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Treatment of Japanese knotweed-infested soils by thermal desorption

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Title	Treatment of Japanese knotweed-infested soils by thermal desorption
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1. Introduction

Japanese knotweed (Fallopia japonica) is an alien plant species in Europe and North America, which means that it is not native to these continents. It originates from East Asia and was introduced as an ornamental and forage plant to Europe and North America in the 19^{th} century. After its introduction, it successfully established and spread itself, thereby outcompeting native species. In addition to harming biodiversity, it can damage human infrastructures such as roads, buildings and river dikes. It is currently listed by the International Union for Conservation of Nature (IUCN) as one of the 100 worst invasive alien species worldwide. Due to the many problems caused by Japanese knotweed, effective management is of great importance. Yet, because the plant species has an extensive and robust rhizome network, the plant is very resistant to management actions targeting the aboveground part of the plant, which makes eradication difficult. In addition, as the plant spreads vegetatively through rhizome and stem fragments, any cutting or mowing action inherently carries the risk of creating new spreading events.

Here, we investigate the feasibility of the Smart Burners™ technology, patented by HAEMERS Technologies, to eradicate Japanese knotweed. This technology is originally developed for thermal desorption, a soil remediation technique whereby contaminated soils are heated to physically separate the contaminants. In the management of Japanese knotweed, it targets the underground parts of the plant by heating affected soils. This document presents the results of a series of experiments to explore the potential of this new eradication method. First, a lab experiment was conducted to finetune the methodology and identify the optimal treatment temperature and period. Rhizomes were excavated and exposed to different temperatures over different periods in lab conditions. In the second ex situ experiment, soil with rhizomes was heated in a large container for one day to a temperature of 80°C. Finally, in the third experiment, an infested site was treated in situ, by heating the soil for three days to 50°C and 1 day at 80°C. After each experiment, treated and control rhizomes were planted in a greenhouse under optimal conditions and monitored for 30 days.

2. Japanese knotweed

2.1 General characteristics

Japanese knotweed belongs to the family of Polygonaceae and the genus Fallopia (Van Landuyt et al., 2006). In the 19th century, Japanese knotweed was brought to Europe from Asia as an ornamental and fodder plant, but it only became invasive in the 1950s. In its native range (Japan, Taiwan and Korea), it is a typical pioneer on volcanic soils, but can also be found along roadsides and ditches. In its introduced range, the knotweed mainly invades river banks as well as anthropogenic environments such as waste grounds, road and railway verges and gardens (Beerling et al., 1994). They like humid, nitrogen-rich grounds and are very fast-growing (Van Landuyt et al 2006). This species is a geophyte forming extensive rhizome networks, allowing the plant to survive belowground in unfavourable conditions and grow back aboveground when the ambient conditions are better. Adult plants can grow one to three meters in height above ground with sturdy, hollow stems that die off during winter (Van Landuyt et al., 2006). The green stems are surrounded by a membrane with red spots. The knotweed flowers from August until September. The flowers are small, cream-white and grow in clusters called racemes, where the flowers grow on short stalks of equal length along an elongated axis at equal distances (Beerling et al., 1994; Van Landuyt et al., 2006).

Figure 1. Japanese knotweed often be found along roadsides, railroads and waterways

2.2 Reproduction

Japanese knotweed largely reproduces via vegetative means. The plant can regenerate from small rhizome or stem fragments (Thoonen & Willems, 2018). These fragments spread via water or accidentally by mowing. The major flooding event in the summer of 2021 in Belgium caused a great increase in the dispersal of Japanese knotweed, especially in the south of Belgium (Van Olmen, 2021). The result of this vegetative reproduction is that there is low genetic diversity between plants. Especially in Europe, all Japanese knotweed plants have been found to be largely genetically identical and thus descend from a small source population (Bailey et al., 2009). The sexual reproduction of the plant is more complicated. Japanese knotweed is a dioecious plant, meaning that female and male flowers occur on different plants. In Europe, the male plant is sterile, which is why the plant mostly reproduces vegetatively. However, the female plant can be fertilized by the pollen of Giant knotweed (Fallopia sachalinensis) resulting in the hybrid plant Bohemian knotweed (Fallopia x bohemica). The pollen of the hybrid plant are also able to fertilize Japanese knotweed (Bailey 2009; Groeneveld et al 2014). The seeds spread via wind over short distances, 50 m more or less. Since the seeds are buoyant and the plants are often found near waterways, they can spread via the waterways as well and travel greater distances (Groeneveld et al., 2014). Researchers warn that sexual reproduction could gain importance in the future (Engler et al., 2011).

