WEED RESEARCH An International Journal of Weed Biology, Ecology and Vegetation Management

DOI: 10.1111/wre.12214

Field emergence and the long-term efficacy of control of *Heracleum sosnowskyi* plants of different ages in southern Poland

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Received 28 December 2015
Revised version accepted 20 April 2016
Subject Editor: Christian Bohren, Agroscope, Switzerland

Summary

Heracleum sosnowskyi is one of the three so-called tall or giant hogweeds currently invading Asia, Europe and North America. These plants are dangerous invasive weeds, causing severe skin injuries in humans and animals. In the present study, based on four field experiments, we assessed seedling emergence in the field and evaluated methods for the long-term mechanical and chemical control of *H. sosnowskyi* of various ages (1–5 years old). The field experiments were set up in the mountainous regions of southern Poland, on soil not previously infested with *H. sosnowskyi* seeds. The results showed that the successful eradication of this species from an invaded area is possible. The results revealed that when no new flush of seeds is delivered to the soil seedbank, the longevity of *H. sosnowskyi* seeds is approximately five years, with the majority of seedlings emerging in the spring of the first year following sowing. Long-term shoot cutting, particularly the intensity of this technique, is ineffective for the control of *H. sosnowskyi*. Cutting three times a year for five years resulted in an *H. sosnowskyi* control outcome of 42–97%. Total control of this weed is obtained either by cutting the roots of plants up to 5 years old at a depth of 15 cm or by continuous (5 years long) herbicide spraying three times during the vegetative season, using a tank mixture of glyphosate and flazasulfuron (1260 g a.i. glyphosate ha^{-1} + 50 g a.i. flazasulfuron ha^{-1}).

Keywords: giant hogweed, seed longevity, glyphosate, flazasulfuron, shoot cutting, root cutting, chemical control.

Klima K & Synowiec A (2016). Field emergence and the long-term efficacy of control of *Heracleum sosnowskyi* plants of different ages in southern Poland. *Weed Research* **56**, 377–385.

Introduction

Heracleum sosnowskyi Manden. is one of the three invasive tall hogweeds; the other two species are *Heracleum mantegazzianum* Sommier and Levier and *Heracleum persicum* Desf. ex Fischer (Pyšek *et al*., 2007a). All three species belong to the botanical family *Apiaceae* and are native to the Caucasus region (Pyšek *et al*., 2007a). *Heracleum sosnowskyi* was introduced to Middle and Eastern Europe during the 1950s as a pasture plant for cattle, reflecting the high biomass production and good nutritional value of this plant (Jahodová *et al*., 2007). The cultivation of this species was soon abandoned, as this plant caused udder irritation and diarrhoea in cattle (Jakubowicz *et al*., 2012). Subsequently, *H. sosnowskyi* has aggressively and widely spread throughout this region. Presently, *H. sosnowskyi* poses a significant threat to national parks, riversides, highway waysides, as well as agricultural and suburban areas (Müllerová *et al*., 2005; Baležentienė & Bartkevičius, 2013).

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Tall hogweeds are considered the most dangerous invasive species in Europe and North America (Pyšek *et al.*, 2007a), reflecting their high competitive ability (Thiele & Otte, 2006), allelopathic potential (Baležentienė & Renco, 2014) and high reproduction rate, features which make these plants a serious threat to the invaded environments under changing climate conditions (Clements & DiTommaso, 2011). Moreover, these plants produce furanocoumarins, which cause severe injuries to human and animal skin (Jakubowicz *et al.*, 2012; Klimaszyk *et al.*, 2014). For these reasons, the efficient eradication of these plants is required, even if eradication is a challenge (Panetta, 2015).

Given the strong potential of this plant to regrow new shoots or regenerate from roots (Pyšek *et al.*, 2007b), any short-term method used to control tall hogweeds will be ineffective. The lack of empirical scientific evidence of the effectiveness of control measures results in a high degree of uncertainty when planning management programmes for tall hogweeds (Pyšek *et al.*, 2007a). Only a few studies in recent literature have addressed the long-term management of tall hogweeds, that is the management protocol for *H. mantegazzianum* chemical control, indicated to run for three to four years (Caffrey, 1999; Caffrey & Madsen, 2001).

The available literature also lacks information about the number of seeds germinating in subsequent years after being shed from the *H. sosnowskyi* maternal plant. This information would determine the time necessary for the effective elimination of this dangerous, seed-dispersing plant, which is particularly important because one plant can produce up to several thousand seeds (Caffrey, 1999). Indeed, Nielsen *et al.* (2005) highlighted the need for such studies.

