers for periods from 2009 to 2019: changes in management intensity (increase or decrease in fertiliser application and/or defoliation frequency), disturbance events (e.g., drought event, intensive trampling, construction of drainage tubes, strong impact of mice or boars), oversowing, and total renovation of sward. Finally, farmers were asked about regulation methods applied on *R. obtusifolius*, which included, for example, application of herbicides to single *R. obtusifolius* plants (case and control parcels), broadcast application of herbicides (cases only), pulling/digging, cutting of aboveground biomass, and application of steam. The data

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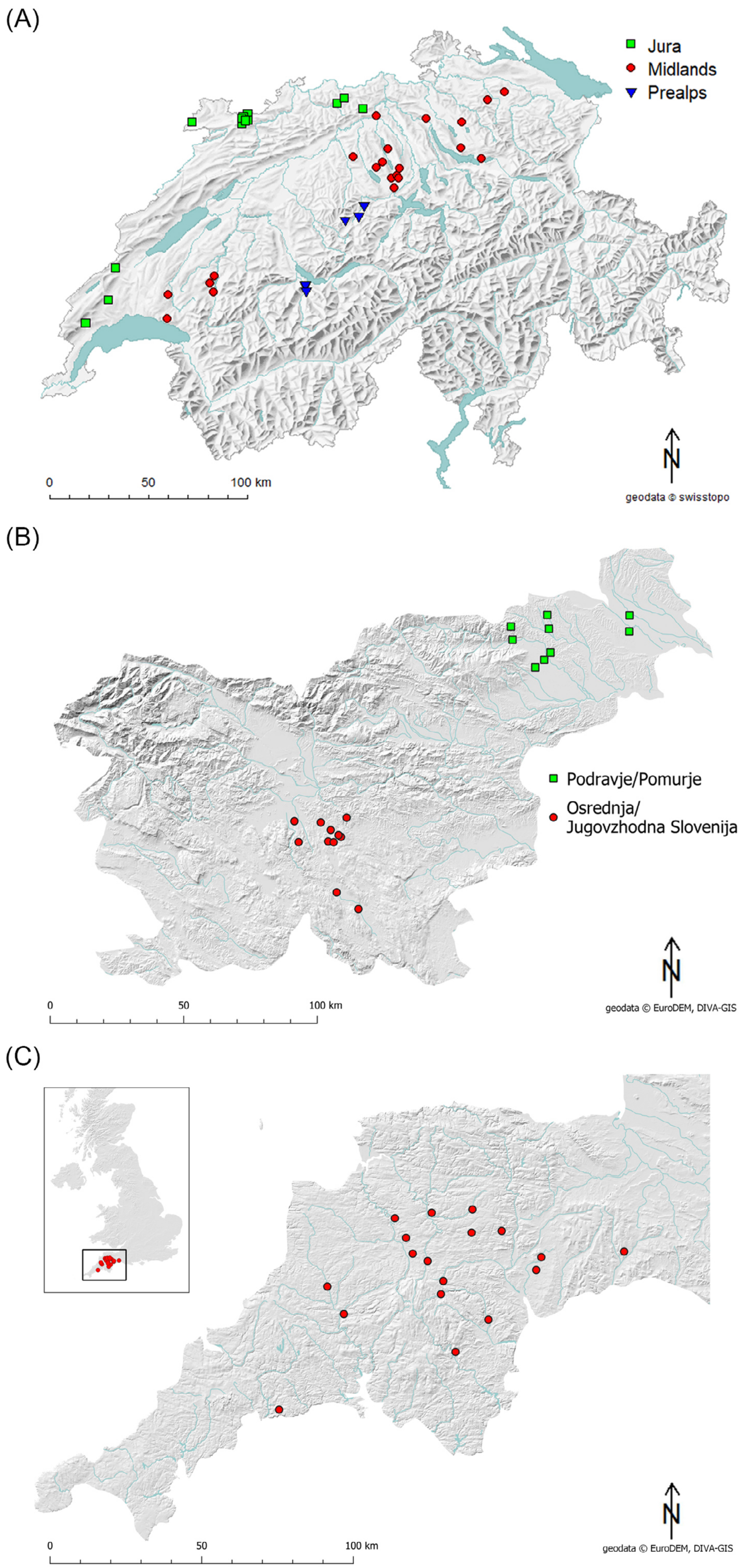

FIGURE 1 Location of the sampling sites in Switzerland (A), Slovenia (B), and United Kingdom (C) with a pair of parcels each to evaluate the risk of the occurrence of *Rumex obtusifolius* in permanent, productive grasslands. In Switzerland and Slovenia, respectively three and two biogeographical regions with differing pedo-climatic conditions were distinguished. Map background is the relief and the waters.