2.3 Impact

The plant species has a negative impact on native biodiversity because it outcompetes the original vegetation by forming tall and dense stands and blocking the majority of incoming sunlight. Another competitive advantage of Japanese knotweed is its dense horizontal network of rhizomes. Moreover, Japanese knotweed produces allopathic substances based on phenolic derivatives causing the necrosis of the neighbouring plants (Murrell et al., 2011). Besides its ecological impact, there are several other severe problems caused by Japanese knotweed. First, during winter, the aboveground vegetation dies off, exposing the bare soil to wind and water, which can cause severe erosion (Van Landuyt et al, 2006). Especially on river banks and dikes, this can cause instability where they settle thereby increasing the risk of flooding. Additionally, the plant is known to be able to penetrate layers of concrete when they find a small crack. As a result, they can even grow inside houses and constructions causing significant economic damage (Thoonen & Willems, 2018). Building land with this invasive species suffers a strong depreciation in value.

2.4 Management

Management of Japanese knotweed has been difficult until now, because of the species’ resistance to techniques used for other invasive species. The knotweed can grow from small pieces of stems or rhizomes, so mowing only accelerates the dissemination. This ability also complicates the eradication of the plant by excavation, as it is difficult to remove every little rhizome fragment. The use of herbicides like glyphosate can help to eradicate the plant, but this is only practically possible for small populations (Thoonen & Willems, 2018). Moreover, the use of such herbicides holds other risks like pollution of the soil and waterways nearby. The process takes at least two years and the results are not always consistent (Gover et al., 2007). Other techniques have been developed: deployment of an opaque tarp over the plants to restrict access to light, thermal weeding, biological control by insertion of herbivorous predators, etc. However, these techniques have not proven to be very effective due to the plant's ability to regenerate new plants from the developed rhizome system. New management methods are thus necessary to obtain successful eradication of the plant in a feasible way. Control by heat treatment has gained more interest these last years. Indeed, the underground parts of invasive plants are sensitive to high temperatures. It has been shown that 50°C could already be lethal for Japanese Knotweed rhizomes (Van Dijck et al., 2021). Thermal treatment appears to be an appropriate candidate for invasive plant regulation and eradication.

3. Thermal treatment

3.1 Workings of thermal desorption

Thermal desorption is a method of volatilizing and removing contaminants from soil and is commonly used to treat soils contaminated with chemical pollutants. The soil is heated to temperatures ranging from 50°C to 560°C depending on the vaporization temperature of the contaminant (Rodríguez et al., 2014). The volatilized contaminants are collected and removed. Depending on the type of soil, different heating techniques are used. Electrical resistance heating heats the soil directly using its resistance to electrical current. Another method, thermal conduction heating, utilizes conduction to heat the soil, using steel pipes filled with hot air (Figure 2). Finally, steam-enhanced extraction uses injected hot steam (Federal Remediation Technologies Roundtable, 2020).

3.2 Smart Burners™ Technology

In Haemers Technologies' process polluted soil is heated by conduction under the action of Smart burners (Belgium Patent No. BE1024596B1, 2016). More precisely, steel tubes are inserted into the soil to be remediated (Figure 2). Hot gases, generated by Smart Burners, circulate in the tubes in order to transfer heat to the soil. This results in the vaporisation of the pollutants in the soil when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapour tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours are then treated in a vapour treatment unit.

