Advances in Weed Science
formerly Planta Daninha

RESEARCH ARTICLE

Comparison of cutting and hot water treatment and glyphosate applications on the control of giant hogweed

Kristian Nikolai Jæger Hansen[a], Benedikte Watne Oliver[b], Zahra Bitarafan[c], Inger Sundheim Fløistad[d], Christian Andreasen[c,e*], Lars Olav Brandsæter[c,f]

[a] Department of Agroecology, Aarhus University, Tjele, Denmark; Norwegian Centre for Organic Agriculture, Tingvoll, Norway; Department of Plant Sciences, Faculty of Biosciences, Norwegian University of Life Sciences, Ås, Norway. [b] Norwegian Public Roads Administration, Lillehammer, Norway; Department of Plant Sciences, Faculty of Biosciences, Norwegian University of Life Sciences, Ås, Norway. [c] Division of Biotechnology and Plant Health, Norwegian Institute of Bioeconomy Research, Ås, Norway. [d] Division of Forestry and Forest Resources, Norwegian Institute of Bioeconomy Research, Ås, Norway. [e] Department of Plant and Environmental Sciences, University of Copenhagen, Taastrup, Denmark. [f] Department of Plant Sciences, Faculty of Biosciences, Norwegian University of Life Sciences, Ås, Norway.

Abstract: Background: Giant hogweed (*Heracleum mantegazzianum* Sommier and Levier) is a perennial herbaceous plant that can grow to a height of 2–5 m. A single flowering plant can produce more than 20,000 seeds. It is one of Europe's most widespread and problematic invasive alien species and a severe threat to native biodiversity. Glyphosate is widely used to control *H. mantegazzianum*. Decades of intensive herbicide spraying have led to environmental pollution, prompting a need to explore new methods to supplement or replace glyphosate. **Objective:** Non-chemical methods to control *H. mantegazzianum* were tested and compared with glyphosate application. **Methods:** In two infested locations in southeast Norway, we compared the efficacy of glyphosate applications with a combination of mechanical cutting of the flowering stem of *H. mantegazzianum* and hot water treatment (80 °C). Hot water or glyphosate was supplied by foliar application or injection into the root crown. **Results:** The best method to reduce cover and the number of *H. mantegazzianum* rosettes and seedlings was achieved with two foliar applications of glyphosate. Cutting the flowering stem and injecting hot water into the root crown was almost as efficient as glyphosate application. Cutting and foliar applications of hot water had the weakest efficacy. Despite the best control and significant growth of grasses after glyphosate treatment, relatively high percentage of bare soil remained in the plots afterwards, increasing the risk of erosion. **Conclusions:** Cutting and injection of hot water in the root crown may be a viable alternative to glyphosate application in areas where herbicides are undesirable.

Keywords: Alternative weed management; Global invaders; Invasive weeds; Non-chemical weed control

Journal Information:
ISSN - 2675-9462
Website: http://awsjournal.org
Journal of the Brazilian Weed Science Society

How to cite: Hansen KNJ, Oliver BW, Bitarafan Z, Fløistad IS, Andreasen C, Brandsæter LO. Comparison of cutting and hot water treatment and glyphosate applications on the control of giant hogweed. Adv Weed Sci 2025;43:e020250026.
https://doi.org/10.51694/AdvWeedSci/2025;43:00026

Approved by:
Editor in Chief: Carlos Eduardo Schaedler
Associate Editor: Ali Ahsan Bajwa

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Received: April 2, 2025
Approved: July 25, 2025

* Corresponding author:
<can@plen.ku.dk>

1. Introduction

Giant hogweed (*Heracleum mantegazzianum* Sommier and Levier) is one of Europe's most widespread and problematic invasive alien plants. Its invasion displaces native plant species at multiple spatial scales within human-disturbed sites with relatively weak competition from other plants (Williamson, Forbes, 1982; Pyšek, Pyšek, 1995). The plant poses a threat to the natural ecosystems (Page et al., 2006). It is a monocarpic perennial species. Typically, it flowers in the 3rd or 4th year, but sometimes it occurs as a biennial or becomes even older than four years (Pergl et al., 2006). Aboveground plant parts die back to the taproot annually in autumn until the year it flowers. After flowering, the whole plant starts senescence and dies (Page et al., 2006). It can harbour agricultural pests and pathogens and cause erosion of riparian areas when populations are senescent and leave behind bare soil (Page et al., 2006). Plants also pose a significant health risk to humans due to the widespread occurrence of within tissue furanocoumarins that can induce severe chemical burns upon contact with the skin and subsequent exposure to ultraviolet light (Rzymski et al., 2015; Page et al., 2006).

Heracleum mantegazzianum is native to the Caucasus region of Southwest Asia and is widely distributed in Europe and North America through intentional or accidental human introduction (Page et al., 2006). In Europe, it has rapidly established in a variety of semi-natural ecosystems, particularly floodplains, riparian zones, forest edges, roadsides, meadows, open forests, and unmanaged urban areas. Although it grows in various climatic conditions, *H. mantegazzianum* is invasive primarily in regions with cool and moist climates, such as its native habitat (Page et al., 2006). The Norwegian Biodiversity Information Centre classified *H. mantegazzianum* as "a species with severe impact", assigning it the highest threat score against the biodiversity in Norway (Norwegian Biodiversity Information Centre, 2018). This species is also regulated through the legislation for alien species, which prohibits importing, planting, and spreading of plant material of *H. mantegazzianum*. The species is mainly registered in the southern to mid-part of Norway, but lower densities are also reported in the northern part.

