Exploiting Waste Heat from Combine Harvesters to Damage Harvested Weed Seeds and Reduce Weed Infestation

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Abstract: Weeds are mainly controlled with herbicides in intensive crop production, but this has resulted in increasing problems with herbicide-resistant weeds and public concerns about the unwanted side-effects of herbicide use. Therefore, there is a need for new alternative methods to reduce weed problems. One way to reduce weed infestation could be to collect or kill weed seeds produced in the growing season. Crop and weeds are harvested simultaneously with the combine harvester, but most of the weed seeds are returned with the chaff to the field creating new problems in future growing seasons. During the harvesting process, the harvester produces heat. Under normal harvest conditions, the exhaust gas temperature measured directly behind the turbocharger of the engine of a combine harvester may reach between 400 °C and 480 °C depending of the size of the engine. These high temperatures indicate that there is a potential for developing a system which perhaps could be utilized to kill or damage the weeds seeds. We investigate how much heat is needed to damage weed seeds significantly and focuses on the germination patterns over time in response to these treatments. We investigated if heat treatment of weed seeds could kill the seeds or reduce seed vigour or kill the seeds before they are returned to the field. The aim is to avoid harvested viable weed seeds being added to the soil seed bank. During the threshing and cleaning process in the combine harvester, most weed seeds and chaff are separated from the crop grains. After this separation, we imagine that the weed seeds could be exposed to a high temperature before they are returned to the field. Seeds of nine common weed species were treated with temperatures of 50 °C, 100 °C, 150 °C, 200 °C, and 250 °C for 0, 2, 5, 10, and 20 s, respectively. Afterwards, the seeds were germinated for fourteen days. Seeds were differently affected by the heat treatments. We found that 50 °C and 100 °C was insufficient to harm the seeds of all species significantly at all durations. Heating with a temperature of 50 °C and 100 °C showed a slight tendency to break the dormancy of *Alopecurus myosuroides* Huds. and *Papaver rhoeas* L., but the results were not statistically significant. Seeds treated with 150 °C gave varying results depending on the duration and the weed species. The germination of *A. myosuroides* was significantly repressed when seeds were exposed to 250 °C for 5 s. Most species were significantly damaged when they were exposed to 250 °C for more than 10 s. Our results showed that there is a potential to explore how the waste heat energy produced by combine harvesters can be exploited to either kill or reduce the vigour of weed seeds before they are returned to the field with the chaff.

Keywords: alternative weed control; combine harvester; seed viability; soil seed bank; weed seeds

1. Introduction

Since the 1960s, weeds have mainly been controlled with herbicides in intensive crop production. The reliance on herbicides has resulted in increasing problems with herbicide-resistant weeds [1]. Pollution of surface and groundwater and other environmental unwanted side-effects of pesticide use have created increasing public concerns and led to further restrictions on herbicide use in Europe and elsewhere. As a consequence, many previously commonly used herbicides have been banned by the authorities or withdrawn from the marketplace by the chemical industry [2,3]. Furthermore, there is an increasing public interest in organic food [4]. Therefore, there is a need to develop integrated weed management strategies which can replace or supplement herbicide use. Crop rotation and soil tillage are alternatives to herbicides [5,6], but are often less efficient than herbicides and, therefore there is a need for developing new techniques to replace and supplement present weed control techniques.

One way to reduce weed problems could be to prevent weed seeds produced in the growing season and collected by the combine harvester to be returned to the soil seed bank. Andreasen et al. [7] estimated the soil seed bank in 40 Danish fields in 2014 to contain on average 20,455 seeds m^{-2} in the 20 cm deep ploughing layer. Although the soil seed bank may be large and contains many problematic weed species, the soil seed bank of many problematic annual weed species (e.g., *A. myosuroides*, *Apera spica-venti* (L.) P.Beauv., and *Poa annua* L.) decays rapidly if no new seeds are added [8–10]. Harvest time represents an opportunity for farmers to collect and destroy weed seeds, and reduce inputs into the soil seed bank. Many weed species retain seeds at a height that makes it possible to collect intact fruits and seeds at crop harvest. A combine harvester collects crop and weed seeds and separates most of the weed seeds together with the chaff from the crop grains. Usually, the chaff and weed seeds are expelled from the harvester and return to the ground creating new weed infestations. An alternative could be to collect chaff and weed seeds, for example by using a transfer mechanism, attached to a grain harvester that delivers the weed seed bearing chaff fraction into a trailing cart. Afterwards, the fraction can be dumped and burned or removed from the field [11]. A chaff chute can also be mounted on the rear of a harvester concentrating the chaff and straw residues into a narrow-windrow (500 to 600 mm) during harvesting, which afterward can be burned [11]. However, burning may not be allowed or appropriate due to fire risk and smoke pollution, and removing organic matter from the field, which is not used for food, feed, or fuel, is not sustainable and makes up one more cost for the farmer that should be avoided, because organic matter contributes to maintaining the fertility and the water holding capacity of the soil.