The results obtained from recent experiments on *H. sosnowskyi* emergence and control are not sufficient for the effective eradication of this species from the invaded environments. Although many methods for the control of *H. sosnowskyi* are listed in the CABI compendium (Datasheet 108958), a thorough, multiyear experiment supported by a statistical analysis of the results is lacking. Thus, the aims of the present study were (i) to characterise seed survival in soil via field emergence of *H. sosnowskyi* seeds in subsequent years and (ii) to determine the efficacy of mechanical or chemical control of *H. sosnowskyi* in a 5-year period.

Materials and methods

Characteristics of the experimental site

Field studies on *H. sosnowskyi* control were conducted in Czyrna near Krynica, the Mountain Experiment Station of the University of Agriculture in Krakow (N 49°25′ E 20°58′, 545 m a.s.l.), in 2005–2014. The average annual air temperature was 7.1°C (13.8°C for the growing season), and the average annual rainfall was 843 mm (485 mm for the growing season) during the study period. Four different experiments were performed to assess *H. sosnowskyi* field emergence and examine different methods employed for the control of this plant. Plots with *H. sosnowskyi* were set up in fields not previously infested with this weed to ensure that the soil seedbank did not previously contain the seeds of this plant. The study was conducted on brown soil, Typic Eutrochrepts (Soil Taxonomy, 1975), pH 5.1 (in KCl); 0.22% total N; 10.6 mg 100 g^{-1} soil P_2O_5; 25.1 mg 100 g^{-1} soil K_2O; 1.84%C_{org}.

Field emergence of Heracleum sosnowskyi

From 2008 to 2014, a one-factor field experiment was established to assess the emergence of *H. sosnowskyi* over time. A total of 5000 seeds were sown on each of four 1 m^2 plots to mimic the flush of seeds from the mature umbels in a natural population. Seeds were sown once, on bare ground, on 12 August 2008. After sowing, *H. sosnowskyi* seeds were left on the soil surface. The soil was not moved and was gradually covered by different species germinating from the natural seedbank. The experimental area was protected from any new inputs of *H. sosnowskyi* seeds. Each year from 2009 through 2014, all of the *H. sosnowskyi* seedlings of approximately 3 cm height with visible true leaves were regularly counted during each vegetative season, since the mid-April, and every 2 weeks, and subsequently removed from the soil.

Shoot cutting

In the three separate field experiments, the efficacy of cutting the shoots of *H. sosnowskyi* plants of different ages during five consecutive years was examined. The plants were sown in mid-August 2006, 2007 and 2008 to produce three-, two- and one-year-old plants, respectively, at a density of 10 plants m^{-2} (in rows, with 50 cm spacing between rows and 20 cm spacing within rows). Moreover, for plants sown in mid-August 2008, 5000 additional seeds of *H. sosnowskyi* m^{-2} were sown between the growing plants in mid-August 2009 to simulate a new flush of seeds from mature plants. The first cutting was performed in the late April 2010 and cutting continued until 2014. A completely randomised field experiment with four replicates was set up. A single plot was 10 m^2 in area (100 plants per plot).

A trimmer with a metal cutting blade was used during four different terms: once (i) in the late April (between 21st and 30th day of April) or (ii) the mid-June (between 11th and 20th day of June); or (iii) two times: in the late April and the mid-June; or (iv) three times: in the late April, the mid-June and the mid-August. Each treatment was conducted every season during the five consecutive years from 2010 to 2014. During these experiments, all the regrown plants were additionally prevented from seed dispersal by cutting all of the generative shoots from the plants prior to flowering. This was done to prevent the evolution of any *H. sosnowskyi* soil seedbank.

The efficacy of shoot cutting was assessed based on counting each of the regrown plants. Counting was performed by the end of each vegetative season in late September. For the experiments in which an additional 5000 *H. sosnowskyi* seeds were undersown, the efficacy of shoot cutting was based on the coverage of each plot by the regrowing shoots, assessed visually and expressed as a percentage.