Various control measures are available for *H. mantegazzianum,* with the most efficacious strategy depending on the habitat and landscape in which the population occurs, as well as the plants' population size and growth stage. Studies indicate that *H. mantegazzianum* is sensitive to most commercial herbicides, including glyphosate, imazapyr, triclopyr, dicamba, 2,4-D, and clopyralid. Treatment typically needs to be repeated annually, and, in some cases, even in the same growing season. Glyphosate is widely used, even in countries where its general use has been restricted (Lundström, Darby, 1994; Buttenschøn, 2003).

Non-chemical means have been used to control *H. mantegazzianum,* including root cutting, mowing, severing the flowering stem or umbels, grazing, trampling, and soil tilling. Severing the roots 8–12 cm below the soil surface is usually very effective in killing the plant (Andersen, Calov, 1996; Tiley et al., 1996; Buttenschøn, 2003). Hand pulling of very young plants can also be efficient. Mowing or scything should be repeated several times during the growing season to be effective, but even a single spring cutting can reduce the number and size of seeds (Tiley et al., 1996). Removal of umbels during early flowering stages can result in a considerable reduction in seed production. Still, new umbels may be established from lower branches, usually with fewer flowers and less viable seeds (Pyšek et al., 1998). Grazing and tramping, especially by black sheep, which are not sensitive to the combination of light and furanocoumarins uptake, can also be efficient (Page et al., 2006). Tilling is reported to be effective in controlling infestations on agricultural land (Tiley et al., 1996). After stem cutting, application of pyrolysis liquid has been compared to the application of plastic PE-mulch, biobased Ökolys® mulch, and glyphosate in a five-year field study (Hyvönen et al., 2023). The results showed that pyrolysis liquid mulch does not control the growth or reproduction of mature *H. mantegazzianum* plants effectively in contrast to the effect of other mulching materials and glyphosate.

Thermal control of *H. mantegazzianum* using the hot water equipment Waipuna System has been suggested as an efficient control method (Sanh, 2003). Thermal weed control methods, such as hot water and flaming, can be crucial in managing weeds on organic farms and in urban areas where use of herbicides is not recommended or prohibited. Thermal weed control transfers heat to plant material, destroying cells and degrading proteins within them. Several factors influence the heat injury of plants, including temperature, duration, weed species, and the plant´s developmental stage. Most thermal methods affect the aboveground parts of the plants. However, some weeds (i.e., perennials) may regrow from their belowground organs. The regrowth of aboveground vegetative tissues is a crucial indicator for validating the effectiveness of a weed control technique and determining the frequency of application required to eliminate the weed (Rask et al., 2013).

Results from several studies demonstrated the susceptibility of *H. mantegazzianum* to glyphosate (e.g., Tiley, Philp, 1997). However, there is a growing interest in alternative approaches, as the European Commission aim, to reduce the use and risk of chemicals and more hazardous pesticides in the EU by 50% by 2030 (Silva et al., 2022). On the other hand, non-chemical methods can be inefficient and costly, leading to the perception that they are less cost-effective than herbicides. Thermal weed control by hot water has been extensively studied. Unfortunately, performance varies, and thermal methods are expensive, requiring high energy input. The method requires further development before it can be considered a viable substitute for glyphosate, but some preliminary results are promising.

This study aims to evaluate the efficacy of combining cutting and hot water to control *H. mantegazzianum*. Two hot water application methods (foliar application and root crown injection) were compared with glyphosate application. A second aim was to evaluate the effect of the treatments on the surrounding vegetation. We hypothesise that it would be possible to achieve the same control efficacy using mechanical cutting and hot water treatment as with glyphosate.

2. Materials and Methods

2.1 Experimental sites

Two identical experiments were conducted in 2016. One in Moss (59.46°N, 10.68°E) and one in Hobøl (59.55°N, 10.78°E) in Southeast Norway. Both places were semi-natural habitats (ruderal and in the forest fringes) with *H. mantegazzianum* plants at different developmental stages. In Moss, the soil consisted of residues from marine depositions on the bedrock, and in Hobøl, the plants were growing in a shallow humus layer on the bedrock. The bedrock in both experimental sites mainly consisted of granite gneiss (Geological Survey of Norway, 2024).

At the experimental sites, most *H. mantegazzianum* plants were at the rosette stage. The *H. mantegazzianum* rosettes covered on average 38% of the plots. Seedlings covered about 10% of the vegetation. The average height of the *H. mantegazzianum rosettes* was 13 cm.

2.2 Experimental design

The experiments employed a randomized block design with four replications and a 2×2 m^2 plot size. The treatments were: T1) control (untreated plots), T2) cutting off the main stem of the plants (flowering stem) and foliar application of hot water. The stem was cut at the soil surface between the two hot water applications, T3) foliar application of glyphosate on the whole plot (flowering stem not cut), T4) cutting off the main stem of plants at the soil surface and root crown injection of hot water. The stem was cut at the soil surface between the two hot water applications and T5) stem injection of glyphosate just above the root crown (flowering stem not cut). Hot water and glyphosate were applied up to two times during the growing season in each treatment. Table 1 shows the application times at each experimental site.