TABLE 1 General characteristics of grasslands regarding altitude, yield, and vegetation, where case and control parcels were selected in Switzerland (CH), Slovenia (SI), and United Kingdom (UK).

	CH	SI	UK
Altitude (m a.s.l.): median	689	321	120
Range	398–967	187–678	26–231
Parcel size (ha): median	1.3	1.6	2.4
Range	0.3–9.4	0.1–16.9	0.6–6.9
Sampling time	May–Oct. 2019	Jan.–Dec. 2019	May–Sep. 2020
Annual forage yield (t ha^{-1}): median[a]	9.8	10.2	–
1st–3rd quartile	7.0–11.0	9.2–11.4	–
Species richness[b]	20	22	12
Grass cover (%)	59	57	73
Legume cover (%)	16	12	14
Forb cover (%)	25	31	13
Most abundant species	*Lolium perenne*	*Lolium perenne*	*Lolium perenne*
2nd most abundant species	*Trifolium repens*	*Dactylis glomerata*	*Holcus lanatus*
3rd most abundant species	*Dactylis glomerata*	*Trifolium repens*	*Trifolium repens*

[a]Based on farmer information; no data from UK.
[b]Number of species per 9 m^2.

obtained from the interviews was input into the analysis as categorical or continuous variables (Table 2).

2.2 | Vegetation records and soil sampling

On each parcel (case, control), a sub-parcel was defined that had homogeneous environmental conditions (e.g., slope, aspect) and also a homogeneous distribution of *R. obtusifolius* plants. At the centre of the sub-parcel, inclination and aspect were recorded (Table 2), and two measurement plots (3 m × 3 m each) were selected with an inter-plot distance of 14–20 m. In each measurement plot, the density of *R. obtusifolius* was recorded (plants m^{-2}). A plant individual was determined on the basis of having a distinct rosette (established plant) or having at least one fully developed leaf (seedling). Further, a vegetation assessment was done by listing all species present to evaluate species richness and composition (nomenclature following Lauber et al. (2001) (CH), Wraber and Martincic (2007) (SI), Stace (2010) (UK)), with the pooled species lists from both measurement plots resulting in the species richness per parcel (Table 1). Percent cover of three groups of plant functional types (grasses, legumes, non-leguminous forbs) as well as the cover of the three most abundant species were visually estimated, and the cover averages across both measurement plots resulted in the cover estimates for the parcel (Table 1). Finally, to determine overall vegetation and basal cover in an objective, non-destructive way, a line-point intercept method was adopted (Wilson, 2011). The census was carried out once during the growing season, at least 3 weeks after the last defoliation. As vegetation development was at different stages at the sampled sites, we focused on the bottom 5 cm of vegetation. Thus, to determine vegetation cover, intercepts of a metal rod with stems and leaves between 0.1 and 5 cm from the ground were recorded every 10 cm along the two diagonals of each of the two measurement plots. Likewise, to determine basal cover, intercepts with a plant basis were recorded at the soil surface. This resulted in 82 potential intercepts for each of vegetation and basal cover per measurement plot, out of which percent vegetation cover and basal cover was calculated. Averaging the percent values of the two measurements plots resulted in the value per parcel.

For the analysis of soil nutrients and texture, samples were taken with an auger from the topsoil (13 cores, 10 cm deep, ca. 1 L per measurement plot). It was confirmed that parcels were not fertilised 3 weeks prior to sampling. Finally, to determine soil bulk density, two cylindrical soil cores were removed down to 10 cm by using metal cylinders with a standardised diameter. Samples for each soil nutrients/texture and bulk density from both measurement plots were pooled to result in one sample per parcel, and all material was stored in plastic bags at 4°C in the dark until further processing.

2.3 | Analysis for soil nutrients and soil texture

All samples for the analysis of soil nutrient contents and texture were first dried to constant weight (60°C max) and then sent to CH, where they were analysed at Agroscope, Zürich. The analyses followed standard methods (Agroscope, 2021). Soil samples were first re-dried at 40°C to constant weight and sieved through a 2 mm mesh before analysis. Contents of P were determined following the P-Olsen method (abbreviated: P_{Olsen}) (VDLUFA, 2012), while contents of K, magnesium (Mg), and calcium (Ca) were determined using extractions with ammonium acetate and ethylene-diamine-tetraacetic acid (abbreviated: K_{AAE}, Mg_{AAE}, Ca_{AAE}). The determination of the potential cation exchange capacity (CEC) followed a reference method of Agroscope (Agroscope, 2020) (see Supporting Information for details on the analysis of P, K, Mg, Ca, and CEC).