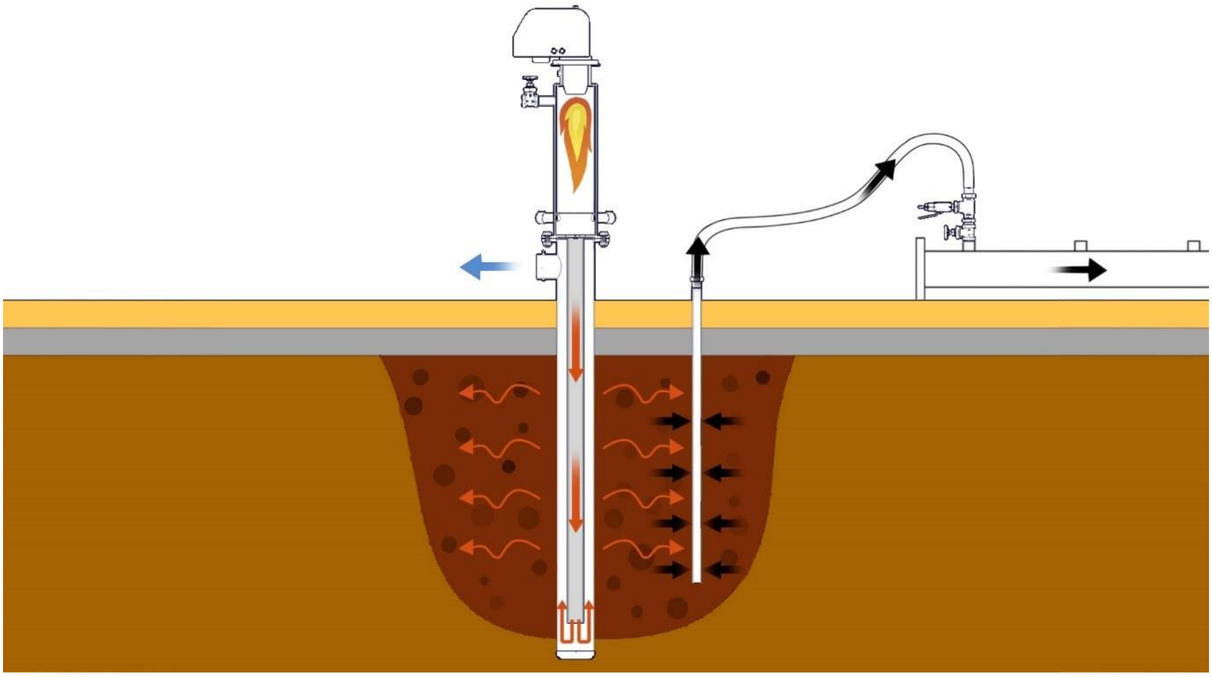


Figure 2. Schematic representation of the Smart Burners™ Technology of Haemers Technologies. Hot gases, generated by Smart Burners circulate in tubes, inserted in the soil, which heats up through conduction (red arrows). Due to the high temperature, contaminants in the soil volatilize and are captured and removed (back arrows).

4. Material and methods

4.1 Experiment 1: Lab experiment

Fallopia rhizomes were dug out in Leuven (50°51'55.0"N 4°40'22.4"E) on the 29th of March 2022. On this location, Japanese knotweed grows abundantly on the top of a south-facing slope, above a small tributary of the river 'Voer'. Root fragments were collected from the upper 30 cm of the soil and divided into three different size categories: thin (< 1 cm diameter), medium (1 – 1.5 cm) and thick (>1.5 cm). Next, the roots were put in an industrial oven in open aluminium containers (20 x 5.5 x 14 cm) together with soil from the invaded site. They were randomly exposed to 6 different heating treatments, consisting of a combination of two temperatures (50 and 80°C) and three treatment durations (1, 2 or 3 days). In total 120 roots were treated (Table 1). Roots that were not treated were taken as a control. All the roots (control and treatment) were subsequently planted in a greenhouse in planting pots with dimensions 37 x 41 x 8 cm (Figure 3). As Japanese knotweed optimally grows in moist to wet soils, they were watered every 2-3 days (depending on the weather). They grew under artificial lighting (20W, 2750 lumen) between 6 am and 10 pm. Sprouting of the roots was monitored for 30 days. Sprouted roots were removed. At the end of the monitoring periods, the remaining roots were removed from the soil and carefully checked for signs of life.

Figure 3. Top row: Greenhouse set up to monitor the vitality of the rhizomes, with clear sprouting of the control samples. Bottom row: Living rhizomes showing shoots

Table 1. Number of rhizome fragments for three size categories (thin (< 1 cm diameter), medium (1 – 1.5 cm) and thick (>1.5 cm)) in each of the warming treatments

	50°C			80°C		
Heating period	Thin	Medium	Thick	Thin	Medium	Thick
1 day	7	7	6	12	9	3
2 days	2	11	2	3	21	2
3 days	5	7	3	15	3	2