Hot water was applied using a hot water weed control machine (Heatweed Mid 22/8, Heatweed Technologies AS, Norway) with a weed lance (16 cm) for foliar spraying (Oliver et al., 2020) and a weed spear with four holes at the tip for injecting (Figure 1a). The Heatweed employs diesel burners to heat water to approximately 99 °C. The system

Table 1 - Treatments and the application time at the two locations Hobøl and Moss. Treatments: T1) control (untreated plots), T2) cutting the main (flowering) stem of the plants at the soil surface and foliar application of hot water, T3) foliar application of glyphosate, T4) cutting of the main stem of plants at the soil surface and root crown injection of hot water, and T5) stem injection of glyphosate just above the root crown

	[1]Assessment time A		Application time 1		Application time 2		Assessment time B		Application time 3		Assessment time C	
Treatment	Hobøl	Moss	Hobøl	Moss	Hobøl	Moss	Hobøl	Moss	Hobøl	Moss	Hobøl	Moss
T1: Control	May 9th	May 2nd	-	-	-	-	June 22nd	June 27th	-	-	Sept. 1st	Sept. 2nd
T2: Foliar-hot water	May 9th	May 2nd	May 10th	May 2nd	[2]May 23rd	[2]May 27th	June 22nd	June 27th	July 7th	July 7th	Sept. 1st	Sept. 2nd
T3: Foliar-herbicide	May 9th	May 2nd	May 10th	May 2nd	-	-	June 22nd	June 27th	July 7th	July 7th	Sept. 1st	Sept. 2nd
T4: Injection-hot water	May 9th	May 2nd	May 10th	May 6th	[2]May 23rd	[2]May 27th	June 22nd	June 27th	- [3]	- [3]	Sept. 1st	Sept. 2nd
T5: Injection-herbicide	May 9th	May 2nd	May 27th	May 23rd	-	-	June 22nd	June 27th	July 21st	July 25th	Sept. 1st	Sept. 2nd

[1] Assessments used as covariates. [2] Cutting the main (flowering) stem at the soil surface before the second hot water application. [3] Treatment was not conducted due to the low regrowth rate.

features automatic temperature control, maintaining a stable temperature and ensuring consistency. The Heatweed machine can be mounted on various carriers for transportation to infested sites. One litre of hot water (≥ 80 °C) was used per living plant for both foliar and injection applications. Glyphosate was applied at the maximum authorized rate for foliar spraying in Norway (0.36 g a.i. m^{-2}, Roundup Eco, Bayer Agriculture BVBA, Antwerp, Belgium). For the glyphosate treatments, the *H. mantegazzianum* plants were injected or foliar-sprayed with the same dose. For foliar spraying, we used a back sprayer with a single nozzle. The volume of glyphosate was 10 ml per plant when injected. Thus, the volume of applied glyphosate and hot water per plot was dependent on plant frequency at each specific plot. Root injections of glyphosate were given by injecting the root crown in all plants with a stem with a diameter ≥ 5 mm using the JK1000 injection tool (JK International LLC, Washington, USA) (Figure 1b). Plants with a stem diameter of ≤ 5mm were not treated. The injection depth of treated plants was 1–2 cm. Stem injection delivers herbicide directly into the hollow cane of the plant. Stem injection of glyphosate is not approved in Norway; however, the method was used in the research plots in agreement with the Norwegian Food Safety Authority (https://www.mattilsynet.no/en).

2.3 Assessments

The height (cm) of *H. mantegazzianum* plants with a stem with a diameter ≥ 5 mm, the number of rosettes, and the area of bare soil in the plots (%) were recorded. The coverage of *H. mantegazzianum* seedlings and rosettes, monocotyledons species, dicotyledons forbs (except woody species), and woody plants (all vascular plants producing a stem with lignin during their life cycle) were assessed three times: A) before the experiment (as covariates), B) after the second treatment, and C) after the third treatment (Table 1). The assessment was based on visual estimations for each plot. The application timing was conducted after *H. mantegazzianum* had started leaf development of the main shoot (BBCH 1; Hess et al., 1997).

2.4 Weather data

Weather data were collected from the weather stations in Ås (59.66°N, 10.78°E) and Rygge (59.40°N, 10.75°E) which are close to the experimental sites of Hobøl and Moss. During the experiment, the monthly mean air temperature was generally higher in Hobøl and Moss than the average temperature during 1991–2020. There was no significant difference between the locations. The mean soil temperatures were higher, except for a relatively lower mean soil temperature in July in Moss. The precipitation deviated slightly from the average values in the region. However, there was no difference between the two experimental sites except for higher rainfall in August in Moss. Thus, the effect of climatic conditions is not further discussed in terms of treatment efficiency.

2.5 Statistical analysis

The statistical software Minitab 18 (Minitab LLC, 2021) was used to analyze the data using a linear mixed model, considering location as a random effect with the Kenward-Roger method for computing the denominator degrees of freedom for the tests of fixed effects. The significant limit used was $p = 0.05$. For significant fixed effects, Tukey's multiple comparison method was used to group the levels.

The response variables were the height of *H. mantegazzianum* plants (cm), the number of rosettes, the coverage of seedlings and rosettes (%), and the coverage of bare soil, grasses, forbs, and woody plants (%). The fixed factors were: 1. The five treatments, 2. The assessment times (B and C), and 3. The interaction between the treatments and the assessment times. For each response variable, the value was observed at time B and C. Observations at time A were used as covariates. The random factors were location, block within location, and plot within block and location. All random factors were assumed