The pH was determined by mixing one part of soil with 2.5 parts of distilled water. The mixture was equilibrated between 12 and 18 h before measurement. The analysis of soil texture included percentage of clay, silt, sand and organic carbon. Finally, soil bulk density was

TABLE 2 Median (min; max) or frequency of variables on environmental conditions and management practice for parcels with high density of *Rumex obtusifolius* (Case) and parcels with very low density or no plants of the species (Control) in Switzerland (CH), Slovenia (SI), and United Kingdom (UK).

Variable	Unit/category	CH		SI		UK	
		Case ($n = 40$)	Control ($n = 40$)	Case ($n = 20$)	Control ($n = 20$)	Case ($n = 18$)	Control ($n = 18$)
Environment							
Inclination	%	10.7 (2.7–34.7)	11.5 (0.9–36.5)	11.0 (1.0–34.0)	8.5 (1.0–33.0)	4.2 (1.2–9.6)	4.7 (1.0–8.2)
Aspect	North	15	10	2	6	3	3
	East	12	11	3	3	4	4
	South	6	8	5	6	7	8
	West	7	11	10	5	4	3
Soil							
P-Olsen[a]	mg kg^{-1}	45.6 (19.2–178.9)	35.0 (7.0–89.9)	26.0 (10.0–59.2)	16.7 (9.5–104.5)	57.3 (5.3–127.0)	43.5 (22.4–106.5)
K-AAE[b]	mg kg^{-1}	297.6 (93.0–1222.2)	237.5 (95.0–1000.6)	136.7 (64.0–436.7)	146.3 (42.5–323.7)	319.6 (131.8–734.2)	249.8 (139.8–432.4)
Mg-AAE[b]	mg kg^{-1}	241.7 (103.1–817.4)	230.1 (129.3–1063.6)	403.0 (191.9–2012.2)	490.0 (260.9–2009.8)	173.1 (120.9–294.9)	172.2 (102.9–292.9)
Ca-AAE[b]	mg kg^{-1}	4462 (1536–33 039)	4687 (1840–26 548)	2683 (771–18 927)	3140 (1834–12 526)	2951 (1277–5150)	2822 (1384–5098)
CEC[c]	cmol kg^{-1}	34.2 (20.2–58.8)	35.0 (23.5–59.6)	27.2 (16.3–47.4)	30.6 (21.2–47.4)	36.9 (20.0–44.0)	35.3 (20.6–46.8)
pH	-	6.4 (5.4–7.7)	6.3 (5.4–7.4)	6.1 (5.7–7.6)	6.5 (5.5–7.7)	6.0 (5.4–6.8)	5.7 (5.3–6.5)
Organic carbon	%	3.7 (1.4–7.6)	3.9 (2.1–7.7)	2.9 (1.2–4.8)	3.0 (2.2–5.9)	3.6 (2.0–5.0)	4.0 (2.4–6.1)
Clay	%	22.6 (12.6–44.0)	24.5 (12.6–54.6)	25.6 (5.2–45.9)	25.4 (12.7–50.1)	26.6 (15.1–37.6)	30.5 (18.7–47.9)
Silt	%	34.8 (25.2–55.8)	34.2 (24.9–56.8)	46.8 (26.9–60.0)	44.9 (26.8–55.7)	37.1 (22.8–45.7)	38.0 (23.7–51.1)
Sand	%	36.8 (8.2–51.3)	34.3 (2.1–52.2)	18.5 (9.4–62.2)	18.7 (11.2–55.7)	29.9 (19.2–55.7)	22.4 (6.2–51.0)
Bulk density	g cm^{-3}	1.04 (0.71–1.45)	0.96 (0.76–1. 23)	1.30 (1.04–1.43)	1.21 (1.00–1.40)	0.93 (0.66–1.23)	0.84 (0.71–1.22)
Management and vegetation							
Type of management	Mowing	9	20	15	16	-[d]	-[d]
	Mixed (mowing-grazing)	14	5	3	4	8	8
	Rotational grazing	14	14	1	0	8	9
	Continuous grazing	3	1	1	0	2	1
Defoliation frequency[e]	Events $year^{-1}$	5 (1–13)	4.5 (1–9)	3 (1–5)	3 (2–5)	6 (1–11)	5 (1–10)
Grazing intensity[e]	LU days ha^{-1} $year^{-1}$	234.9 (0.0–1196.3)	198.6 (0.0–1325.8)	0.0 (0.0–1800.0)	0.0 (0.0–1980.0)	607.9 (143.3–1941.7)	409.3 (102.3–2344.3)
Plant-available nitrogen applied[e]	kg ha^{-1} $year^{-1}$	98.3 (0.0–281.0)	84.3 (0.0–272.8)	154.5 (60.0–290.0)	135.0 (27.0–217.0)	2.6 (0.0–62.5)	0.0 (0.0–62.5)
Land-use intensity[f]	-	1.7 (1.0–2.4)	1.6 (1.3–2.3)	1.6 (1.2–2.9)	1.4 (1.0–3.1)	1.7 (0.5–2.6)	1.7 (0.5–2.6)
Change in management intensity	No change	21	23	5	10	8	6
	Increase	13	11	12	7	2	1
	Decrease	6	6	3	3	8	11