Root cutting

In a two-factor field experiment (2005–2013), the effect of the depth of root cutting on the growth of *H. sosnowskyi* in relationship to the age of the plants was studied. A completely randomised design with four plots per replicate was set up. Each plot was 1 m^2 in area, with 10 plants. The *H. sosnowskyi* plants were seeded in mid-August of 2005, 2007 and 2009 to obtain three-, five- and seven-year-old plants respectively. The roots of all plants from each age group were cut at a depth of 10 or 15 cm during the first 10 days of May 2013 using a shovel marked at 10 and 15 cm heights. The efficacy of root cutting was assessed in late September 2013. The number of new regrown shoots was counted for each of the plants. The roots of four control plants from different age groups were dug from the soil to a depth of 0.6 m, and their biomass as well as the root-crown length was measured. During the experiment, all plants were prevented from flowering and seed dispersal by cutting the generative shoots from the plants prior to flowering. The efficacy of root cutting was assessed based on counting each of the regrown plants.

Herbicide control

The chemical treatments were applied in the years 2010–2014. In August 2007, seeds of *H. sosnowskyi* were sown on 24 plots, each 10 m^2 in area. After emergence, the number of plants was reduced to 10 m^{-2}. The efficacy of two herbicides was tested. The mono isopropylamine salt of glyphosate (Roundup Ultra 360 SL, 360 g a.i. L^{-1}, SL, Monsanto Europe S.A.) and flazasulfuron (Chikara 25 WG, 250 g a.i. kg^{-1}, WG, ISK Biosciences Europe N.V.) was applied when the plants were 3 years old, and these treatments were continued for the next 5 years. Glyphosate was used as a single treatment (1.8 kg a.i. ha^{-1}) or tank-mixed with flazasulfuron (1.26 kg a.i. ha^{-1} glyphosate + 50 g a.i. ha^{-1} of flazasulfuron). The plants were sprayed using a hand-held sprayer. The following scheme was used for the six different chemical treatments: a single treatment with glyphosate in late April or early June; a single treatment with the mixture in late April or early June; two treatments with the mixture in late April and early June; three treatments with the mixture in late April, early June and mid-August. Each one- to three-year-old *H. sosnowskyi* plant was treated for five consecutive years, starting in 2010. The dead residues of *H. sosnowskyi* plants and the accompanying weeds, *Elymus repens* L. (Gould) and *Galeopsis tetrahit* L., were not removed from the sprayed area. The injuries resulting from herbicide treatment were visually assessed for the entire plot area and expressed as a percentage of shoot injury.

Statistical analysis

The results were statistically analysed using STATISTICA PL ver. 10 (StatSoft, 2011) software. The data from the germination test were analysed using a non-parametric Kruskal–Wallis rank test. One-way ANOVA was used to determine the correlated samples (years) in the shoot cutting and herbicide experiments. The data from root cutting were analysed using two-way ANOVA. The data were assessed for homogeneity of variance using the Levene test. When necessary, to meet the assumptions of the parametric test, the data were square-root-transformed and ANOVA was performed on the transformed values (McDonald, 2014). For the percentage values, the analysis was performed on Bliss transformed data (Bartlett, 1947). The significance of differences between the mean values was calculated using Tukey's test for absolute numbers (shoot cutting and root cutting experiments) or the Newman–Keuls test for percentage values (herbicide experiment and shoot cutting with undersown seeds experiment), at $P = 0.01$ (Tallarida & Murray, 1987).

Results

Field emergence of Heracleum sosnowskyi

The number of seedlings emerged after sowing decreased in a time-dependent manner (Fig. 1). The highest number of seedlings emerged in the first year