4.2 Experiment 2: Ex situ treatment

HAEMERS Technologies conducted an ex situ experiment in May and June 2022. This test was carried out in a 3 m³ container and aimed to treat soil contaminated with Japanese Knotweed by heating it to a target temperature of 80°C. This target was set based on the lab experiment conducted earlier in the season. Rhizomes were excavated in Wijnegem (51°14'09.4"N 4°30'16.9"E). A proportional sample was taken from three soil layers (0-30 cm, 30-60 cm and 60-90 cm). For the unheated control, roots from the different layers were planted separately in the greenhouse to be able to evaluate the relationship between rooting depth and the vitality of the roots. For the treatment, the roots of the three layers were mixed and transferred together with soil from the excavation site into a 3 m³ container (Figure 4). A new generation burner system was placed on top of the container. Hot gases were inserted in the soil via a vertical steel tube in the middle of the container. Since the Fallopia roots were to be treated here, no vapour extraction system was installed. Once the container was filled, the burner was switched on and the heat treatment started. The test started on the 30th of May 2022 at the end of the day and was stopped on the 7th of June in the morning after 7.5 days of treatment. To monitor the temperature in the soil continuously, three thermocouple tubes, containing three temperature sensors each (at 0.75 m; 1.5m; 2.25m deep) were placed at 15, 30 and 45 cm from the heating tube. According to the same protocol as the first experiment, 72 control rhizome fragments (length 20 cm) and 84 treated fragments (length between 10 to 20 cm) were planted and monitored in the greenhouse for 30 days (Table 2).

Table 2. In the second experiment, 156 rhizome fragments were planted in the greenhouse. The control fragments (each 20 cm in length) were homogeneously divided across the three thickness classes and three sampled soil depths. Roots from different depths were mixed before the treatment

	Thin (< 1 cm)	Medium (1 – 1.5 cm)	Thick (> 1.5 cm)
Control			
0-30 cm	8	8	8
30-60 cm	8	8	8
60-90 cm	8	8	8
Treatment	46	19	19

Figure 4. Left: The container for the ex situ experiment was filled with soil and Fallopia rhizomes. The soil in the container was heated through a steel pipe inserted in the middle of the container. Right: The container is insulated to minimize heat loss at the sides.

4.3 Experiment 3: In situ treatment

The in situ experiment took place in the Netherlands, more precisely in Vossepark, Heerlen (50°53'13.0"N 6°00'14.1"E). The target soil temperature for the top 4 meters of the soil was set at 80°C for 24h and 3 days at 50°C. These temperature targets have been chosen based on the outcome of the lab experiment. In total, an area of 26 m^2 was treated. The site preparation started at the end of May 2022. Before installation of the burners, the aboveground biomass of Japanese knotweed was removed.

As both the treatment depth and target temperature were low compared to other projects of HAEMERS Technologies, it was decided to use 8 Smart Burners. These burners were directly connected to secondary tubes to recuperate the hot gas of the main tubes (hence, in total 16 tubes). In this way, the energy efficiency of the treatment could be increased significantly. The expected time to reach the target temperature was 13 days and the cooldown time was set to 1 day. The burners were turned on the 23rd of June and the treatment was completed on the 12th of July. The treatment took longer than expected due to some fan malfunctions, so the treatment time increased from 13 to 15 days. During the engineering phase, it was decided not to cover the treatment area (neither with concrete nor with thermal insulation) due to the relatively low-temperature target. However, due to the fan problem encountered during the heating phase, it was decided to add an 8 cm thick layer of rockwool insulation during the treatment to avoid losing too much temperature during the fan repair and to promote quick recovery of heating afterwards.

Figure 5. In situ installation of HAEMERS Technologies in Heerlen. Eight smart burners were installed to treat the soil of a site infested with Japanese knotweed

During the treatment, soil temperature was monitored at six points with measurements at 1.5 m and 3 m below ground level. The six measurement points corresponded to six cold points identified during a simulation made beforehand. For the last days of the treatment, the first 30 cm of soil below ground level were also monitored at the same six points, as the Japanese knotweed rhizomes were mainly located in this soil layer. Twenty days after the end of the treatment (1st of August 2022), rhizome samples have been collected in the top 30 cm of the soil and planted in a greenhouse for monitoring. To assess the vitality of the rhizomes, a small sample of rhizomes was collected before the treatment started.

According to the same protocol as the first experiment, six control and 24 treated rhizome fragments (length 18-20 cm) were planted and monitored in the greenhouse for 30 days (Table 3). The test location in Heerlen will be monitored in situ for the following 3 years by the Plantengezondheidsdienst.