(Continues)

TABLE 2 (Continued)

Variable	Unit/category	CH		SI		UK	
		Case ($n = 40$)	Control ($n = 40$)	Case ($n = 20$)	Control ($n = 20$)	Case ($n = 18$)	Control ($n = 18$)
Oversowing	No	21	20	11	16	16	16
	Yes	19	20	9	4	2	2
Renovation	No	38	38	16	17	9	14
	Yes	2	2	4	3	9	4
Disturbance	No	2	4	17	16	13	14
	Yes	38	36	3	4	5	4
Regulation	No	5	7	0	14	0	4
	Yes	35	33	20	6	18	14
Basal cover	%	7.3 (1.2–22.0)	8.5 (0.6–20.7)	28.4 (12.8–57.3)	24.1 (8.5–50.0)	24.4 (8.5–56.6)	29.3 (14.0–77.4)
Vegetation cover	%	83.5 (62.8–98.8)	88.4 (59.1–98.8)	89.0 (72.6–98.8)	93.0 (75.6–98.8)	92.7 (70.1–100.0)	97.0 (84.2–100.0)

Note: See Section 2 for detailed explanations of variables.
[a]Olsen method.
[b]Ammonium acetate extraction.
[c]Potential cation exchange capacity.
[d]No mowing at UK.
[e]Not used as regression predictor (component of land-use intensity).
[f]Land-use intensity is an index based on nitrogen applied, defoliation frequency, and grazing intensity.
n = number of parcels; LU: livestock unit.

determined (see Supporting Information for a detailed description of the analysis of soil texture and bulk density).

2.4 | Data analysis

The influence of the recorded variables on the occurrence of *R. obtusifolius* was analysed using multiple logistic regression, the response variable being the presence (case) or absence (control) of *R. obtusifolius* in high density, equivalent to case–control parcels (Agresti, 2002). In a preliminary generalised linear mixed-effects model, the 'sampling location' consisting of a pair of parcels (case/control) was also included as a random factor (random intercept). This random variance, however, was estimated to be zero and 'sampling location' was therefore omitted, which led to a generalised linear model with logit link function and an assumed binomial distribution of the response. Using the combined data of the three countries, the predictor variables presented in Table 2 were tested with forward selection, and the second-order Akaike Information Criterion (AICc, Burnham & Anderson, 2002) was applied to justify the inclusion of a variable into the model. The variable 'country' (factor with three levels) was always included, and interactions between each of the finally selected variables and 'country' were tested (see Supporting Information for more details on predictor variables in this analysis). The regression parameters of the finally selected model allowed the relative risk of the occurrence of *R. obtusifolius* to be calculated, that is, the ratio of the probability of *R. obtusifolius* presence in high density comparing two levels of a predictor variable, for example, of a parcel being grazed versus mown. Finally, as generally established, the relative risk cannot directly be obtained from a logistic regression in a case–control study, however, the odds ratio can be, and the odds ratio is very similar to the relative risk when the probability of the outcome of interest is close to zero (Agresti, 2002). This probability, that *R. obtusifolius* is generally present in high densities in the grasslands of the three countries, is estimated by the agricultural extension services to be less than 0.01.