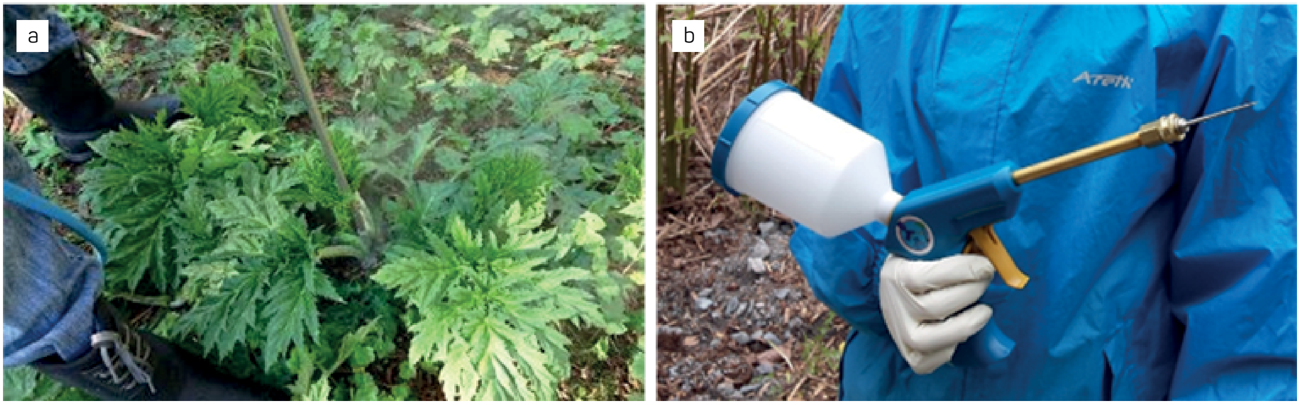

Figure 1 - a) Root crown injection of hot water using a hot water weed control machine (Heatweed Mid 22/8, Heatweed Technologies AS, Norway) with a weed spear with four holes at the tip for injecting, b) JK1000 injection tool (JK International LLC, Washington, USA) used for root crown injection of glyphosate.

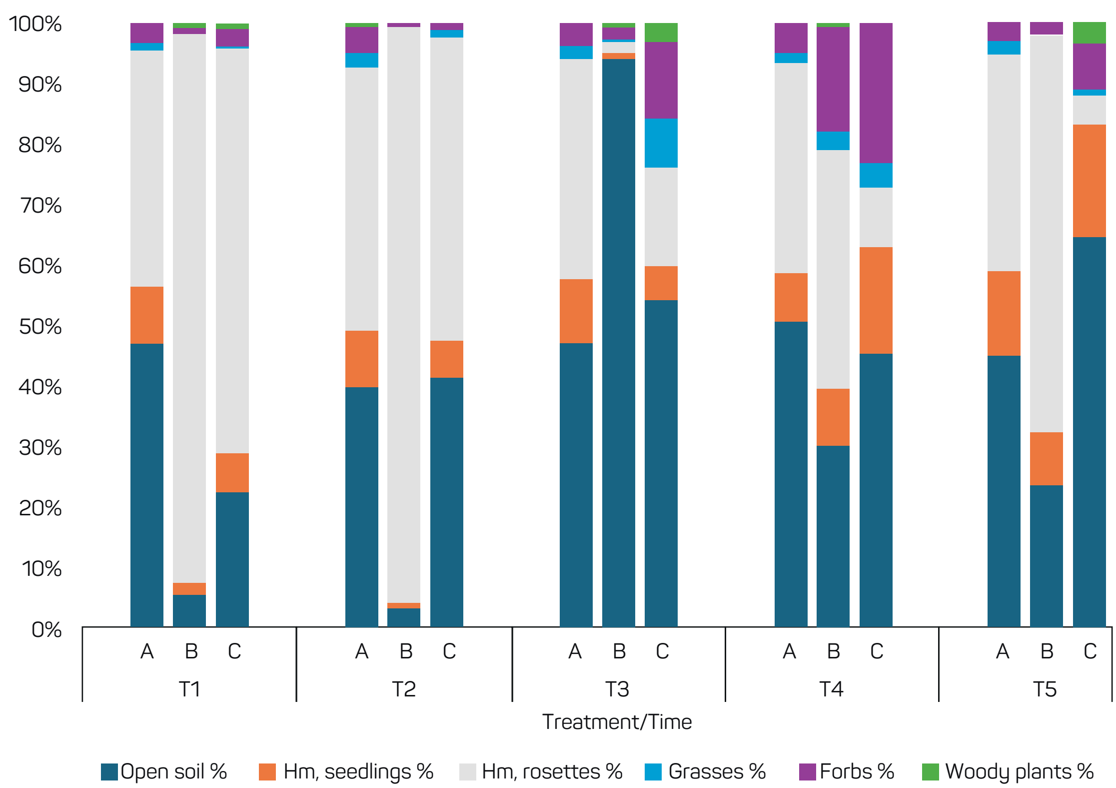

Figure 2 - Mean values of cover of *Heracleum mantegazzianum* seedlings and rosettes, grasses, forbs, woody plants, and bare soil (%). All data were collected from the two sites in Hobøl and Moss at assessment times A (May), B (June), and C (September) (Table 1). The data are shown for all treatments: T1 (Control) T2 (foliar - hot water), T3 (foliar - herbicide), T4 (injection - hot water), and T5 (injection - herbicide) (Table 1)

to be independent and normally distributed random variables with an expected value of zero and their respective variances. The interaction between location and treatment was also analysed. The residuals of the response variables were normally distributed. It was also tested to see if transformed response variables would yield a different impact. However, the results were nearly equal to those of the untransformed variables. Thus, only the untransformed response variables were used.

3. Results and Discussion

The treated plots were 2 m x 2 m, If the plots were covered with large plants, i.e. if the plants were in the reproductive stage or forming large rosettes they might have been too small. However, in the current locations, the main proportion of plants were seedlings and rosettes in their second year of growth, and, therefore, the plot size was considered appropriate.