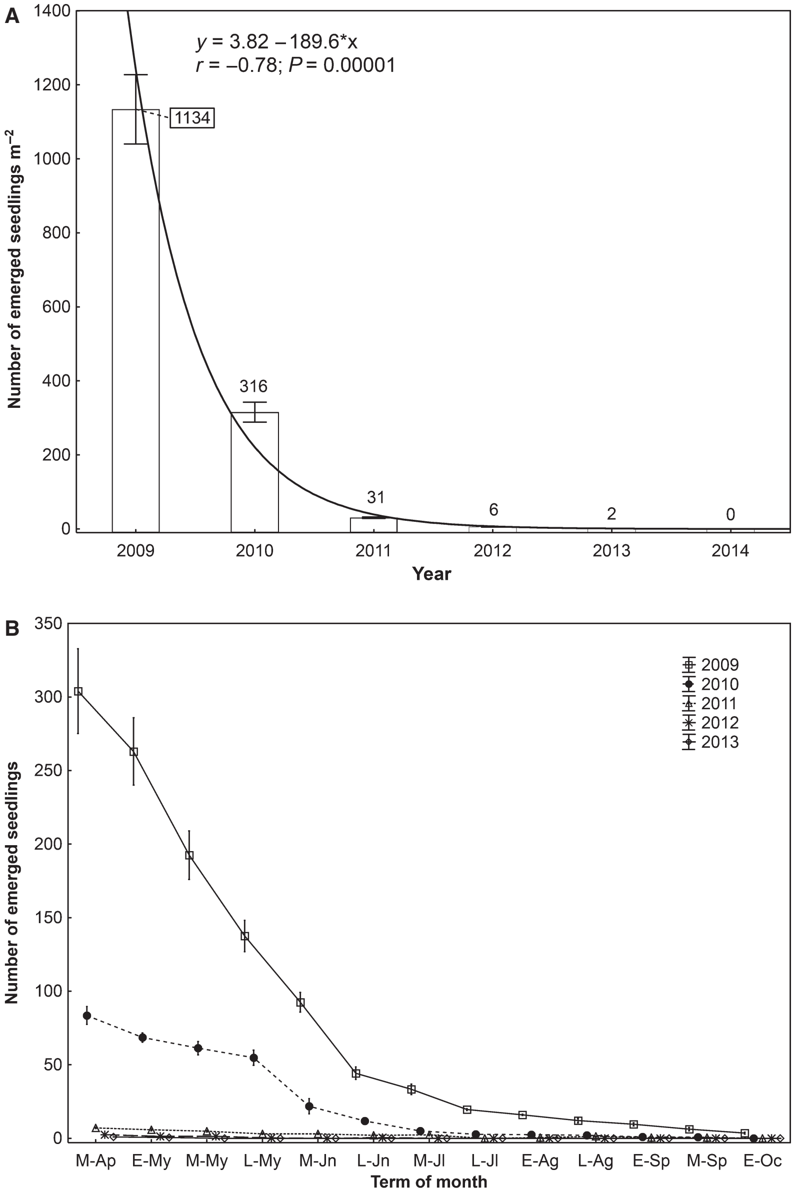

Fig. 1 *Heracleum sosnowskyi* field emergence. (A) The average number of *H. sosnowskyi* seedlings emerged during 6 years from 5000 seeds m^{-2} sown in August 2008. Error bars ± SE. The data were statistically analysed using the nonparametric Kruskal–Wallis test H (5, n = 24) = 22.5; P < 0.001. (B) Emergence of *H. sosnowskyi* seeds in the periods April–August of consecutive years 2009–2013, measured every 2 weeks. Term of month: E – early month (first ten days); M – mid-month (between 11th and 20th day); L – late month (between 21st and 30th (31st) day); Ap – April; My – May; Jn – June; Jl – July; Ag – August; Sp – September; Oc – October.

following sowing was approximately 22.6% of the total seeds sown. In the second year after sowing, the number of germinated seeds dramatically decreased to 6.3%. In the third year, the number of germinated seeds was only 0.6%, and in the fourth and fifth years, only 0.11% and 0.02% seeds were observed respectively. In the sixth year, no new *H. sosnowskyi* seedlings were recorded (Fig. 1A). In total, only 29.7% of the sown seeds germinated. The distribution of emerging seedlings during the growing season was similar each year. Most of the seedlings emerged during the period from mid-April to late May (Fig. 1B). The number of emerging seedlings was visibly lower each ten-day period. Single seedlings emerged until early October only in the first year after sowing (2009). From 2010 to 2011, the emergence of seedlings was observed until September (single occurrences). In 2013, single seedlings emerged until early May (Fig. 1B).

Shoot cutting efficacy

Shoot cutting, initiated in the second or third year of *H. sosnowskyi* growth and continued for the next five years, destroyed on average 21.5 and 10.4 plants respectively (Table 1). In both experiments, a single cutting performed in late April was better for plant control compared with a cutting conducted in mid-June. The most efficient method was the cutting of two-year-old plants performed three times in the vegetative season (in April, June and August) and continued for the next 5 years. This method destroyed 97.2 of the initial 100 plants after 5 years (Table 1). The

Table 1 Number of destroyed plants of *Heracleum sosnowskyi* (±SE) out of initial 100 plants per 10 m^2, following mechanical cutting of different intensity, started when plants were two and three years old (yo) and continued for the next five years. Statistical analysis was performed for square-root-transformed data to meet the assumptions of variance homogeneity using ANOVA for the repeated measurements. The table contains raw data