The indicator species occurring in plots with high or low densities of *R. obtusifolius* were determined using the Indicator Value of species (Ind-Val) following Dufrêne and Legendre (1997). The index ranges between zero and one; it is calculated for each species and is at maximum when a particular species is observed on all plots of only one group (here: with high or low densities of *R. obtusifolius*). This analysis was done separately for each country. All analyses were performed using the statistical software R, version 4.2.2 (R Core Team, 2023) and the package labdsv for the analysis of the Ind-Val (Roberts & Roberts, 2019).

3 | RESULTS

3.1 | Factors influencing the occurrence of *Rumex obtusifolius* in high densities

Across the three countries, three variables significantly and consistently explained differences in the occurrence of *R. obtusifolius* in high density: vegetation cover, soil P content (P_{Olsen}), and soil bulk density (Table 3, Figure 2). Increase in vegetation cover by 10% reduced the relative risk of *R. obtusifolius* occurrence to about half (Figure 2). The two other variables raised the relative risk: an increase in P_{Olsen} of 13 mg kg^{-1} (the mean difference between case and control parcels) resulted in a relative risk of 1.24, and an increase in bulk density of 0.1 g cm^{-3} in a relative risk of 1.32 (Figure 2). These effects were consistent across countries, indicated by non-significant interaction terms between country and either vegetation cover ($p = 0.28$), P_{Olsen}

TABLE 3 Variables with significant effects on the relative risk of the occurrence of *Rumex obtusifolius* in high density in grasslands of Switzerland, Slovenia, and United Kingdom.

Variable	df	χ^2	*p* value	ΔAICc[b]
Country[a]	2	2.02	0.364	-
Vegetation cover	1	9.07	0.003	−7.0
P_{Olsen}	1	7.63	0.006	−5.5
Soil bulk density	1	4.20	0.040	−2.0

Note: Variables of Table 2 were tested with forward selected using a generalised linear model with logit link function. Terms added sequentially (first to last) given country, and only variables that lowered the AICc upon inclusion in the model are given. See Figure 2 for the calculated relative risks and Table S1 for the parameter estimates.
[a]Inference of 'Country' based on single term deletion from the final model.
[b]Change of the AICc by inclusion of variable.

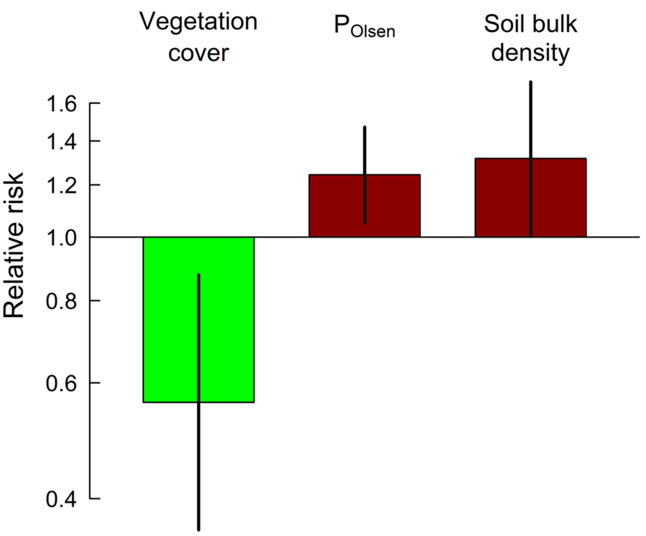

FIGURE 2 Variables significantly affecting the relative risk of the occurrence *Rumex obtusifolius* in high density in grasslands of Switzerland, Slovenia, and United Kingdom. The relative risk (green: decreasing; dark red: increasing) across sites and 95% confidence intervals are given for a 10% increase in vegetation cover, an increase in P_{Olsen} of 13 mg kg^{-1} (mean difference between case and control parcels), and an increase in bulk density of 0.1 g cm^{-3} (approximate mean difference between case and control parcels). The *y* axis is log-scaled to equalise distances around 1.0. See Table 3 for the corresponding model summary.