Table 3. Number of control and treated rhizomes that were planted and monitored in the greenhouse for experiment 3

	Thin (< 1 cm)	Medium (1 – 1.5 cm)	Thick (> 1.5 cm)
Control	3	0	3
Treatment	8	8	8

5. Results and discussion

5.1 Temperature measurements

5.1.1 Experiment 2

The temperature was monitored during the ex-situ experiment by three thermocouple tubes (15, 30 and 40 cm from the heating tube). Each tube measured the temperature at the 3 measurement depths (Figure 6). Temperatures at 15 cm from the heating tube were well above the 80°C target, particularly at 0.75 m and 1.5 m deep, where the temperature reached 300°C. There is no apparent explanation as to why the temperature at 2.25 m depth was much lower, although it was still well above the target temperature of 80°C. Once the system was switched off (after 07-06-22), the temperature in the container decreased rapidly. Temperatures at 30 cm from the tube showed a temperature range between 85°C and 100°C at the end of the treatment. The heating was relatively homogeneous over the depth. Finally, temperatures measured by the third thermocouple tube (at 40 cm from the tube) reached the target temperature after 5 heating days and stayed at this temperature for 2 days before the system was switched off. Also here, we see a relatively homogeneous heating along the depth profile. The temperature curves show that the target temperature of 80°C was reached throughout the tank after one week of heating. Some of the data from the beginning of the treatment is missing but could be simulated by the Ansys Fluent software.

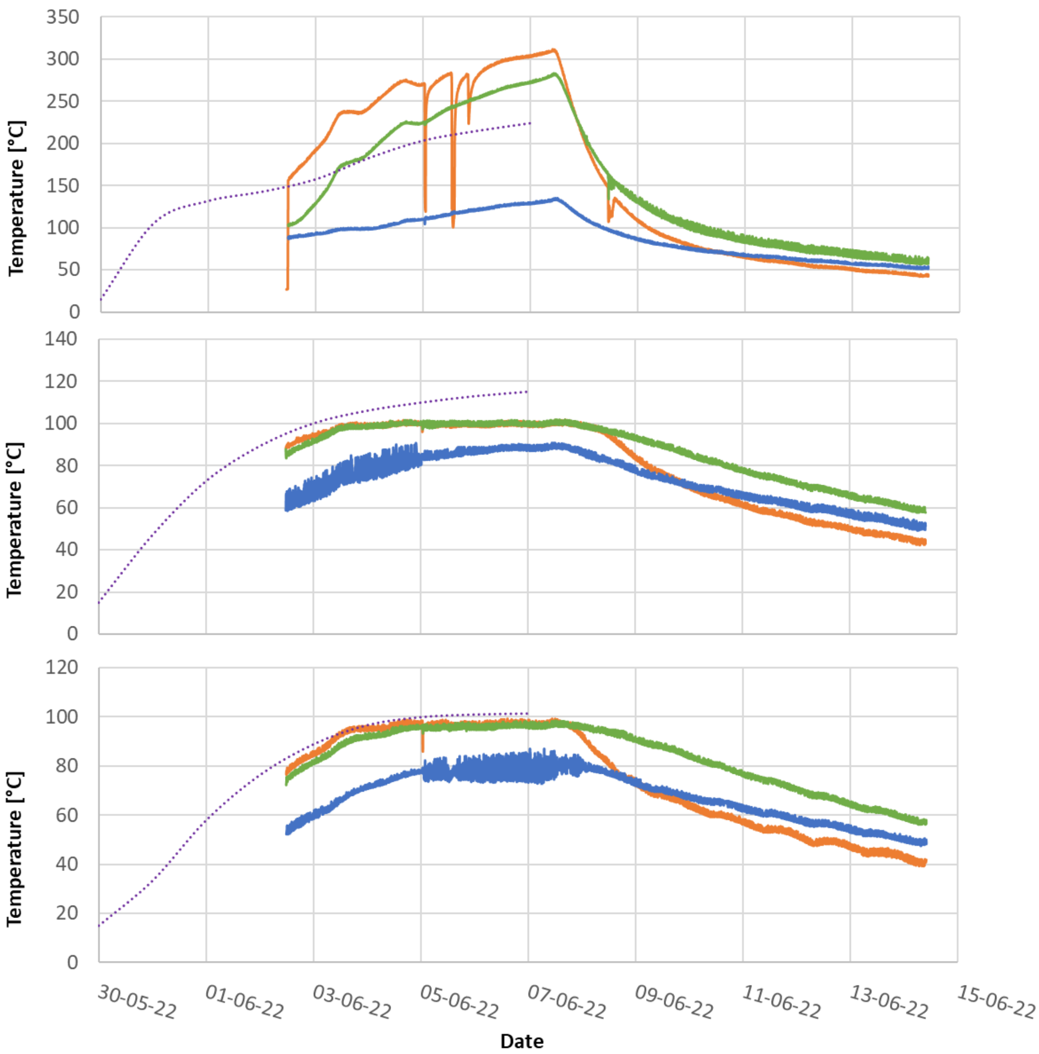
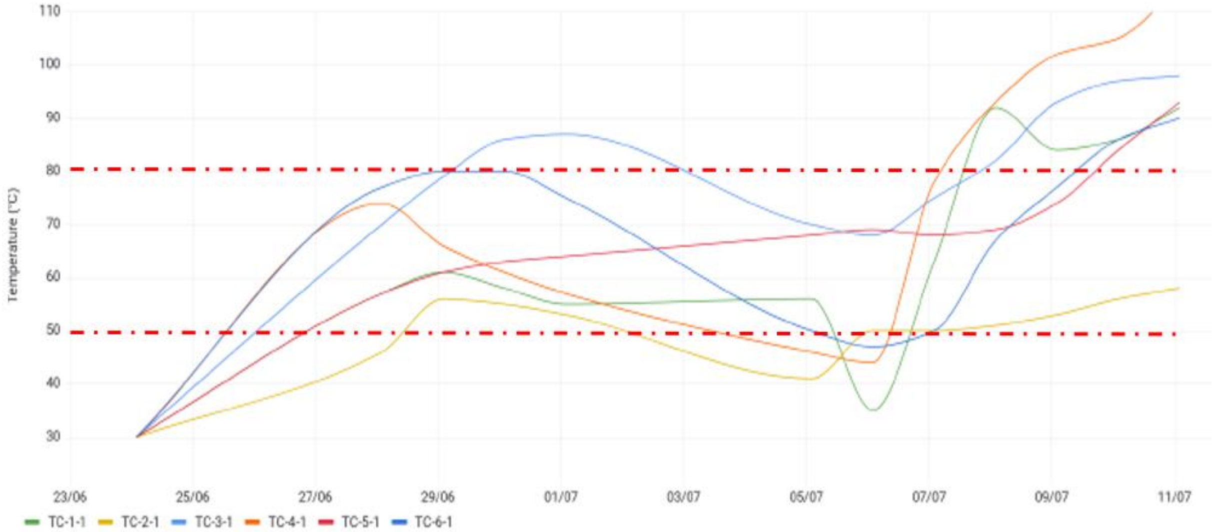