	Number of destroyed plants					
Number of cuttings and their terms	2010 2 yo*	2011 3 yo	2012 4 yo	2013 5 yo	2014 6 yo	Average
Once in late April	5.00 ± 0.91	7.25 ± 0.63	9.25 ± 0.63	9.75 ± 0.48	10.5 ± 0.65	8.35 b
Once in mid-June	1.75 ± 0.48	2.25 ± 0.25	4.25 ± 0.48	5.00 ± 0.41	5.75 ± 0.25	3.80 a
Two times†	7.00 ± 0.41	13.2 ± 0.48	21.7 ± 0.75	32.0 ± 0.82	43.2 ± 1.49	23.4 c
Three times†	11.50 ± 0.87	27.2 ± 1.11	45.7 ± 0.86	69.7 ± 1.75	97.2 ± 0.85	50.3 d
Average	6.31 a	12.5 b	20.2 c	29.1 d	39.2 e	21.5
d.f. error (cutting variants*years) 48; SED 0.1						
	3 yo	4 yo	5 yo	6 yo	7 yo	Average
Once in late April	2.25 ± 0.25	3.00 ± 0.41	3.50 ± 0.29	3.75 ± 0.25	4.00 ± 0.41	3.30 b
Once in mid-June	1.00 ± 0	1.75 ± 0.48	2.50 ± 0.29	3.00 ± 0.41	3.00 ± 0.41	2.25 a
Two times*	4.00 ± 0.41	6.25 ± 0.48	8.00 ± 0.41	9.25 ± 0.25	10.0 ± 0.41	7.50 c
Three times*	8.00 ± 0.82	14.2 ± 0.86	26.0 ± 1.47	40.0 ± 1.68	54.7 ± 1.49	28.6 d
Average	3.81 a	6.31 b	10.0 c	14.0 d	17.9 e	10.4
d.f. error (cutting variants*years) 48; SED 0.1						

Means followed by the same letter do not differ according to Tukey's test, at $P = 0.01$; $n = 4$; d.f. error – degrees of freedom for error, SED – standard error of the difference between means.

*yo – year old.

†Two times cutting was performed in the early April and mid-June; three times cutting was performed in the late April, mid-June and mid-August.

same intensity of cutting initiated when the plants were 3 years old resulted destroyed 54.7 of the initial 100 plants in the fifth year of continuous cutting. Nevertheless, none of the cutting regimes provided total *H. sosnowskyi* control.

In another experiment, where an additional 5000 seeds were undersown between the growing plants to mimic conditions where the flowering shoots were left to persist to the fruiting stage, the effect of cutting was even lower (Table 2), reflecting the enormous number of plants germinating from the soil surface. The number of destroyed plants did not exceed 42% (for cutting performed three times in the season and after five years of continuous cutting).

Root cutting efficacy

In this experiment, we characterised the effect of different root cutting depths on *H. sosnowskyi* control. The roots of *H. sosnowskyi* plants of different ages (3, 5, and 7 years old) were mechanically cut at two different depths, 10 or 15 cm (Table 3). The control of *H. sosnowskyi* was assessed in the same year at the end of the vegetative season. Three-year-old *H. sosnowskyi* plants were completely destroyed after root cutting at both depths. The 5-year-old plants were completely destroyed only after deeper root cutting. After 10-cm-deep root cutting, 92.5% of the plants were destroyed (Table 4). The seven-year-old plants were not completely destroyed after root cutting, but deeper root cutting was more effective; 87.5% of the plants did not regrow. After cutting at a depth of 10 cm, approximately 30% of the seven-year-old *H. sosnowskyi* plants showed regrowth (Table 3). Compared with the three-year-old plants, the seven-year-old plants had approximately four times the amount of root biomass and approximately three times the length of root crown (Table 3).

Herbicide control efficacy

The results presented in Table 3 confirm the high effectiveness of the herbicide treatments against *H. sosnowskyi*. In the present study, over a span of 5 years, the single application of glyphosate resulted in poorer *H. sosnowskyi* control compared with the use of a mixture of glyphosate and flazasulfuron, showing approximately 12% and 8% for April and June treatments respectively (Table 4). An increased frequency of treatments with a tank mixture of glyphosate and flazasulfuron improved the control of *H. sosnowskyi*. The most effective treatment involved spraying three times with a mixture of glyphosate and flazasulfuron, resulting in 91% control of *H. sosnowskyi* in the second year

Table 2 Per cent of control of *H. sosnowskyi* plants (±SE) by cutting the shoots in the second year following sowing, when the additional 5000 seeds per 1 m^2 were undersown in between the growing plants