There was no interaction between location and treatment for the measured variables. Figures 2 and 3 show the mean values of coverage (%) of *H. mantegazzianum* seedlings, rosettes, grasses, forbs, woody plants, and bare soil at times A (May), B (June), and C (September). The rosette coverage significantly increased from time A to B but decreased at time C for all treatments except T3 (foliar glyphosate application). In contrast, the grass coverage decreased from time A to B but increased at time C for all treatments except for T4 (cutting + root injection of hot water), for which grass cover seems to increase in both intervals. The bare soil coverage decreased from A to B but increased to time C for all treatments except for T3 (Figure 2).

At time C, both coverage and the number of *H. mantegazzianum* rosettes were reduced for all treatments compared to the controls. However, there was no significant difference between the controls and the cutting and foliar application of hot water (T2). Foliar application of glyphosate (T3), cutting + root injection of hot water (T4), and stem injection of glyphosate (T5) showed the same effect (Tables 3 and 4). Treatment T3, T4, and T5 showed 87%, 77% and 62% reductions in rosettes compared to the controls, respectively. Treatment T3, T4, and T5 showed 85%, 63%, and 47% reductions in coverage of rosettes, respectively, compared to the controls. The two injection treatments (T4 and T5) resulted in the highest coverage of *H. mantegazzianum* seedlings, as the seedlings were not exposed to injections; however, they did not show significantly differential from the controls (Table 3). Hence, new plants may quickly be established after the treatment.

The coverage of bare soil increased after all treatments, though there was no significant difference between the controls and the cutting + foliar application of hot water (T2). Foliar application of glyphosate (T3) resulted in the largest area with bare soil and was the only treatment that increased the grass coverage. Cutting + root injection of hot water (T4) Significantly increased the coverage of forbs. No significant changes were recorded for the coverage of woody plants and *H. mantegazzianum* plant height (Figures 2 and 3; Tables 2 and 3).

Foliar application of glyphosate was more efficient than stem injection. Grguric (2018) reported 90% control or more when glyphosate was injected into the stem in the generative stage at doses of 0.9, 2.7, and 5.4 g glyphosate m^{-2}, which are higher doses than we used. In our experiments, foliar glyphosate application reduced the number and coverage of rosettes and seedlings most. Cutting + root injection of hot water (T4) resulted in almost the same control as the glyphosate treatments. It should be emphasised that root injection with hot water was only applied once due to the high mortality rate of matured plants.

The root injection of hot water could have been repeated if the experiment had allowed enough time to achieve the same efficiency as glyphosate. Thermal weed control only has a local effect in contrast to glyphosate, which is a systemic herbicide. Therefore, it is often necessary to repeat the treatment during the growing season (Antipina, Maganov, 2018). Cutting + foliar application of hot water on leaves (T2) was the weakest method. This method may produce excess hot water, which could have an impact on other organisms, such as insects and soil fauna.

Cutting + root injection of hot water (T4) may be an alternative to glyphosate due to the overall efficacy. However, the cons include an increasing workload, higher costs, and increased energy consumption.

It should be noted that foliar hot water treatment was applied twice in this study, and further applications may show a better effect. Oliver et al. (2020) also used cutting and hot water to control *Impatiens glandulifera* Royle and calculated the workload to be 2.1 min m^{-2} for small plants and

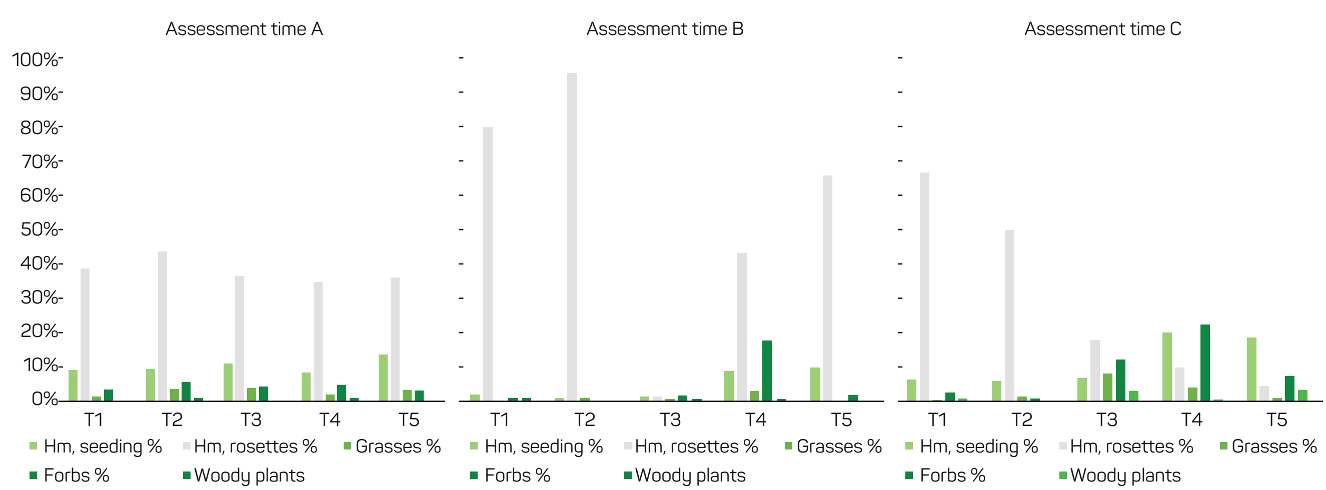

Figure 3 - Mean values of cover of *Heracleum mantegazzianum* seedlings and rosettes, grasses, forbs, woody plants. All data were collected from the two sites in Hobøl and Moss at assessment times A (May), B (June), and C (September) (Table 1). The data are shown for all treatments: T1 (Control) T2 (foliar - hot water), T3 (foliar - herbicide), T4 (injection - hot water), and T5 (injection - herbicide) (Table 1)