A system has been developed that consists of a trailer with a diesel motor and a cage mill, which is mounted and connected to the harvester with a chaff and straw transfer systems. The cage mill crushes the chaff with a cage mill [10]. Walsh et al. [10] found that it was able to destroy at least 95% of the weed *Lolium rigidum* Gaudin in the chaff fraction of harvest residues. However, the system called the Harrington Seed Destructor, constitutes a considerable cost regarding machine investment and energy consumption.

Jakobsen et al. [12] investigated whether exhaust gas from a combine harvester could be used to kill weed seeds. The idea was to explore the potential to develop a system implemented in the combine harvester that could expose the chaff and weed seeds to the large air pressure and waste heat energy from the exhaust gas before the material was returned to the field. Under normal harvest conditions, the exhaust gas temperature measured directly behind the turbocharger of the engine of a combine harvester may reach between 400 °C and 480 °C, depending of the size of the engine [13]. These high temperatures indicate that there is a potential for developing a system utilizing the heat to kill or damage weed seeds.

Jakobsen et al. [12] found that seeds treated with 110 °C exhaust gas gave varying results depending on the duration of exposure and the weed species, while the germination of all seeds exposed to exhaust gas with a temperature of 140 °C for 2 s was repressed. They concluded that the method seemed promising.

The engine of the combine harvester irradiates significant heat while harvesting, which potentially could be exploited to damage weed seeds before the seeds are returned to the fields. We investigate how much heat is needed to damage weed seeds significantly and focus on the germination patterns over time in response to these treatments. We used a heating system based on electric heating to

explore which temperatures and durations are needed to reduce seed vigour or kill seeds of some summer and winter annual weed species common in Northern Europe.

2. Methods

2.1. Weed Seeds

We chose nine weed species with different seed morphology, size, and weight representing a broad spectrum of common winter and summer annual weed species of Northern Europe (Table 1).

Table 1. Weed species exposed to heat treatments, characteristics of the seeds, thousand seed weight, size, and vessel type used for the species. Vessel A was made from a woven wire cloth of stainless steel with an aperture width of 0.71 mm and a wire diameter of 0.224 mm. Vessel B was made from a woven metal filter cloth with an aperture width of 0.40 mm and a wire diameter of 0.330 mm.

Weed Species	Short Descriptions	Thousand Seed Weight (g)	Average Size (mm)	Vessel Type
Alopecurus myosuroides Huds.	Spikelet with one seed and with a 5–6 mm awn	2.0	5.7 × 1.9 × 0.9	A
Amzinckia micranta (Suksd.) Druce	Surface uneven rough	1.3	2.2 × 1.4 × 1.3	A
Artemisia vulgaris L.	With longitudinal ribs	0.1	1.5 × 0.5 × 0.5	B
Centaurea cyanus L.	Seeds with stiff hairs (4 mm) at the apex	4.5	2.4 × 1.7 × 1.2	A
Erodium cicutarium (L.) *L'Hér.*	Seeds with spiral shaped awn	2.7	5.4 × 1.1 × 1.1	A
Papaver rhoeas L.	Seeds net meshed in curved row pattern	0.1	0.8 × 0.5 × 0.6	B
Silene noctiflorum (L.) Fr.	Kidney-shaped seeds, dark brownish to black seed	1.0	1.4 × 1.2 × 0.9	A
Tripleurospermum inodorum (L.) Sch. Bip.	Cross-section triangular to square	0.4	1.8 × 0.7 × 0.7	A
Veronica arvensis L.	Orange to yellow-brown	0.1	1.0 × 0.7 × 0.3	A

2.2. Heat Treatment

A heating experiment was carried out at Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Germany to investigate how the seed germination was affected by different temperatures and exposure times. A double-tube heating unit with a glass tube inside was used. We used an electrical heating unit Carbolite Type HST 12/200 (Carbolite Gero Ltd., Hope, Hope Valley, UK) providing a maximum temperature of 1200 °C and a power of 1000 W. Vessels made from two different types of metal meshes (A and B; see Chapter 2.5) were used to bring the seeds in the tube where the seeds were exposed to the heat. The air pressure and flow were controlled by a regulator, and the volume flow was measured with a flow meter and adjusted with a needle valve. We used ambient air. The pressurized air was heated by 'Heating Unit I' (Figure 1). The 'Heating Unit II' provided the energy for a radiative heat transfer. This evokes a combination of radiative and convective heat transfer onto the seeds (Figure 1).
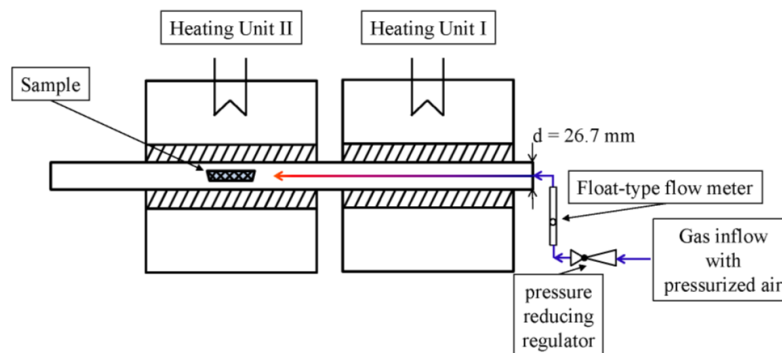

Figure 1. Principle drawing of the setup of the double-tube heating unit for convective and radiative heating.