	Destroyed plants (%)*					
	Year					
Number of cuttings	2010	2011	2012	2013	2014	Average
Once in late April	6.25 ± 0.48	7.50 ± 0.65	8.00 ± 0.41	8.50 ± 0.5	8.75 ± 0.48	7.80 b
Once in mid-June	2.00 ± 0.41	2.75 ± 0.25	3.00 ± 0.41	3.50 ± 0.29	3.50 ± 0.29	2.95 a
Two times†	8.75 ± 0.86	12.0 ± 0.82	13.7 ± 0.95	16.7 ± 0.63	21.5 ± 0.65	14.5 c
Three times†	16.25 ± 1.11	21.5 ± 1.19	28.7 ± 1.11	35.2 ± 1.11	41.7 ± 0.85	28.7 d
Average	8.31 a	10.9 b	13.4 c	16.0 d	18.9 e	13.50
d.f. error (cutting variants*years) 48; SED 2.0						

Means followed by the same letter do not differ at $P = 0.01$ significance level, according to Newman–Keuls test, $n = 4$; d.f. error – degrees of freedom for error, SED – standard error of the difference between means.
*Destroyed plants assessed visually, based on the percentage of ground (10 m^2) covered by the regrowing plants.
†Two times cutting was performed in the late April and mid-June; three times cutting was performed in the late April, mid-June and mid-August.

Table 3 Number of *Heracleum sosnowskyi* plants (out of initial 10 plants per 1 m^2) destroyed after root cutting at a different plant age and cutting depth, showing changes in the root biomass and the length of the root crown following root cutting. Analysis of variance for the number of destroyed plants was performed for the square-root-transformed data. The table contains raw data

	Number of destroyed plants			
	Depth of cutting			
Plant age	10 cm	15 cm	Mean root biomass (kg)	Mean length of crown (cm)
3 yo* plants	10.0 ± 0 d	10.0 ± 0 d	0.72 ± 0.05 a	2.05 ± 0.16 a
5 yo plants	9.25 ± 0.3 c	10.0 ± 0 d	1.55 ± 0.1 b	3.77 ± 0.17 b
7 yo plants	7.0 ± 0.4 a	8.75 ± 0.3 b	2.74 ± 0.1 c	6.50 ± 0.17 c
Average	8.75 a	9.58 b	d.f. error 9 SED 0.12	d.f. error 9 SED 0.23
d.f. error (depth of cutting*plant age) 18; SED 0.055				

Means (± SE) followed by the same letter in columns do not differ at $P = 0.01$ significance level according to Tukey's test, $n = 4$; d.f. error – degrees of freedom for error, SED – standard error of the difference between means.
*yo – years old.

of spraying. In the following years, the efficacy of this spraying method was more evident, reaching 100% *H. sosnowskyi* control in the fifth year (Table 4). During the experiment, we also observed that *H. sosnowskyi* plants sprayed three times during each vegetative season did not produce any generative shoots.

Discussion

In the field experiments conducted herein, both the number of mature *H. sosnowskyi* plants per m^2 and the number of seeds sown were consistent with the numbers of plants and seeds observed under natural conditions according to Pyšek *et al*. (2007a). In total, only 29.7% of the *H. sosnowskyi* seeds sown emerged during the following six years. The majority of seedlings emerged in the year following sowing. In the subsequent years, the number of emerging seedlings was significantly lower. Moravcová *et al*. (2006) obtained similar results for *H. mantegazzianum* seeds under laboratory and field conditions. These authors also showed that the highest number of seeds buried in soil germinated in the first year following burial, and the number of viable and dormant seeds decreased to 1.2% after 3 years. Additionally, the initial dormancy of *H. mantegazzianum* was completely disrupted until the first spring; subsequently, only single seeds became dormant again. Krinke *et al*. (2005) demonstrated a seasonal pattern of *H. mantegazzianum* germination similar to the previous data of Moravcová *et al*. (2006). The average percentage of living *H. mantegazzianum* seeds was 56% in autumn, 42% in spring and 15% in summer, whereas the percentage of dormant seeds was 99.7% in autumn, 12.5% in spring and again 97% in summer, showing a large and significant decrease in dormancy from autumn to spring and an increase in dormancy from spring to summer (Krinke *et al*., 2005). These findings are consistent with those obtained in the present study; indeed, we observed that

Table 4 The percentage of injuries of *H. sosnowskyi* plants ± SE by herbicide treatments continued for five years

