Phytotoxic Effect of Invasive Heracleum mantegazzianum Essential Oil on Dicot and Monocot Species

Martina Matoušková 1, Jana Jurová 1, Daniela Grul’ová 2-*, Anna Wajs-Bonikowska 3, Marek Renčo 1, Vincent Sedlák 4, Janka Poračová 4, Zuzana Gogaľová 4 and Danuta Kalemba 3

1 Institute of Parasitology, Slovak Academy of Sciences, Hlinkova 3, 04001 Košice, Slovakia; matouskova@saske.sk (M.M.); jjurova@saske.sk (J.J.); renco@saske.sk (M.R.)
2 Department of Ecology, Faculty of Humanities and Natural Sciences, University of Prešov, 17. Novembra 1, 08001 Prešov, Slovakia
3 Institute of General Food Chemistry, Lodz University of Technology, Stefanowskiego 4/10 St., 90924 Łódź, Poland; anna.wajs@p.lodz.pl (A.W.-B.); danuta.kalemba@p.lodz.pl (D.K.)
4 Department of Biology, Faculty of Humanities and Natural Sciences, University of Prešov, 17. Novembra 1, 08001 Prešov, Slovakia; vincent.sedlak@unipo.sk (V.S.); janka.poracova@unipo.sk (J.P.); zuzana.gogalova@smail.unipo.sk (Z.G.)
* Correspondence: daniela.grulova@unipo.sk; Tel.: +421-948-030-412

Abstract: Spreading of the plant species in new areas is supported by the hypothesis in which chemicals produced by alien species are allopathic to native plants. A novel weapon hypothesis was tested by using essential oil of dangerous alien species Heracleum mantegazzianum in laboratory conditions. Aboveground plant material was collected in south-east part of Slovakia, dried and hydrodistilled for essential oil isolation. Dominant compounds as octyl acetate (62.6%), hexyl 2-methylbutyrate (10.7%), hexyl isobutyrate (7.5%) and hexyl butyrate (6.5%) were identified by GC-MS. Potential phytotoxic activity was tested on three dicot plant species garden cress (Lepidium sativum L.), radish (Raphanus sativus L.) and lettuce (Lactuca sativa L.) and on one monocot plant species wheat Triticum aestivum L. Germination of the seeds of model plant species after influencing by different doses of essential oil of H. mantegazzianum as well as the roots length was evaluated. Lepidium sativum L. and Raphanus sativus L. were generally not sensitive to applied doses of essential oil although a little stimulation effect at some concentrations prevailed over inhibition effect. Similarly, in monocot species Triticum aestivum L., stimulation was visible in both root length and root number at two or one highest doses, respectively.

Keywords: allelopathy; biological activity; GC-MS; giant hogweed; aliphatic esters

1. Introduction

Heracleum mantegazzianum Sommier et Levier (giant hogweed) belongs to the genus Apiaceae. It was introduced to Europe from central Asia (Caucasus) as an ornamental species. The first information about its presence in Europe comes from London’s botanical garden Kew Gardens in 1817 [1,2]. Nowadays, the plant is considered to be extremely dangerous in Slovakia as well as in other European countries as Czech Republic, Germany, Poland, Switzerland, and countries of Benelux, Great Britain etc. [3–7].

Giant hogweed is a plant of impressive growth. In the conditions characteristic for central Europe, it grows from 2 until 5 m. In original ecosystem it grows only until 1.5 m high. Plant is monocarpic [1], which means that under natural conditions, it dies after fructification [8]. Full bloom starts from
middle June and last until the end of July. The species produce 20,000–30,000 seeds, in extreme occasion 100,000 seeds per plant individual. In addition, it is found mainly on anthropogenic sites, most often along roads and waterways. They also spread to neglected meadows, forest clearings, and places around parks. Since it is a species with strong vitality, rapid growth, large seed production and lack of natural enemies, its spreading to new sites is uncontrollable by common methods.

Chemicals produced by alien species are allopathic to native plants. This is also called as a ‘novel weapon hypothesis’ [9]. This effect spreads alien species to new areas and suppress original flora [6]. Mentioned hypothesis was already tested on invasive species such as Eucalyptus globulus [10], Plantago virginica [11], Solidago gigantea, Impatiens glandulifera, Erigeron annuus [12,13] and other.