2.3. Temperature Monitoring

We exposed the eight species to five temperatures (50 °C, 100 °C, 150 °C, 200 °C and 250 °C). However, *A. vulgaris* was only exposed to two temperatures (200 °C, and 250 °C) due to a lack of seeds. We chose this range because we considered these temperatures to be realistic to obtain in a seed transfer system in a conventional combine harvester. The temperature was monitored with a thermocouple type K (NiCr–NiAl) (3 mm × 50 mm) (Kongsberg Maritime Ltd., Trondheim, Norway) resistant to oxidation and corrosion [14]. The temperature was monitored at the sample location during heat exposure to define the heating conditions of unit I and II and to achieve the desired temperatures.

2.4. Velocity of the Gas Flow

For the test execution, the pressure of the gas inflow was adjusted with a pressure reducing regulator. The volume flow was settled before the entry of the tube (Figure 1). The volume flow was measured by a float-type flowmeter calibrated for a pressure of 1.2 bars and a temperature of 20 °C. Equation (1) was used to calculate the change of the volume flow (V_{new}) for higher pressure (p_n) before the flow meter at volume flow V_n [14]:

$$\dot{V}_{new} = \sqrt{\frac{p_{new}}{p_n}} \times V_n \tag{1}$$

The volume flow increases with increasing temperature in Heating Unit I. The equation of the ideal gas law (Equation (2)) relates the volume to the temperature:

$$p \times V = n \times R \times T \tag{2}$$

where n denotes the amount of substance, R is the gas constant, and T denotes the temperature. The change of pressure due to tubular pressure drop is insignificant and can be neglected. The simplification of the formula reveals that only the temperature T influences the volume V:

$$V \sim T \tag{3}$$

When the temperature increases, the velocity in the tube rises. With a tube diameter $d = 26.7$ mm the velocity v can be calculated (Equations (4) and (5)) [15]:

$$\dot{V} = v \times A = v \times \frac{\pi}{4} \times d^2 \tag{4}$$

$$v = \frac{\dot{V} \times 4}{\pi \times d^2} \tag{5}$$

The resulting values for the velocity v at different temperatures at the sample location are presented in Table 2.

Table 2. Volume flow ($\dot{V}$) and velocity v at different flow temperatures.

Temperature (°C)	Volume Flow (L hour^{-1})	Velocity (m s^{-1})
50	2983	1.48
100	3445	1.71
150	3906	1.94
200	4368	2.17
250	4829	2.40

2.5. Vessels

Two different types of metal sieves were applied as vessels depending on the size of the weed seeds (Table 1). The vessel A was made from a woven wire cloth of stainless steel with an aperture width of 0.71 mm and a wire diameter of 0.224 mm (DIN ISO 9044, DIN ISO 4783). Vessel B had a smaller mesh size for smaller weed seeds and was made from a woven metal filter cloth with an aperture width of 0.40 mm and a wire diameter of 0.330 mm. Less air flew over the seeds of vessel B, and the seeds had more surface contact to this sieve. This increased the heat transfer compared to the samples in vessel A.

2.6. Test Execution

For each species, 60 seeds were treated with the five temperatures for 0, 2, 5, 10, and 20 s. All treatments were replicated four times for each species. The large seeds were placed in vessel A and the small seeds in vessel B (Table 1). The vessel with 60 seeds was placed inside in the middle of 'Heating Unit II' (Figure 1). After the heat treatment, the seeds were put in a closable vial and sent to the germination laboratory at Department of Plant and Environmental Sciences, University of Copenhagen, Taastrup, Denmark.

2.7. Germination Experiments

Four times 50 seeds of each species from each treatment were germinated in Petri dishes (94 mm Ø) and placed in a Termaks KB8000L climate chamber (Termaks AS, Nino lab, Køge, Denmark) with a diurnal cycle of 12 h/12 h light/dark, at a constant temperature of 15 °C. Each Petri dish contained a filter paper. Demineralized water was added to the Petri dishes and the 50 seeds were placed on the filter paper. We used a 0.2% KNO_3 solution for *A. micranta*, *A. vulgaris*, *C. cyanus*, *E. cicutarium*, and *S. noctiflorum* to release dormancy and increase the germination percentage. Germinated seeds were counted and removed every 24 h. A seed was considered germinated when it had developed a radicle of 2 mm. The germination tests were terminated after fourteen days. Altogether 35,400 seeds were investigated (50 seeds × 4 replicates × 4 durations × 5 temperatures × 8 species) + (50 seeds × 4 replicates × 4 durations × 2 temperatures × 1 species) + (50 seeds × 4 replicates × 9 species) (controls).