Herbicide and number of treatments	Single dose of herbicide per ha	Total dose of a.i. in grams per season	*H. sosnowskyi* injury (%)* Year 2010	2011	2012	2013	2014	Average
Glyphosate, late April	5 L	1800	49.7 ± 2.95	56.2 ± 2.78	60.7 ± 2.29	68.5 ± 1.55	73.5 ± 1.04	61.7 b
Glyphosate, early June	5 L	1800	43.2 ± 2.21	51.0 ± 1.47	54.7 ± 0.859	61.0 ± 1.08	68.2 ± 1.93	55.6 a
Glyphosate + flazasulfuron, late April	3.5 L + 200 g	1260 + 50	59.2 ± 2.69	66.7 ± 2.1	77.0 ± 1.589	81.7 ± 0.85	86.2 ± 0.85	74.2 c
Glyphosate + flazasulfuron, early June	3.5 L + 200 g	1260 + 50	51.2 ± 2.69	56.5 ± 1.94	64.0 ± 1.089	70.2 ± 1.31	77.7 ± 1.11	63.9 b
Glyphosate + flazasulfuron, two times†	3.5 L + 200 g	2520 + 100	61.5 ± 2.90	74.2 ± 1.55	85.5 ± 1.33	93.7 ± 1.19	98.2 ± 0.85	82.6 d
Glyphosate + flazasulfuron, three times†	3.5 L + 200 g	3780 + 150	79.2 ± 3.40	91.0 ± 3.77	96.0 ± 1.78	98.0 ± 1.22	100.0 ± 0	92.8 e
Average			57.4 a	65.9 b	73.0 c	78.9 d	84.0 e	71.84
d.f. error (herbicide treatments) 18; SED 2.32 d.f. error (herbicide treatments*year) 72; SED 1.66								

Means followed by the same letter do not differ at $P = 0.01$ significance level according to Newman–Keuls test, $n = 4$; d.f. error – degrees of freedom for error, SED – standard error of the difference between means.

*Injury based on the visual assessment of the percentage of destroyed shoots on each plot.

†Two times spraying performed in the late April and early June; three times spraying performed in the late April, early June and mid-August.

during the vegetative season, the majority of *H. sosnowskyi* seeds emerged in spring, up to late May. This pattern was observed in the first and second year following seed sowing, while from the third to the sixth year following sowing, the number of emerging seedlings significantly decreased. This promising finding suggested that the longevity of *H. sosnowskyi* seeds is approximately five years and the regular cutting of flowering shoots or the use of other control methods that prevent *H. sosnowskyi* from producing seeds will eventually lead to the depletion of *H. sosnowskyi* seeds from the soil seedbank after five years.

The reaction of *H. sosnowskyi* to mechanical control (shoot cutting or root cutting) depended on the intensity of the treatments and the age of plants. The efficacy of shoot cutting initiated in the second or third year of *H. sosnowskyi* growth and continued for the next five years was approximately 21.5 and 10.4 of destroyed plants out of the initial 100 plants respectively. Cutting was more efficient in the earlier developmental stages of the plants, consistent with MacDonald and Anderson (2012), who showed that the mechanical control of tall hogweeds should be initiated when the plants are two to three years old. *Heracleum sosnowskyi* produced flowering shoots since the second year of growth and these shoots were regularly cut prior to seed establishment. Similar to *H. mantegazzianum*, *H. sosnowskyi* is a perennial monocarpic species (Nielsen *et al.*, 2005). In the present study, the regular cutting of the flowering shoots of *H. sosnowskyi* resulted in the removal of so-called determinate floral apices, the impetus for the plants to produce new generative shoots in subsequent years, thereby prolonging the life cycle of these plants. Thomas (2013) and Tiley *et al.* (1996) described a similar mechanism, reporting the removal or destruction of the flowering shoots of *H. mantegazzianum* resulted in the production of new flowering shoots from auxiliary buds or even the remaining leaves or bract axils. The increased intensity of shoot cutting (three times per vegetative season) resulted in a higher number of destroyed plants, likely reflecting the gradual reduction of the nutrient reserves in the taproots. Schuldes and Kübler (1991, cited by Tiley *et al.* (1996)) made a similar observation for *H. mantegazzianum*. In summary, the regular, multiyear cutting of *H. sosnowskyi* shoots weakens plants, but does not eradicate this species from the infested area; moreover, this method prolongs the life of these plants. However, this method seems reasonable for the removal of shoots prior to flowering in areas where chemical control cannot be applied, consistent with Dalke and Chadin (2008).