Giant hogweed produces a large amount of chemical compounds. The novel weapon hypothesis can be helpful to understand the success of the giant hogweed in Europe [14]. Few studies were performed to evaluate impact of water extracts and root exudates of giant hogweed to native species [6,15–17]. Furanocoumarins produced by giant hogweed have negative effects on the germination of native species affected by soil or soil water extracts [14]. The water extract from the aboveground parts of giant hogweed were tested as inhibitors of the seed germination [2] and seedling growth (shoot length, root length) [6].

Volatiles as essential oil (EO) present second class of abundant compounds in genus Heracleum [18]. Composition of essential oil isolated by hydrodistillation from giant hogweed seeds as well as their potential antimicrobial effect was previously determined [7,18,19].

Thousands of plants belonging to different families are known to produce volatile oils serving as pollinator attractants, determinants of vegetation patterning or regulator of community structure via allelopathy [20].

Present study evaluates the content and composition of EO hydrodistilled from giant hogweed as well as the impact of EO on monocot (wheat—Triticum aestivum L.) and dicot species (garden cress—Lepidium sativum L., radish—Raphanus sativus L. and lettuce—Lactuca sativa L.). According to our knowledge this is the first report about the potential phytotoxic effect of EO from giant hogweed.

2. Results

2.1. Essential Oil Content and Composition

Total amount of EO hydrodistilled from the dried samples of giant hogweed collected on July was 0.91% of dry mass. There were identified 35 components which constituted 98.0% of total compounds. Dominant components were octyl acetate (62.6%), hexyl 2-methylburate (10.7%), hexyl isobutyrate (7.5%) and hexyl butyrate (6.5%). Four other components (octanal, hexyl acetate, hexyl hexanoate and octyl 2-methylbutyrate) were in the amounts slightly over 1% (Table 1). The rest of identified components were in the amounts below 1%.

| Compound Name            | [%] | RI | RI Lit. |
|--------------------------|-----|----|---------|
| n-Nonane                 | 0.1 | 899| 900     |
| α-Pinene                 | t   | 927| 934     |
| Isobutyl butyrate        | 0.1 | 937| 939     |
| Octanal                  | 1.3 | 979| 982     |
| n-Hexyl acetate          | 1.1 | 993| 995     |
| p-Cymene                 | 0.5 | 1012| 1016    |
| n-Butyl 2-methylbutyrate | 0.2 | 1024| 1026    |
| (E)-β-Ocimene            | t   | 1036| 1042    |
| 3-Methylbutyl butyrate   | t   | 1039| 1041    |
| γ-Terpinene              | 0.1 | 1049| 1055    |
| Octan-1-ol               | 0.5 | 1059| 1063    |
| Terpinolene              | 0.1 | 1074| 1081    |
Table 1. Cont.

| Compound Name                  | [%] | RI     | RI Lit. |
|-------------------------------|-----|--------|---------|
| n-Hexyl propionate            | 0.4 | 1084   | 1085    |
| n-Hexyl isobutyrate           | 7.5 | 1133   | 1132    |
| n-Hexyl butyrate              | 6.5 | 1173   | 1176    |
| n-Octyl acetate               | 62.6| 1200   | 1191    |
| (Z)-Oct-3-enyl acetate        | 0.3 | 1208   | 1200    |
| n-Hexyl 2-methylbutyrate      | 10.7| 1228   | 1224    |
| n-Hexyl isovalerate           | 0.8 | 1229   | 1227    |
| Lavanduloyl acetate           | 0.1 | 1268   | 1270    |
| Octyl propionate              | 0.1 | 1284   | 1280    |
| n-Octyl isobutyrate           | 0.8 | 1327   | 1329    |
| n-Hexyl hexanoate             | 1.4 | 1367   | 1371    |
| n-Octyl butyrate              | 0.4 | 1371   | 1371    |
| Dec-9-enyl acetate            | 0.1 | 1374   | 1378    |
| β-Bourbonene                  | 0.1 | 1379   | 1378    |
| n-Decyl acetate               | 0.1 | 1390   | 1390    |
| (E)-β-Caryophyllene           | 0.1 | 1413   | 1418    |
| n-Octyl 2-methylbutyrate      | 1.1 | 1416   | 1421    |
| Germacrene D                  | 0.3 | 1476   | 1479    |
| δ-Cadinene                    | t   | 1514   | 1520    |
| n-Octyl hexanoate             | 0.5 | 1558   | 1567    |
| β-Caryophyllene oxide         | 0.1 | 1570   | 1578    |

* t—traces less than 0.05%; RI—retention index compared between software prediction and literature [21,22].