2.8. Statistical Analysis

We used the open-source program *R* (*R* version 3.2.3, *R* Core Team 2015, Vienna, Austria) for the statistical analysis of the germination data. The germination was modelled with the function $F(t)$ (Equation (6)), using the add-on package *drc* [16].

$$F(t) = \frac{d}{1 + exp[b\{\log(t) - \log(t_{50})\}]} \tag{6}$$

where $F(t)$ denotes the fraction of seeds germinating between the onset of the experiment (at time 0) and time t. The upper limit parameter d denotes the proportion of seeds that germinated during the experiment. The parameter b is proportional to the slope of F at time t equal to the parameter t_{50}, which denotes the time where 50% of the seeds, which germinated during the experimental period, germinated. The estimation and model checking procedures are based on treating the data as event times, that is, to record the time it takes for germination (the event of interest) to occur, as described by Ritz et al. [17].

3. Results

Table 3 shows the estimated *d*-parameters of the germination curves with standard errors. Untreated seeds of eight of the weed species germinated at 15 °C had a relatively high germination percentage (above 76%) and reached the upper limit (*d*-parameter) within fourteen days (Table 3 shows 10 days). Only *P. rhoeas* differed from the rest having a germination percentage about 50%. The effect of the five temperatures and durations on the grass weed *A. myosuroides* and the broad-leaved species

T. inodorum are shown in Figures 2 and 3, respectively, as examples at all temperature and durations. The black line represents the control samples (15 °C). Heat treatments with 50 °C and 100 °C did not have any significant negative effect on the germination of any of the weeds but seem to release dormancy and improve the germination of *A. myosuroides*, *P. rhoeas* and *T. inodorum* (Figures 2 and 3, Table 3). This also happened when *A. myosuroides* was exposed to 150 °C for 2 s and *T. inodorum* and *P. rhoeas* for 2 and 5 s. Figure 4 shows the resulting germination curves of the seven other weed species exposed to 250 °C. Even 2 s exposure of 200 °C seemed to improve the germination of *P. rhoeas* and *T. inodorum*, while longer durations reduced the germination (Table 3). The germination of all weed species was negatively affected when they were exposed to 200 °C for 5 s except *C. cyanus*, but 10 s also reduced germination of *C. cyanus* (Table 3). The germination of all species was reduced when they were exposed to 250 °C for 5 s and 20 s killed all seeds of all weeds except a few seeds of *C. cyanus* and *S. noctiflorum*. *S. noctiflorum* showed a deviant response as only a few seeds almost germinated when they were exposed to 250 °C for 10 s but 20 s immediately triggered the germination of approximately 20 percent of the seeds (Figure 4).
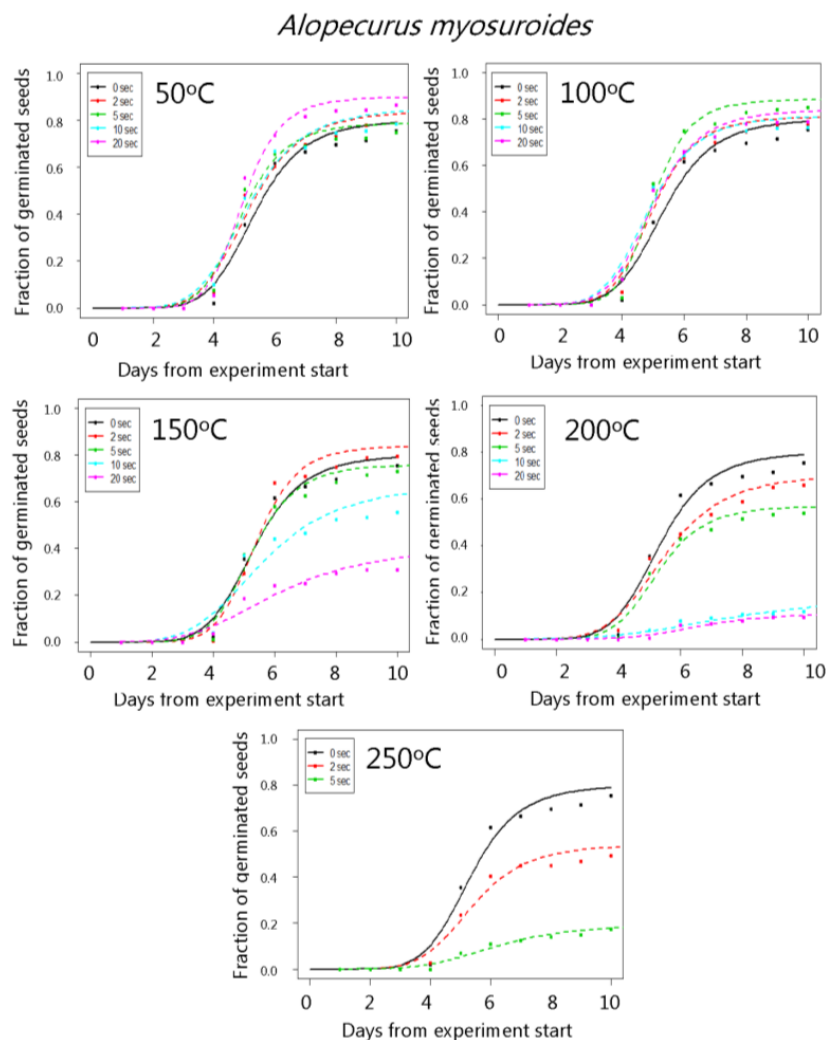