Table 2 - ANOVA table with *p*-values for the different assessments. Treatment to control the species *Heracleum mantegazzianum*: T1 (Control) T2 (foliar - hot water), T3 (foliar - herbicide), T4 (injection - hot water), and T5 (injection - herbicide) (Table 1)

Fixed factors	Response variables							
			Coverage (%)					
	H. mantegazzianum				Other species			
	Number of rosettes m^{-2}	Plant height (cm)	Seedlings	Rosettes	Grasses	Forbs	Woody plants	Open soil
Start (covariate)	0.026	0.777	0.034	0.636	< 0.001	0.086	0.469	0.477
Time	< 0.001	< 0.001	0.004	< 0.001	0.007	0.019	0.002	0.002
Treatment	< 0.001	0.258	0.003	< 0.001	< 0.001	0.006	0.382	< 0.001
Time*Treatment	0.211	< 0.001	0.775	0.002	0.002	0.573	0.407	< 0.001

Significant at $p < 0.05$. The density of *H. mantegazzianum* before initiating the experiment was included as a covariate

Table 3 - Effect of the treatments on *Heracleum mantegazzianum* and other species at time C (September). Mean number of *H. mantegazzianum* plants m^{-2} and coverage (%) averaged over sites after Tukey's test. Treatments T1–T5: T1 (Control) T2 (foliar - hot water), T3 (foliar - herbicide), T4 (injection - hot water), and T5 (injection - herbicide) (Table 1)

Treatment	Response variables							
			Coverage (%)					
	H. mantegazzianum				Other species			
	Number of rosettes m^{-2}	Plant height (cm)	Seedlings	Rosettes	Grasses	Forbs	Woody plants	Bare soil
T1: Control	17.0 A	99.3 A	4.8 AB	73.5 A	2.2 BC	2.9 B	1.4 A	13.3 D
T2: Foliar-hot water	10.3 AB	66.4 A	4.0 B	72.3 A	1.2 C	0.2 B	2.2 A	23.2 CD
T3: Foliar-herbicide	2.2 C	36.3 A	3.9 B	11.0 C	7.8 A	7.0 AB	3.8 A	74.0 A
T4: Injection-hot water	3.8 BC	37.6 A	16.8 A	26.9 BC	6.7 AB	20.7 A	1.5 A	35.2 BC
T5: Injection-herbicide	6.4 BC	143.3 A	14.1 AB	38.4 B	0.7 C	6.1 AB	2.4 A	43.9 B

Values with the same letters are not significantly different at the 5% level

4.8 min m^{-2} for large plants. We did not record the workload but experienced that more time was needed to control larger *H. mantegazzianum* plants. Time consumption of treatments is crucial for the practical application of the treatment. The treatment using hot water is more work-intensive than foliar application of glyphosate. However, the differences in terms of cost between the various applications need to be further assessed. Plants should be treated at the early developmental stages to reduce time and energy consumption. The higher energy consumption may be acceptable to avoid the negative environmental impact of glyphosate close to water, where *H. mantegazzianum* thrives (Tresnakova et al., 2021). The injection method for hot water and glyphosate may pose less risk to soil and aquatic organisms (and native vegetation than foliar application, but the method is not appropriate to control *H. mantegazzianum* seedlings. Unfortunately, stem injection of glyphosate is not yet approved as a management method in Norway.

The lack of significant differences between the foliar application of hot water (T2) and the controls (T1) may show a need for more treatments during the growing season. The necessity of repeated hot water treatments has been emphasised in several studies. Antipina and Maganov (2018) reported that the foliar application of hot water eradicated all *Heracleum sosnowskyi* Manden plants when hot water was applied once a week to 3–4-year plants from the end of April to the start of June. They found a similar effect of repeated hot water treatment on seedlings.

The emergence and growth of native species after controlling *H. mantegazzianum* is essential to suppressing and outcompeting new emerging *H. mantegazzianum* seedlings (Pergl et al., 2007). The highest coverage of grasses was found in the plots where glyphosate was applied on leaves (T3), but a high grass coverage was also established in plots where hot water was injected into the roots (T4). The highest coverage of forbs was found in plots with hot water injection into the roots (T4). The reduced number and coverage of *H. mantegazzianum* rosettes resulted in increased competition from the grasses and forbs. The lack of native vegetation can be a problem if there are extensive areas with bare soil, which can result in soil erosion after weed control, for example, along riverbanks. Bare soil also allows *H. mantegazzianum* to re-establish from the soil seed bank similar to native plant species, if no additional management strategies are implemented.

There was a relatively high coverage of bare soil in plots treated with foliar-applied glyphosate, resulting from the best control of *H. mantegazzianum* rosettes. Glyphosate, or the decomposition of glyphosate, does not affect the seeds in the soil (Wang et al., 2016). Hot water may, however, thermally harm or kill the seeds depending on how fast the temperature drops before the water reaches the seeds in the soil. To prevent re-establishment from the seed bank, additional management methods should be applied. These strategies may include monitoring the site, planting at high density, and follow-up spot treatment if seedlings of *H. mantegazzianum* re-establish. The experiment does not address the long-term effects of the suppresion of *H. mantegazzianum*.