2.2. Phytotoxic Effect

The biological effect of EO hydrodistilled from giant hogweed toward three dicot species (*Lepidium sativum* L., *Raphanus sativus* L. and *Lactuca sativa* L.) and one monocot species (*Triticum aestivum* L.) was evaluated as (a) influence on seed germination of four species (Table 2), (b) root elongation of four species and (c) number of roots in *Triticum aestivum*, respectively (Table 3). Six different doses (from 0.062 to 2.5 µg/mL) of EO were applied on seeds and their effect was evaluated.

Evaluation of seed germination was based on number of germinated seeds from 10 seeds placed into the Petri dish in the beginning of experiment (Table 2). Each EO dose was triplicated. No statistical difference was noted for evaluation seeds of *L. sativum* and *R. sativus* that appeared resistant toward applied concentrations of giant hogweed EO. On the contrary, *L. sativa* was sensitive to all EO concentrations. All ten seeds were germinated in control Petri dish, while only a slight difference was noted between control and the highest (2.5 µg/mL) and two lower doses (0.25 and 0.125 µg/mL). The number of germinated seeds in mentioned doses decreased from 8.7 ± 0.5 to 7.0 ± 0.8. The highest impact was noted in lowest dose (0.062 µg/mL) where the number of germinated seeds was about 47% lower (5.3 ± 1.3 germinated seeds) comparing to control. Impact of EO on germination of monocotyledonous seeds of *T. aestivum* was similar to that of lettuce. Statistical significance was noted in three doses (1.25, 0.25 and 0.062 µg/mL) and numbers of germinated seeds were 8.0 ± 0.0, 6.7 ± 0.9 and 6.3 ± 0.9, respectively.
Table 2. Effect of different doses of the essential oil from aerial parts of *Heracleum mantegazzianum* on the seed germination of four model plant species.

| EO Dose [µg/mL] | *Lepidium sativum* | *Raphanus sativus* | *Lactuca sativa* | *Triticum aestivum* |
|-----------------|---------------------|--------------------|------------------|---------------------|
| control         | 10.0 ± 0.0 a        | 10.0 ± 0.0 a       | 10.0 ± 0.0 a     | 9.0 ± 1.0 a         |
| 0.065           | 10.0 ± 0.0 a        | 10.0 ± 0.0 a       | 5.3 ± 1.3 c      | 6.3 ± 0.9 b         |
| 0.125           | 10.0 ± 0.0 a        | 9.7 ± 0.5 a        | 7.0 ± 0.8 b      | 8.7 ± 0.9 a         |
| 0.250           | 10.0 ± 0.0 a        | 10.0 ± 0.0 a       | 7.0 ± 1.4 b      | 6.7 ± 0.9 b         |
| 0.625           | 10.0 ± 0.0 a        | 9.3 ± 0.5 a        | 9.8 ± 0.8 a      | 8.3 ± 0.5 a         |
| 1.250           | 10.0 ± 0.0 a        | 10.0 ± 0.0 a       | 8.0 ± 0.8 a      | 8.0 ± 0.0 ab        |
| 2.500           | 10.0 ± 0.0 a        | 9.3 ± 0.5 a        | 8.7 ± 0.5 ab     | 9.3 ± 0.5 a         |

Each value is an average of 3 replications; SD = standard deviation; the letters a,b,c in each column present statistical differences according to Least Significant Difference’s Test (p = 0.05).