Figure 2. Germination curves of seed lots of the grass weed *Alopecurus myosuroides* treated with various temperature and durations.
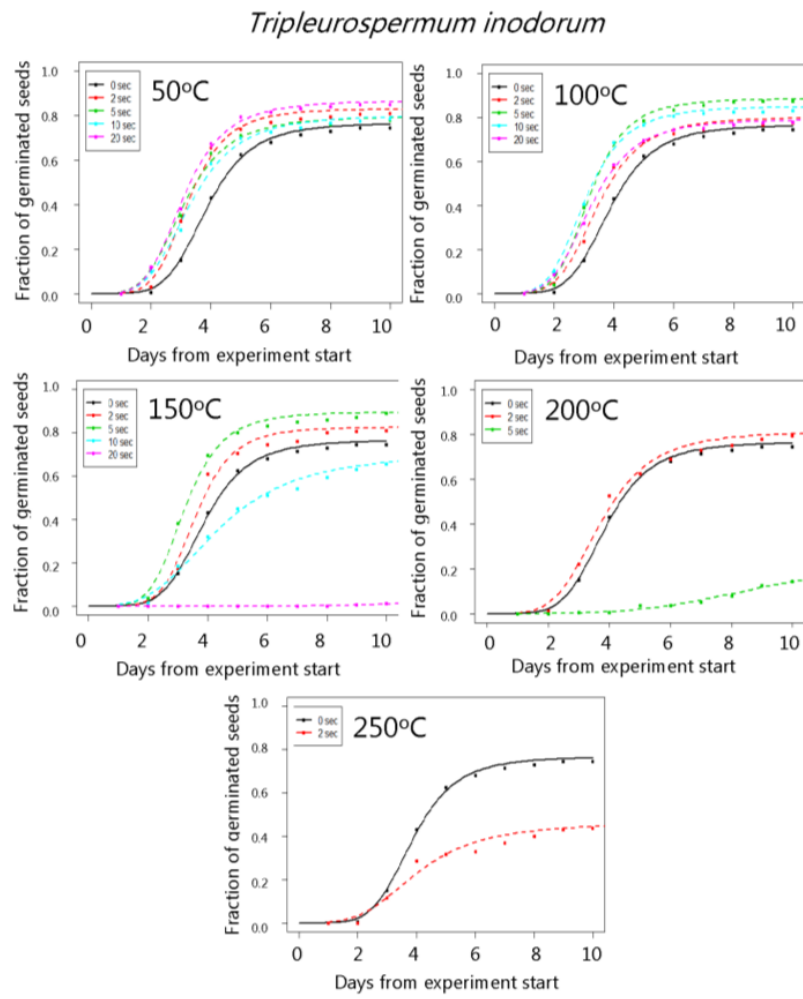
Figure 3. Germination curves of seed lots of the broad-leaved weed *Tripleurospermum inodorum* exposed to various temperature and durations.
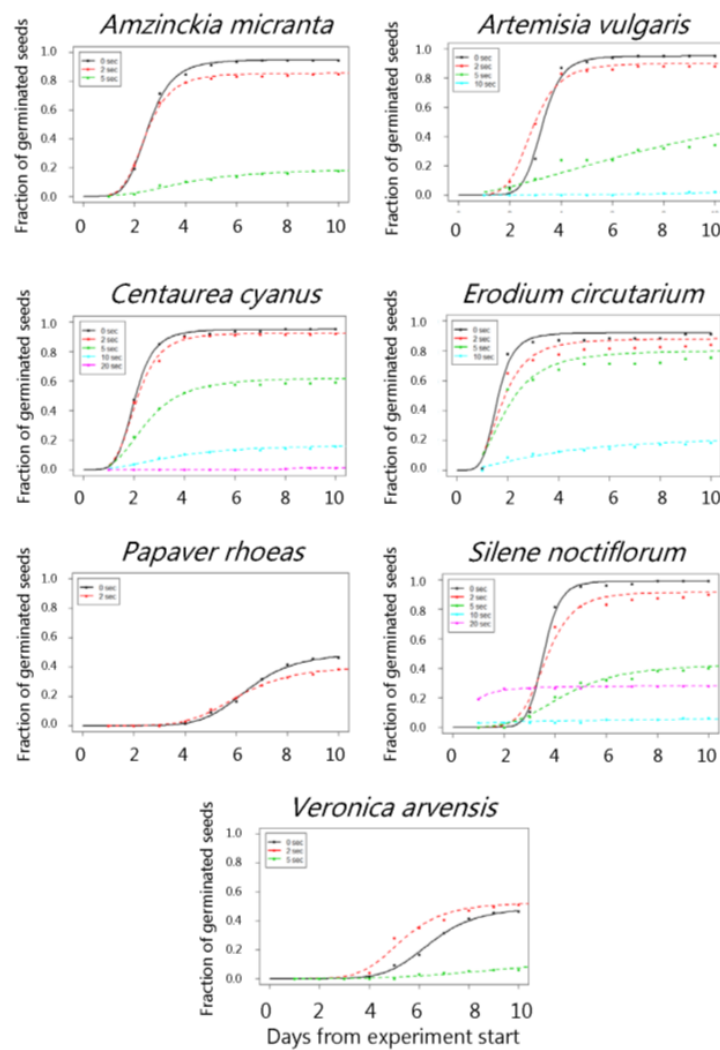
Figure 4. Germination curves of seed lots of seven weed species exposed to 250 °C at various durations.