Heracleum mantegazzianum posseses many features that contributed to it successful as an invasive alien species enable it to survive and compete under a wide range of geographical and climatic conditions. The habitat of *H. mantegazzianum* often has running water, making herbicide spraying particularly problematic. The use of herbicides can also be problematic from a wider environmental and health perspective (Kudsk, Streibig, 2003). The need for alternative methods to manage the species is therefore in demand. However, the compared methods in the current study do not consider the overall climatic or environmental impact of the different treatments. There are likely trade-offs in climatic and environmental impact between heating hot water and the use of herbicides. A high control level was achieved with a cutting and a single hot water root crown injection. This method may be a part of an integrated management program where combinations of methods are used. Plants should be treated when they are in an early stage of development to reduce energy consumption, amount of hot water, and labour power (Hansson, Ascard, 2002). Cutting the aboveground biomass can be done before or in between the hot water injection treatments to ease access to the plants. The long-term effects of *H. mantegazzianum* control technigues and the re-infestation of native vegetation should be a research focus area in the future.

Root cutting can also be an efficient method for controlling *H. mantegazzianum,* although the depth of cutting plays a crucial role. Tiley and Philp (1997) found that cutting the taproot at 15 cm below ground level prevented further regrowth and effectively killed the plant, while cutting at 5 cm below ground level (through stem tissue above the hypocotyl region) or at ground level resulted in weakened growth and flower. Root cutting of a large, infested area may be laborious and hard work depending on the conditions (e.g., soil type and moisture), thus mainly suitable for single plants and small stands. However, it could be a good alternative to the methods tested in this study under certain conditions. Management of *H. mantegazzianum* should be conducted with consideration for operator safety. The stem injection treatments require closer contact with the treated plants than foliar application of glyphosate or hot water. Therefore, extra consideration should be given to operator safety.

4. Conclusions

In areas where herbicide spraying is prohibited or unwanted, alternative methods are necessary to control the invasive perennial weed giant hogweed (*Heracleum mantegazzianum)*. Cutting the flowering stem to prevent the seed setting of giant hogweed combined with hot water treatment at the root-crown (T4) controlled plants almost as well as glyphosate applications.

Cutting the flowering stem of the plants at the soil surface combined with applying hot water to all remaining leaves (T2), did not significantly reduce the number and coverage of rosettes, nor the coverage of seedlings of *H. mantegazzianum,* compared to the untreated plots. It should be tested whether repeating the treatment more than three times could be effective.

Repeating applications during the growing season was essential to achieve a significant effect from all the methods tested, as new plants were continuously established from the soil seed bank. The impact of the different treatments on the flora in the experimental plot varied greatly over the season, showing a significant interaction between treatment and application timing in most cases, except for the number of seedlings and the coverage of forbs.

Author's contributions

All authors read and agreed to the published version of the manuscript. ISF and LOB: conceptualization of the manuscript and development of the methodology. BWO and KNJH: data collection and curation. KNJH: data analysis. KNJH, and ZB: data interpretation. ISF and LOB: funding acquisition and resources. ISF and LOB: project administration. ISF, LOB and ZB: supervision. KNJH, ZB, and CA: writing the original draft of the manuscript. ZB and CA: writing, review and editing.

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation. Please contact KJNH.

Acknowledgements

We acknowledge Samuel Beyene Habte and Sophie Van Meteren for the practical implementation and Torfinn Torp for helping with the statistical analyses.

Funding

This work was done as a part of the projects 1) “Effective and sustainable control of alien invasive plants in the county

Østfold" financed by the Regional Research Fund Oslofjord (RFF-Oslofjord), Grant Number 245824, and 2) Integrated approach to ecosystems protection against invasive alien plants in southern Poland (IAS/EcoSystemCARE) implemented under the program "Environment, Energy and Climate Change", co-financed by EEA Financial Mechanism 2014–2021 for the action aimed at "Increasing the protection of ecosystems against invasive alien species", the national funding from Poland and with the financial contribution of project Partners in Poland, The University of Silesia in Katowice, The University of Agriculture in Kraków, The Institute of Technology and Life Sciences - State Research Institute, The Magura National Park, The National Research Institute of Animal Production - State Research Institute, the Institute of Nature Conservation, Polish Academy of Sciences and the Norwegian project Partner, Norwegian Institute of Bioeconomy Research, Grant Number MFEOG.07.02.02-50-0032/21-00.

References

Andersen UV, Calov B. Long-term effects of sheep grazing on giant hogweed *(Heracleum mantegazzianum)*. In: Caffrey JM, Barrett PRF, Murphy KJ, Wade PM, editors. Management and ecology of freshwater plants: proceedings of the 9th International Symposium on Aquatic Weeds. Doorwerth: European Weed Research Society; 1996. p. 277-84. Available from: https://doi.org/10.1007/978-94-011-5782-7_44

Antipina GS, Maganov IA. [Thermal treatment as a method of controlling *Heracleum sosnowskyi*]. Hort Bot. 2018;13:1-13. Russian. Available from: https://doi.org/10.15393/j4.art.2018.5122

Buttenschøn RM. Experiences from management of giant hogweed (*Heracleum mantegazzianum*) in Denmark and results from a pilot study on nonchemical control methods. Botanical Electronic News. Nov 21, 2003[access Sept 1, 2022]. Available from: https://www.ou.edu/cas/botany-micro/ben/ben316.htm

Geological Survey of Norway. [Bedrock: national bedrock database]. Trondheim: Geological Survey of Norway; 2024[access Feb 19, 2024]. Norwegian. Available from: https://geo.ngu.no/kart/berggrunn_mobil

Grguric M. Evaluation of chemical and physical control methods for the control of giant hogweed (*Heracleum mantegazzianum* Sommier and Levier) [thesis]. Guelph: The University of Guelph; 2018.