($p = 0.69$), and soil bulk density ($p = 0.87$). Also, vegetation cover, P_{Olsen}, and soil bulk density were not correlated to each other (Figure S2, $p > 0.10$ each), meaning that they affected *R. obtusifolius* occurrence largely independently. Following the selection procedure, none of the other variables recorded (Table 2) were relevant in explaining high density occurrence of *R. obtusifolius*, neither when tested in addition to the final model (no improvement of the model based on the AICc, Table 3), nor when tested alone (all $p > 0.05$, mostly $p > 0.3$). The only exception was soil K_{AAE} content when tested alone ($\chi^2 = 7.10$, df = 1, $p = 0.008$, ΔAICc = −5.0): an increase in soil K_{AAE} of 78 mg kg^{-1} (the mean difference between case and control parcels) resulted in a relative risk of 1.22. Thus, K_{AAE} increased the relative risk of *R. obtusifolius* occurrence to the same degree as P_{Olsen}, which was due to a positive correlation between P_{Olsen} and K_{AAE} (Figure S3, $p < 0.0001$).

In CH only, management that included grazing (mixed mowing-grazing, rotational and continuous grazing) increased the relative risk of the occurrence of *R. obtusifolius* about three-fold to 3.25 as compared to mowing only (pooled effect of grazing: $\chi^2 = 5.69$, df = 1, $p = 0.017$, ΔAICc = −3.5), while there was no effect of management type in SI and the UK ($p > 0.39$).

3.2 | Indicator species

Two indicator species were found for case parcels: *Plantago major* L. subsp. *major* in CH and *Poa annua* L. in the UK (Table 4). No distinct species was found for case parcels in SI. In all three countries, indicators for control parcels were species typical for grasslands under medium to high management intensity, such as *Agrostis capillaris* L., *Anthoxantum odoratum* L., *Cynosorus cristatus* L., *Festuca arundinacea* Schreb., *Festuca rubra* aggr., *Plantago lanceolata* L., *Trisetum flavescens* (L.) P. Beauv., and *Vicia sepium* L. (Table 4). The indicator species associated with *R. obtusifolius* had Ellenberg N values ≥6, indicating a preference for soils with high fertility, and indicator species of control parcels had Ellenberg N values of ≤5, preferring habitats with intermediate soil fertility.

4 | DISCUSSION

4.1 | Factors influencing the occurrence of *Rumex obtusifolius* in high densities

Our study highlights drivers of the proliferation of *R. obtusifolius* at large spatial scales across gradients of nutrients, disturbance, and different types of management by evaluating hypotheses derived from small-scale manipulative experiments, and so clearly covers a research gap (Maskell et al., 2020). Importantly, the study was implemented in the well-established case–control design, allowing for thorough statistical testing. Moreover, while manipulative experiments on the control of *R. obtusifolius* generally run for 2 or 3 years (Hann et al., 2012; Hopkins & Johnson, 2002; Niggli et al., 1993), our on-farm study revealed effects that acted over a much longer time scale, based on our records at least 10–20 years. The factors identified here that influence *R. obtusifolius* (vegetation cover, soil P and K content, soil bulk density, grazing) should therefore be seen as indicative of medium- to long-term processes, and all of them are sensitive to management, either directly or indirectly. The risk of occurrence of *R. obtusifolius* in high densities was explained by the same factors in all three countries (grazing management excluded), despite differing soil conditions and a gradient of climate from Atlantic to continental (Metzger et al., 2005).

Vegetation cover had a strong suppressive impact on *R. obtusifolius*. One of the proposed mechanisms for weed suppression in high yielding, intensively managed multispecies leys is their high capture for light and soil resources, which impairs growth and survival of weed species (Suter et al., 2017). Under shading by neighbouring vegetation, young *R. obtusifolius* plants were found to invest relatively more in above-than belowground biomass, which weakens the roots' ability to compete for soil nutrients (Jeangros & Nösberger, 1990) and their potential to establish. The risk reduction caused by higher vegetation cover can thus be explained by interspecific plant competition suppressing *R. obtusifolius* (Jeangros & Nösberger, 1990). Moreover, dense swards intercepting more radiation should lower the recruitment success from the soil seed bank, as germination of *R. obtusifolius* is strongly impaired under low light availability (Benvenuti et al., 2001; Totterdell & Roberts, 1980). Thus, a management that promotes dense swards and avoids periods of bare ground should impede the germination and growth of *R. obtusifolius* seedlings and reduce the risk for grassland infestation with the species.