Table 3. Weed species and treatments (temperatures and durations) and estimates of the germination percentage (standard error). "-" means that no seeds germinated or too few seeds germination to estimate a germination curve.

Species	Temperature	0 s	2 s	5 s	10 s	20 s
Alopecurus myosuroides	50 °C	80.1 (2.3)	84.1 (2.5)	79.1 (2.9)	85.2 (2.5)	90.0 (2.1)
	100 °C	80.1 (2.3)	84.2 (2.6)	88.5 (2.3)	81.6 (2.7)	84.0 (2.6)
	150 °C	80.1 (2.3)	84.0 (2.6)	76.1 (3.0)	67.5 (3.4)	41.1 (3.7)
	200 °C	80.1 (2.3)	71.3 (3.2)	57.0 (3.6)	18.5 (3.2)	11.1 (2.2)
	250 °C	80.1 (2.3)	54.2 (3.5)	19.3 (2.8)	-	-
Amzinckia micrantha	50 °C	95.0 (1.5)	84.5 (2.6)	90.6 (2.0)	90.3 (2.1)	94.0 (1.7)
	100 °C	95.0 (1.5)	84.5 (2.6)	93.0 (1.8)	89.0 (2.2)	90.5 (2.1)
	150 °C	95.0 (1.5)	95.5 (1.5)	86.6 (2.4)	80.6 (2.8)	45.7 (3.5)
	200 °C	95.0 (1.5)	92.0 (1.9)	70.6 (3.2)	22.2 (3.0)	-
	250 °C	95.0 (1.5)	85.5 (2.5)	19.0 (2.8)	-	-
Artemisia vulgaris	200 °C	95.0 (2.1)	98.0 (13)	81.3 (3.9)	77.9 (37.9)	-
	250 °C	95.0 (2.1)	90.0 (3.0)	81.9 (23.9)	53.3 (2.7)	-
Centaurea cyanus	50 °C	95.0 (1.5)	88.5 (2.3)	100.0 (0.0)	96.0 (1.3)	86.6 (2.4)
	100 °C	95.0 (1.5)	88.5 (2.3)	88.5 (2.3)	96.0 (1.3)	96.0 (0.6)
	150 °C	95.0 (1.5)	95.6 (1.4)	93.5 (1.7)	93.0 (1.8)	83.0 (2.6)
	200 °C	95.0 (1.5)	81.2 (2.8)	94.0 (1.6)	63.8 (3.4)	27.3 (3.1)
	250 °C	95.0 (1.5)	92.5 (1.9)	62.1 (3.4)	17.1 (2.7)	1.0 (1.0)

Table 3. *Cont.*

Species	Temperature	0 s	2 s	5 s	10 s	20 s
	50 °C	92.0 (1.9)	82.0 (2.7)	82.3 (2.7)	87.9 (2.3)	86.6 (2.4)
	100 °C	92.0 (1.9)	82.0 (2.7)	86.6 (2.4)	91.0 (2.0)	89.5 (2.2)
Erodium cicutarium	150 °C	92.0 (1.9)	91.7 (2.0)	92.5 (1.9)	88.6 (2.2)	73.7 (3.1)
	200 °C	92.0 (1.9)	85.5 (2.4)	78.7 (2.8)	70.1 (3.2)	11.0 (2.3)
	250 °C	92.0 (1.9)	88.1 (2.2)	80.2 (2.8)	23.2 (3.4)	-
	50 °C	49.2 (3.6)	58.6 (3.5)	60.3 (3.5)	64.3 (3.5)	59.3 (3.5)
	100 °C	49.2 (3.6)	58.6 (3.5)	51.8 (3.7)	59.2 (3.5)	55.1 (3.5)
Papaver rhoeas	150 °C	49.2 (3.6)	58.7 (3.5)	59.7 (3.4)	34.8 (3.4)	-
	200 °C	49.2 (3.6)	52.6 (3.5)	15.3 (4.1)	-	-
	250 °C	49.2 (3.6)	40.3 (3.5)	-	-	-
	50 °C	99.0 (0.6)	100 (0.0)	99.5 (0.5)	99.4 (0.5)	100.0 (0.0
	100 °C	99.0 (0.6)	100.(0.0)	100.0 (0.0)	100.0 (0.0)	99.0 (0.7)
Silene noctiflorum	150 °C	99.0 (0.6)	100.0 (0.0)	90.5 (2.0)	76.6 (3.0)	37.1 (3.4)
	200 °C	99.0 (0.6)	100.0 (0.0)	73.5 (3.1)	20.1 (2.9)	2.0 (0.1)
	250 °C	99.0 (0.6)	91.5 (2.0)	43.0 (3.5)	18.7 (17.0)	28.1 (3.1)
	50 °C	76.6 (3.0)	83.0 (2.7)	79.6 (2.9)	80.2 (2.8)	86.6 (2.4)
	100 °C	76.6 (3.0)	83.0 (2.6)	88.5 (2.3)	85.0 (2.5)	79.1 (2.9)
Tripleurospermum inodorum	150 °C	76.6 (3.0)	82.5 (2.6)	89.6 (2.1)	70.5 (3.4)	1.5 (0.9)
	200 °C	76.6 (3.0)	81.2 (2.7)	24.1 (4.0)	18.4 (3.2)	11.1 (2.2)
	250 °C	76.6 (3.0)	50.0 (3.5)	19.3 (2.8)	-	-
	50 °C	92.0 (1.8)	94.0 (1.7)	95.4 (1.5)	97.0 (1.2)	92.4 (1.8)
	100 °C	92.0 (1.8)	94.0 (1.7)	95.5 (1.5)	96.5 (1.3)	94.5 (1.6)
Veronica arvensis	150 °C	92.0 (1.8)	88.5 (2.3)	96.0 (1.4)	81.0 (2.8)	5.8 (1.8)
	200 °C	92.0 (1.8)	86.0 (2.5)	58.6 (3.5)	0.5 (0.5)	-
	250 °C	92.0 (1.8)	62.5 (3.4)	14.0 (0.0)	-	-