Figure 6. The temperature in the container during the ex-situ experiment at 15 (top), 30 (middle) and 45 cm (bottom) from the heating tube. Measurements were conducted at different depths: 75 cm (orange), 150 cm (green) and 225 cm (blue). The purple dotted line shows the simulations by Ansys Fluent software

5.1.2 Experiment 3

For every measurement location and depth in the in situ experiment, the target of 50°C for 3 days in a row has been reached (Figure 7, Figure 8). The target of 80°C for 24 hours was achieved in all, but two locations. It was not reached at TC-2 (located at one corner of the site) at a depth of 1.5 and 3 m, nor for TC-3 (located at a cold point between 3 burners) at a depth of 3 m. Also, the top 30 cm layer of the soil reached the 50°C temperature target during the last week of treatment. Due to the beginning of the dismantling phase and the end of the generator rental period, it was not possible to monitor the cooling phase.



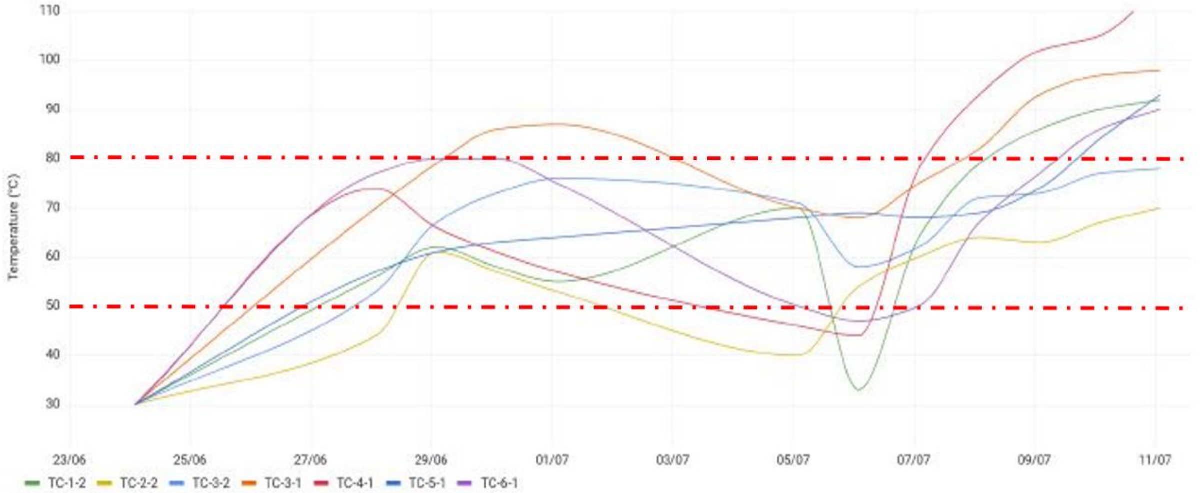


Figure 7. Soil temperatures during the in situ experiment in Heerlen (The Netherlands) were measured at the six measurement points at 1.5 m (top) and 3 m (bottom) depth. The temperature reached a plateau from the 29th of June until the 4th of July due to a fan malfunction. The two red lines represent the dual target temperature set at the beginning of the project.

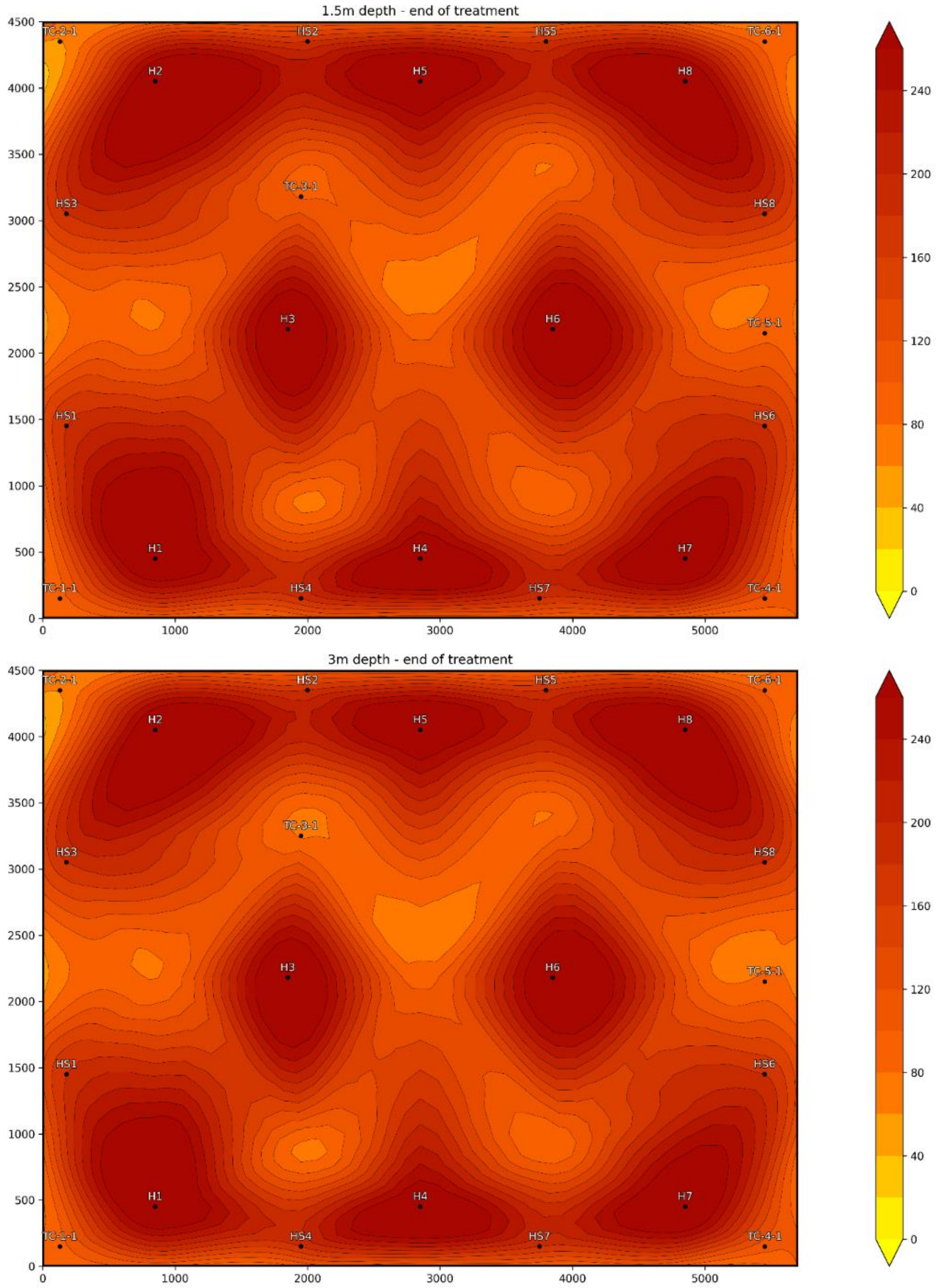


Figure 8. Thermographies showing the temperature distribution over a horizontal slice of the treated area at a depth of 1.5 (top) and 3 m (bottom) at the end of the treatment