Our results highlight that high soil P and K levels favour *R. obtusifolius*. Generally, all soils in our study were well supplied with P and K, suggesting a history of P and K fertilisation. The medians of soil P content (Table 2) were in line with values under medium to high LUI in permanent grasslands of CH (Frossard et al., 2004), and such values have been shown to be non-limiting for about 90% maximum production for many grassland species in contrasting soil types and climates (Gourley et al., 2019; Jouany et al., 2021; McCaskill et al., 2019). Thus, the higher risk of occurrence of *R. obtusifolius* at increased soil P and K contents reflects that the species can take an advantage from high availability of these nutrients (O'Donovan et al., 2023). In a study based on a 30-year national survey in the UK to assess changes in abundance of weed species in grasslands (Maskell et al., 2020), abundance of *R. obtusifolius* was positively related to indicators of soil fertility, specifically Ellenberg nutrient scores. This was confirmed in our study by the fact that the indicator species for high *R. obtusifolius* density also had high Ellenberg N values (Table 4). This implies that, to reduce the competitive ability of *R. obtusifolius*, P and K fertilisation should be adapted to the forage plants' requirements to achieve a balance between nutrient provision and removal, which can be done based on regular soil tests.

We did not find an effect of LUI on the risk of the occurrence of *R. obtusifolius*. Land-use intensity in our study reflects an overall average N fertiliser application of 92 kg ha^{-1} $year^{-1}$ and 5 defoliation events (see Table 2 for medians and ranges for each country). Despite a range of LUI in case and control parcels, the medians of the index were very similar. There is indication from the survey in the UK (Maskell et al., 2020) that *R. obtusifolius* was less abundant on

TABLE 4 Indicator species for parcels with high density of *Rumex obtusifolius* (Case) and parcels with no or very low density of the species (Control) in the three countries Switzerland (CH), Slovenia (SI), and United Kingdom (UK).

(a) CH				
	Frequency of species' occurrence			
Indicator species	**Case ($n = 40$)**	**Control ($n = 40$)**	**Ind-Val**	***p* value**
Case				
Rumex obtusifolius (9)	40	7	0.85	<0.001
Plantago major (6)	32	22	0.47	0.031
Control				
Cerastium fontanum (5)	24	34	0.50	0.026
Plantago lanceolata (4)	22	33	0.50	0.016
Anthoxantum odoratum (3)	3	12	0.24	0.021
Festuca rubra (5)	1	10	0.23	0.008
Festuca arundinacea (5)	0	8	0.20	0.005
Agrostis capillaris (4)	2	9	0.18	0.048
Trisetum flavescens (5)	1	8	0.18	0.029
(b) SI				
Indicator species	**($n = 20$)**	**($n = 20$)**		
Case				
Rumex obtusifolius (9)	20	3	0.87	<0.001
Control				
Vicia sepium (5)	0	5	0.25	0.047
(c) UK				
Indicator species	**($n = 18$)**	**($n = 18$)**		
Case				
Rumex obtusifolius (9)	18	4	0.82	<0.001
Poa annua (8)	13	6	0.49	0.044
Control				
Cerastium fontanum (5)	7	15	0.57	0.016
Anthoxantum odoratum (3)	5	12	0.47	0.044
Cynosorus cristatus (4)	4	11	0.45	0.040
Ranuculus acris (4)	3	10	0.43	0.036

Note: The indicator value of species (Ind-Val) was calculated following Dufrêne and Legendre (1997). Only species with $p < 0.05$ are displayed. Nomenclature: Lauber et al. (2001) (CH), Wraber and Martincic (2007) (SI), Stace (2010) (UK). Each species is followed by its Ellenberg indicator value for Nitrogen (a general indicator of soil fertility and (aboveground) biomass productivity (Schaffers & Sýkora, 2000); values from Ellenberg and Leuschner (2010) (CH, SI) and Hill et al. (1999) (UK). Where original values were 'x' (broad amplitude) or '?' (unknown), estimated values for the UK have been used. A value of 9 is an indicator of extremely fertile situation, 7 of richly fertile places, 5 of intermediate fertility and 3 of more or less infertile sites. n = number of parcels.

extensively managed grassland under an agri-environment scheme than without such a scheme. However, because our study focused on intensively managed grasslands, we would not detect such differences along our range of LUI. Previous studies that experimentally manipulated cutting frequency and fertilisation revealed no conclusive results about the potential of management intensity to control *R. obtusifolius* (Hann et al., 2012; Hopkins & Johnson, 2002; Niggli et al., 1993). For example, Hann et al. (2012) reported that decreased cutting frequency and reduced N-P-K fertilisation led to a decline in *R. obtusifolius* plant density, but the effect occurred in only one of three sites and the effect size was moderate (Hann et al., 2012). Based on our result and previous work, we infer that LUI in terms of a balanced cutting frequency and (N) fertilisation should not act as a primary driver on the risk for grassland infestation with *R. obtusifolius*, and that high management intensities should not *per se* have a high infestation risk for *R. obtusifolius*. Rather, our results stress the importance of good management practice, as balanced defoliation and fertilisation can be achieved under any LUI.