4. Discussion

The germination of the seed samples was either positively affected, unaffected, or negatively affected by the heat treatments. At the lower temperatures (50 °C, 100 °C, and 150 °C) seed samples containing dormant seeds improved their germination (d-parameter), while seeds without dormancy were unaffected. The duration had a significant influence on the effect. The heat treatments affected all three parameters in Equation (6). The aim of the study was to explore how heat treatments reduced seed germination and killed the seeds, and how the t_{50} and b parameters were affected because these parameters describe seed vigour, and illustrate whether seeds perform better or worse after treatment. t_{50} increased with increasing durations at high temperatures (200 °C and 250 °C), and the slope of the germination curve became less steep (expressed by the b-parameter) showing that the seed samples perform worse. High temperatures were needed to be able to damage the seeds of the chosen weed species significantly. The lower temperature, the longer a duration was necessary to damage the seeds.

We terminated the experiments after 14 days for all species. For most plant species, The International Seed Testing Association (ISTA) [18] recommends duration of 10–14 days, but for some species, it is appropriate to increase the duration of the germination test. The germination was reduced significantly if seeds were treated with high temperatures (200 °C and 250 °C) and the longest durations (10 and 20 s), but the germination curves were less precisely estimated (large standard errors of the parameter, Table 3). A longer duration of the experiments with more observations would probably have improved the estimation of the curve parameters. However, the effects of increasing durations are seen in Table 3 and Figures 2–4.

We did test more species than shown, but unfortunately the control samples germinated poorly and therefore we had to exclude these experiments. As a consequence, we began to germinate the seeds in a 0.2% KNO$_3$ solution to improve the germination. It is well-known that many wild plant species exhibit seed dormancy which in some cases can be released by pre-chilling, adding phytohormones (e.g., gibberellic acid) or other chemicals (e.g., 0.2% KNO$_3$) [19,20]. We did not add potassium nitrate to the water for the germination test of *A. myosuroides*, *R. rhoeas,* and *T. inodorum*, although they did not have a high germination percentage. The results from the three species illustrate well that a short exposure

to high temperatures (in our experiments 50 °C to 200 °C) also can release dormancy (Table 3 and Figure 3). The heating might have released the protecting glumes of some of the seeds of *A. myosuroides* and may have broken the seed coat of *R. rhoeas* and *T. inodorum* resulting in easier water uptake and subsequent germination. Martin et al. [21] also found that a short pulse of heat can trigger germination of some plant species and that this could happen for a certain fraction of the seeds.

Triggering seed germination with a short pulse of a high temperature can be an advantage because weed seeds germinating just after harvest can easily be controlled mechanically or chemically before the sowing of the next crop. However, it would be preferable if the seeds were killed by a heat treatment in the combine harvester and thereby controlled immediately instead, but that requires that the seeds are exposed to a high temperature for approximately 10 s or longer.