5.2 Rhizome monitoring

In the lab experiment (Experiment 1), all the roots in the control samples sprouted, while only half of the planted roots were able to survive at 50°C for one day (Table 4). This number reduced drastically after 2 days. Only 50% of the thin roots and none of the medium and thick roots were viable. Three days of 50°C was apparently enough to kill all the roots, as none survived this treatment. No roots survived any of the treatments at 80°C. Three days at 50°C or 1 day at 80°C are thus successful warming treatments to eradicate Japanese knotweed populations.

When looking at the control roots of the ex situ experiment (Experiment 2), we see a clear difference among the three sampled soil layers (Table 5). All rhizomes in the upper layer (0-30 cm) and 96% of the rhizomes in the second layer (30-60 cm) were vital. In the deepest soil layer (60-90 cm), the roots of the thinnest class were all viable, while only 13% and even 0% of the medium and thick roots were viable. Heating the roots for 1 day to a temperature of 80°C successfully killed all the rhizomes, as none of the 84 treated rhizome fragments showed any signs of life after 30 days in the greenhouse. The very high temperatures close to the heating tube (up to 300°C) even charred the rhizome fragments.

In the third experiment, all the roots of the control sample sprouted within 30 days after the start of the experiment, while none of the treated samples survived the in situ heating treatment. Also here, the heating treatment was successful to kill all the roots.

Table 4. Survival rates (% of the planted rhizomes) of the rhizomes of experiment 1 for the three size categories (thin (< 1 cm diameter), medium (1 – 1.5 cm) and thick (>1.5 cm)) in each of the warming treatments

	50°C			80°C		
Heating period	Thin	Medium	Thick	Thin	Medium	Thick
1 day	57	43	50	0	0	0
2 days	50	0	0	0	0	0
3 days	0	0	0	0	0	0

Table 5. Proportion (%) of the planted control and treated rhizomes in experiment 2 that were alive and/or were able to sprout after 30 days of monitoring

	Thin (< 1 cm)	Medium (1 – 1.5 cm)	Thick (> 1.5 cm)	All roots
Control				
0-30	100	100	100	100
30-60	100	100	88	96
60-90	100	13	0	38
Treatment	0	0	0	0

6. Conclusions

Japanese knotweed is an invasive alien species causing much harm to native biodiversity and human structures such as roads, buildings and dikes. Current management strategies are often not very successful and could even increase the risk of spread. According to the literature, heating the roots could be a potentially interesting avenue to eradicate knotweed populations. Here, we investigated the feasibility and effectiveness of the Smart Burners™ technology, patented by HAEMERS Technologies to treat invaded sites.

We conducted three experiments to test and optimize the treatment. In the first experiment conducted in lab conditions, we tried to identify the optimal temperature and treatment period to kill 100% of the rhizomes. Three days at 50°C or 1 day at 80°C were identified as effective warming treatments. This information was subsequently applied in an ex-situ and situ experiment. In the ex situ experiment, knotweed rhizomes and soil were transferred in a steel container of 3 m^3 and heated for 1 day at 80°C. The results of this experiment confirmed the conclusions of the first experiment: no rhizomes were found to survive the applied treatment. In the last experiment, the technology was tested under field conditions. A full-scale set-up was installed in an invaded site in the Netherlands and the soil was heated up to 4 meters deep to a temperature of 50°C for 3 days and a temperature of 80°C for one day. Although the latter temperature goal was not achieved at all monitored locations at the treated site, no living roots were found after the treatment.

From these experiments, we conclude that the Smart Burners™ technology of HAEMERS technologies could be used to eradicate knotweed species. Importantly, the experiments were performed during spring and summer. Effectivity of the proposed treatment in winter conditions, when all energy of the plant is stored belowground, remains to be tested. Careful screening of the site before treatment is always necessary to accurately map the rhizome network to treat a sufficiently large area. During the treatment, all precautions should be taken to avoid the additional spread of rhizomes or stem fragments, as they could start new populations. Finally, monitoring the treated site for several years is also recommended to check for any regrowth and to take corresponding actions.

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