In the Swiss data, we have found an increased risk of *R. obtusifolius* occurrence in parcels that were under grazing (mixed mowing-grazing, rotational and continuous grazing) compared to mowing only. We admit that this finding refers only to CH; there were no mown parcels in the UK and only one parcel under each rotational and continuous grazing in SI, making a reasonable comparison impossible. The relevance of cattle grazing for the proliferation of *R. obtusifolius* in grasslands can be attributed to selective grazing of surrounding species, allowing the weed to produce seeds, and to the disturbance of the vegetation in a way that creates microsites, which favours invasion by non-resident species (Eskelinen & Virtanen, 2005; Renne et al., 2006; Thompson et al., 2001). In our study, case parcels in CH had on average a soil seed bank of about 860 germinable seeds of *R. obtusifolius* m^{-2} (Suter et al., 2023), and we have to infer repeated seed production of the species in the past. Moreover, the indicator species found in case parcels, namely *Plantago major* L. and *Poa annua* L. (Table 4), are both indicators for disturbed sites and intensive trampling. Thus, on grazed parcels in CH, we presume that propagule and microsite availability may have created conditions that are very favourable for the recruitment of *R. obtusifolius* from the soil seed bank (Benvenuti et al., 2001; Jeangros & Nösberger, 1990). Therefore, we assign the increased risk of *R. obtusifolius* occurrence under grazing mainly to effects that come along with shortcomings of management. A grazing management that minimises bare ground through adapted stocking densities and intervals and cleaning cuts after grazing are of major importance.

Higher bulk density was found to increase the risk of the occurrence of *R. obtusifolius* in high densities. In line with this, the indicator species of case parcels, *P. major* and *P. annua*, are both indicators for compacted soils (Landolt et al., 2010). Because the grasslands of our study had all been intensively managed over years, we presume the higher soil bulk density to be related to regular livestock trampling and/or the frequent use of (heavy) machinery. It has been repeatedly shown that intensive grazing increases bulk density and decreases porosity (Mayel et al., 2021 for review). Over a longer time, increase in soil compaction can negatively affect the soil quality and decrease grassland yield (Drewry et al., 2008 for review). *R. obtusifolius* can benefit from both, reduced yields and increased soil compaction, as its thick taproots seem well suited to penetrating compacted soils (Materechera et al., 1992).

4.2 | Implication for management practices to prevent *Rumex obtusifolius* infestation

The results of our study provide evidence for informing the management of productive grasslands to prevent problematic infestations of *R. obtusifolius*, and we suggest two lines of action to reduce the risk. First, it is important that management practices promote a competitive forage grassland and prevent sward gaps that arise through damage. Oversowing with fast growing and persistent species (Huguenin-Elie et al., 2006) can help to prevent further *R. obtusifolius* infestation from the soil seed bank. Inhibiting the species' seed formation should be given a high priority, which can occur through removal of flowering stems or cleaning cuts after grazing. Second, practices should aim at targeting P and K fertilisation to the forage plants' requirements based on soil nutrient analyses. Soil compaction should be minimised as far as possible, which can be achieved through lower grazing intensities, avoidance of grazing under wet conditions, and careful use of heavy machinery. Such measures do not contradict intensive management of grasslands but reinforce the need for an ideal timing of management actions that are adapted to the local site conditions.

Prevention is one of the central elements of integrated weed management (Schaffner et al., 2022), and its benefits are accentuated by the costs and inefficacy of many control measures applied against *R. obtusifolius*. For example, in SI and UK all case parcels were repeatedly treated with either herbicides and/or weeding, as were many in CH (see Table S2 for details). Despite these measures, *R. obtusifolius* was observed in high densities, pointing to a permanent recruitment from the soil seed bank and/or to the challenge of controlling *R. obtusifolius* once the species is abundant. We are aware that, with large *R. obtusifolius* populations (>5–8 small to big plants m^{-2}), our suggestions for improved management are not sufficient to eliminate the species (Hopkins & Johnson, 2002; Niggli et al., 1993). However, we contend that for any control measure to be effective it must be accompanied by an adapted management that reduces the risk for infestation. Prevention and control measures should aim at regulating *R. obtusifolius* at early stages of grassland infestation before large populations have established.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analysed during the current study will be made available on request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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