The weed species reacted differently to the heat treatments. *P. rhoeas* and *V. arvensis* were the most sensitive species, both having small seeds, while *C. cyanus* and *E. cicutarium* were the least sensitive having the largest seeds (Tables 1 and 3, Figures 2–4). Jakobsen et al. [12] also found that *C. cyanus* were less sensitive to a short pulse of heat than the other tested species with smaller seed weight. Large seeds might be more protected against a pulse of high temperature because it takes a longer time to distribute the heat in a large seed than in a small one [22]. High temperatures can break cell walls and damage other cell structures. The heat requirement to kill the seeds will probably depend on the thickness of the seed coat, the morphology of the seed (e.g., shape, glumes, structure of the seed coat, protecting hairs), and the water content. Wet and immature seeds will be better protected against a short temperature increase as the energy will be used to evaporate the water. The water content of the seeds depends on the maturity of the seed, and as weed seeds often are shed when they become mature, a combine harvester may harvest weed seeds that are not fully matured and therefore might have a higher water content than the dry seeds we used in our experiments. Thus, it would also be important to study the relation between the water content of the seeds and their sensitivity to heating. Jakobsen et al. [12] studied how exhaust gas from a combine harvester could be used to kill weed seeds. They found seeds exposed to 140 °C in 2 s were all seriously affected, but some seeds were still able to germinate. However, no seeds were able to germinate after 4 and 6 s exposure to 140 °C. The considerable air velocity (38 m s^{-1}) and air volume (902 L min^{-1}) from the exhaust pipe seemed to transfer and distribute the heat much more efficiently than our heating system did. Based on our and the study by Jakobsen et al. [12], we believe there is a potential to develop a heating system to damage or kill weed seeds before they are returned to the soil seed bank. The concept should be further explored and the design and capacity of the heater should be developed in close collaboration with the companies producing the combine harvesters.

We used two vessel types in our experiment made of woven wire cloths of stainless steel with different aperture widths and diameters to retain seeds of various sizes. We do not know whether the vessel types transferred the heat equally efficiently to the seeds and whether this may also contribute to explain why the small seeds were more affected by the heat than the big seeds. Moreover, for smaller seeds, less exposure time is needed to heat the core sufficiently and evaporate the water content to inactivate the germination ability of the seed. In preliminary experiments, we saw a significant influence of the vessel when a vessel made of glass was used. When a glass vessel at room temperature was used, it had a significant cooling effect on the seeds during short heat exposure times and no significant effect on reducing the germination could be observed. Using a pre-heated glass vessel led to the effect that seeds had a longer heat exposure time by direct contact to the vessel and thus the results were also affected. Because of this experience the vessels used for this work were designed as a sieve to minimize the effect of contact. The aperture width was chosen as dense as needed to prevent seeds from falling out and as open as possible to have the biggest possible effect of convective heat.

The biology of weed species varies a lot. Weeds may shatter a smaller or larger proportion of their total seed production before harvest, while others shatter their seeds later in the season if they are not harvested. Therefore the possibility to reduce the soil seed bank by destroying harvested seeds will depend on the composition of the weed flora in the field. In Australia, Walsh and Powels [23] observed,

that *L. rigidum*, *Raphanus raphanistrum* L., *Bromus* spp., and *Avena fatua* L., which are among the most important weed species, retained 85%, 99%, 77%, and 84% of their seeds above a 15 cm harvest cutting height at wheat (*Triticum aestivum* L.) maturity. Consequently, it should be possible to empty or reduce the soil seed bank of these species significantly if the harvested seeds are collected or destroyed during the harvesting procedure.

However, many common weed species may remain small (e.g., *Poa annua* L., *Stellaria media* (L.) Vill., *Viola arvensis* Murray, and *Veronica* sp.), and escape the header of the combine harvester, and most of the seeds may already be shed at harvest time. In high yielding production systems, like in Northern Europe, light competition in a dense crop often results in higher weed plants with longer internodes [24]. This reduces the risk that the weeds escape the header of the combine harvester.

The weed seeds are usually transported together with the chaff through the combine harvester. If the weed seeds are not separated from the chaff, for example by sieves, the chaff may have an isolating effect protecting many weed seeds from the heat of a heating system, and consequently, the temperature needs to be even higher to have a significant effect.

It is also important to consider the fire hazard associated with heat treatments. Crops are harvested under dry conditions and overheated material may accidentally catch fire. Jakobsen et al. [12] reported that they placed chaff directly over the exhaust pipe in a filter for 2 min with an exhaust gas temperature of 200 °C and they did not see any sign of ignition.

5. Conclusions

The experiments showed that relatively high temperatures (200 °C to 250 °C) are needed to be able to damage the seeds of the chosen weed species significantly with our heating system based on heat radiation and forced convection. It can be conclude that the necessary exposure time and temperature varies a lot between the very different weed species, but 200 °C in 10 s killed most of the weed species tested. Especially species with small seeds were sensitive to heat treatments, but the effect varied substantially between species. At the lowest temperatures (50 °C, 100 °C, and 150 °C) seed dormancy was released for the two species with the smallest seeds (*P. rhoeas* and *T. inodorum*). The lower temperature, the longer duration is necessary to damage seed samples significantly, and as seeds and chaff travel rapidly through a combine harvester, it is important to make a heating system exposing the seed for a relatively high temperature. Developing a heating system using the waste energy from the engine of the combine harvester or the exhaust gas would probably over time reduce the amount of viable and vigorous seeds in the soil seed bank, especially of the small-seeded species which retain a substantially part of their seasonal seed production on the plant until harvest.

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