Hansson D, Ascard J. Influence of developmental stage and time of assessment on hot water weed control. Weed Res. 2002;42(4):307-16, Available from: https://doi.org/10.1046/j.1365-3180.2002.00290.x

Hess M, Barralis G, Bleiholder H, Buhr L, Eggers T, Hack H et al. Use of the extended BBCH scale: general for the descriptions of the growth stages of mono; and dicotyledonous weed species. Weed Res. 1997;37(6):433-41. Available from: https://doi.org/10.1046/j.1365-3180.1997.d01-70.x

Hyvönen TT, Hagner MM, Hurme TK, Lindqvist BE, Ojanen HJ. Control of *Heracleum mantegazzianum* with pyrolysis liquid products. Weed Res. 2023;63(5):311-6. Available from: https://doi.org/10.1111/wre.12593

Kudsk P, Streibig JC. Herbicides: a two-edged sword. Weed Res. 2003;43(2):90–102. Available from: https://doi.org/10.1046/j.1365-3180.2003.00328.x

Lundström H, Darby E. The *Heracleum mantegazzianum* (Giant Hogweed) problem in Sweden: suggestions for management and control. In: de Waal LC, Child LE, Wade PM, Brock JH, editors. Ecology and management of invasive riverside plants. Chichester: John Wiley and Sons; 1994. p. 93-100.

Minitab LLC. Home page. State College: Minitab LLC; 2021[access Feb 18, 2024]. Available from: https://www.minitab.com

Norwegian Biodiversity Information Centre – NBIC. The alien species list of Norway: ecological risk assessment 2018. Trondheim: Norwegian Biodiversity Information Centre; 2018[access Sept 04, 2024]. Available from: https://www.biodiversity.no/alien-species-2018

Oliver BW, Berge TW, Solhaug KA, Fløistad IS. Hot water and cutting for control of *Impatiens glandulifera*. Inv Plant Sci Manag. 2020;13(2):84-93, Available from: https://doi.org/10.1017/inp.2020.7

Page NA, Wall RE, Darbyshire SJ, Mulligan GA. The biology of invasive alien plants in Canada 4: *Heracleum mantegazzianum* Sommier and Levier. Can J Plant Sci. 2006;86(2):569-89. Available from: https://doi.org/10.4141/P05-158

Pergl J, Hüls J, Rerglová I, Eckstein R, Pyšek P, Otte A. Population dynamics of *Heracleum mantegazziaanum*. In: Pyšek P, Cock MJ, Nentwig, W, Ravn HP, editors. Ecology and Management of H. mantegazzianum (*Heracleum mantegazzianum*). Wallingford: CAB International; 2007. p. 92-111

Pergl J, Perglová I, Pyšek P, Dietz H. Population age structure and reproductive behavior of the monocarpic perennial *Heracleum mantegazzianum* (Apiaceae) in its native and invaded distribution ranges. Amer J Bot. 2006;93(7):1018-28. Available from: https://doi.org/10.3732/ajb.93.7.1018

Pyšek P, Kopecky M̌, Jarošík V, Kotkova P. The role of human density and climate in the spread of *Heracleum mantegazzianum* in the Central European landscape. Div Distr. 1998;4:9–16. Available from: https://doi.org/10.2307/2999808

Pyšek P, Pyšek A. Invasion by *Heracleum mantegazzianum* in different habitats in the Czech Republic. J Veg. Sci. 1995;6(5):711-8. Available from: https://doi.org/10.2307/3236442

Rask AM, Larsen SU, Andreasen C, Kristoffersen P. Determining treatment frequency for controlling weeds on traffic islands using chemical and non-chemical weed control. Weed Res. 2013;53:249-58. Available from: https://doi.org/10.1111/wre.12019

Rzymski P, Klimaszyk P, Poniedziałek B. Invasive giant hogweeds in Poland: risk of burns among forestry workers and plant distribution. Burns. 2015;41(8):1816-22. Available from: https://doi.org/10.1016/j.burns.2015.06.007

Sanh M. Waipuna and giant hogweed (*Heracleum mantegazzianum*). Botanical Electronic News. Nov 21, 2003[access July 2, 2022]. Available from: http://www.ou.edu/cas/botany-micro/ben/ben316.html

Silva V, Yang X, Fleskens L, Ritsema CJ, Geissen V. Environmental and human health at risk: scenarios to achieve the Farm to Fork 50% pesticide reduction goals. Environ Int. 2022;165:1-15. https://doi.org/10.1016/j.envint.2022.107296

Tiley GED, Dodd FS, Wadet PM. Biological flora of the British Isles. J Ecol. 1996;84(2):297-319. Available from: https://doi.org/10.2307/2261365

Tiley GED, Philp, B. Observations on flowering and seed production in *Heracleum mantegazzianum* in relation to control. In: Brock JH, Wade PM, Pys˘ek P, Green D, editors. Plant invasions: studies from North America and Europe. Leiden: Backhuys; 1997. p. 123-37

Tresnakova N, Stara A, Velisek J. Effects of glyphosate and its metabolite AMPA on aquatic organisms. Appl Sci. 2021;11(19):1-15. Available from: https://doi.org/10.3390/app11199004

Wang T, Ren J, Qu G, Liang D, Hu S. Glyphosate contaminated soil remediation by atmospheric pressure dielectric barrier discharge plasma and its residual toxicity evaluation. J Haz Mat. 2016;320:539-46. Available from: https://doi.org/10.1016/j.jhazmat.2016.08.067

Williamson JA, Forbes JC. Giant Hogweed (*Heracleum mantegazzianum*): its spread and control with glyphosate in amenity areas. In: British Crop Protection Council, editor. Proceedings of British Crop Protection Conference: Weeds; 1982. London: BCPC Publications, 1982. p. 967-72.