The other, more effective mechanical method for the control of *H. sosnowskyi* was root cutting.

Perennial and plurennial *Heracleum* species regrow from buds located on the root crown in the second and subsequent years of the vegetation (Sheppard, 1991; Page *et al*., 2006). Thus, root cutting has been cited as one of the most effective methods of tall hogweed control, second only to chemical methods (EPPO, 2009; Motyl & Galynskaya, 2010). The present experiment showed the potential complete control of three- and five-year-old *H. sosnowskyi* plants after cutting the roots at 10 and 15 cm respectively. In addition, the older the plant, the lower the control effect of root cutting, likely reflecting the increasing biomass of the roots and the increasing length of the root crown as the plants age. The seven-year-old plants showed approximately four times the amount of root biomass and approximately three times the length of the root crown compared with three-year-old plants. These differences might explain why the seven-year-old plants showed regrowth, as perhaps the entire root crown was not destroyed, even by 15-cm-deep root cutting. Moreover, according to Otte and Franke (1998), *H. mantegazzianum*, a species closely related to *H. sosnowskyi*, vertically contracts the tap root, hiding the vegetation point up to 10 cm deep in the soil, potentially explaining the poorer control of older plants subjected to shallower (10-cm-deep) root cutting.

Chemical control has been recommended as the most efficient method for the control of invasive *Heracleum* species (Nielsen *et al*., 2005; EPPO, 2009). Many authors have reported glyphosate as an effective herbicide for *H. mantegazzianum* control (Caffrey & Madsen, 2001; Nielsen *et al*., 2005; EPPO, 2009). However, some studies have also demonstrated the poor control of *H. sosnowskyi* solely treated with this herbicide (Hairullina & Pavlyuchenkova, 2012). Hairullina and Pavlyuchenkova (2012) used herbicides only once during the vegetative season of 2011, in May, when *H. sosnowskyi* was 20–40 cm tall. A single spraying with the isopropyl amine salt of glyphosate (1.35 kg a.i. ha^{-1}) resulted in 27% *H. sosnowskyi* control by the end of the vegetative season. In the following season, all of the plants treated with this herbicide showed regrowth. According to Yakimovich (2011) and Motyl and Galynskaya (2010), the most effective agents against *H. sosnowskyi* are sulfonylurea herbicides, including sulfuron-methyl, triasulfuron or imazapyr. In the present study, we also demonstrated the sufficient efficacy of combined treatment with flazasulfuron, a sulfonylurea herbicide (Bernard & Chantelot, 2013), and glyphosate, but these effects were observed after two years of continuous control, resulting in the complete eradication of living plants in the fifth year of the experiment.

Conclusions

Heracleum sosnowskyi emerges from the soil surface for up to 5 years, yielding a significantly smaller number of seedlings each year. The majority of seedlings emerge in the first year following sowing, and within the vegetative season, the majority of seedlings emerge in the spring (April–May). If no new flush of seeds is delivered to the soil seedbank, reflecting the regular removal of flowering shoots, the depletion of *H. sosnowskyi* seeds from the soil seedbank after five years is expected.

In the long-term field experiments conducted on soil not previously infested with *H. sosnowskyi* seeds, we showed that the complete control of the *H. sosnowskyi* population is possible. The best control outcomes are achieved when initiated with 2-year-old plants. The more the frequent intensity of the control methods, the better the control outcomes. *Heracleum sosnowskyi* plants were the best controlled when the control treatments were performed three times during the vegetative season: in April, June and August and continued for the next five years. It is the case that the flowers of *H. sosnowskyi* were removed from all treatments each year and a control with uncut flowers was not included in both experiments. The effect of cutting would have been to prolong the life of these monocarpic plants, so any impact is unlikely to have been significant.

Root cutting is an efficient mechanical means of control when initiated early, that is when *H. sosnowskyi* plants are up to 5 years old. At this age, the effective depth of root cutting is 15 cm. When *H. sosnowskyi* is younger, root cutting is effective at 10 cm below the ground. Both treatments provide 100% control of *H. sosnowskyi* plants during one vegetative season. The three applications of a mixture of herbicides comprising glyphosate and flazasulfuron applied three times over 5 years is the most effective chemical solution, ensuring 100% control of *H. sosnowskyi*. Moreover, spraying three times during one season prevents the flowering of *H. sosnowskyi*.

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