Table 3. Effect of different doses of the essential oil from aerial parts of *Heracleum mantegazzianum* on the root elongation of four model plant species and roots number of monocotyledoneous species.

| EO Dose [µg/mL] | *Lepidium sativum* | *Raphanus sativus* | *Lactuca sativa* | *Triticum aestivum* Radial Elongation [cm] | *Triticum aestivum* Roots Number |
|-----------------|---------------------|--------------------|------------------|--------------------------------------------|-----------------------------|
| control         | 10.69 a             | 4.52 a             | 1.58 a           | 3.13 a                                     | 2.73 a                      |
| 0.065           | 11.82 b             | 4.35 a             | 0.55 c           | 2.74 a                                     | 2.53 a                      |
| 0.125           | 10.94 a             | 4.11 a             | 0.86 b,c         | 2.69 a                                     | 2.90 a                      |
| 0.250           | 10.12 a             | 5.04 a             | 1.28 a,b         | 2.00 b                                     | 2.36 a                      |
| 0.625           | 11.11 a             | 4.98 a             | 1.15 a,b         | 2.19 a                                     | 2.70 a                      |
| 1.250           | 9.30 c              | 4.88 b             | 0.99 b,c         | 3.21 a                                     | 2.63 a                      |
| 2.500           | 11.28 a             | 4.52 a             | 1.38 a,b         | 3.52 c                                     | 3.50 b                      |

Each value is an average of 3 replications; the letters a,b,c in each column present statistical differences according to Least Significant Difference’s Test (p = 0.05).

More variable effect was noted in evaluation of root elongation after application of EO in different doses (Table 3). Except expected inhibition effect, also stimulation effect was noted. Significant stimulation effects were observed in dicotyledonous model plants. Roots of *L. sativum* at the lowest EO dose (0.062 µg/mL) were 10% longer in comparison to control. In monocotyledonous model plant *T. aestivum* the influence was the most significant at the highest dose (2.5 µg/mL) when the roots were 67% longer than in control.

On the contrary, inhibitory effect on root elongation was noted in *L. sativa* at all EO doses although only at three doses differences were statistically significant. Specific evaluation focused on different number of roots in monocotyledoneous plant species. The average number in control was 2.73 roots. Significant difference was evaluated after application of the highest dose (2.5 µg/mL) when average number of roots increased to 3.5 roots (p = 0.05).

3. Discussion

The content of EO isolated from giant hogweed was previously determined for different parts of the plant. There were noted 0.45% in stems and 0.95% in fruits [19], as well as others evaluated 3% of EO in fruits [18]. Our finding of 0.91% EO in whole aerial parts is within the range presented by other authors.

Comparison of the identified compounds in giant hogweed EO also revealed good accordance with published study. As a major component octyl acetate was previously identified followed by hexyl-2-methylbutyrate, octanol, octyl butyrate, octyl-2-methylbutyrate, hexyl acetate, octyl isobutyrate and hexyl isobutyrate in flowers and fruits, p-cymene in roots, and stems and β-guaiene
in leaves [18,19]. Aliphatic esters were identified as the main group of compounds in EO of giant hogweed from Poland [7]. Dominated components in EO identified in giant hogweed from Russia were octyl butyrate (32.0%), octyl acetate (18.0%) and hexyl butyrate (9.2%) [23]. Similar composition of seed EO as in H. mantegazzianum was noted in H. sosnowskyi [24]. Chemical composition of H. mategazzianum as well as H. sosnowskyi seed EOs that contained mainly octanol and hexanol esters of acetic acid, butyric and isobutyric acids differ from most of the evaluated EOs, in which terpenes dominate.

The root elongation response of L. sativum on EO could be generally explained by the hormesis theory. Hormesis can be defined as a biphasic response in which high doses of a toxic agent could cause inhibition of growth while low dose of the same toxic can cause stimulation [25]. The factors responsible for inducing hormesis are known as hormetins or stressors. In this sense, it has been established that in plants the challenge with different levels of stress constitutes an adaptive process, having reminiscence with the phenomenon of hormesis abovementioned. This stress can be established as “eustress” (beneficial stress) if the effect is similar to the hormetic effect in low doses of a toxin, or “distress” (harmful stress) if the level of this generates an irreversible or negative damage in the plant [26]. This explanation could be applied to the different effects visible in Lactuca sativa and Triticum aestivum in evaluation of germination and root elongation.

No significant differences were found in the chemical composition of the examined seed samples of Heracleum sosnowskyi and Heracleum mantegazzianum (Apiaceae), which confirms the suggestions that the species can be closely related [7]. The study useful for comparison of our results tested allopatic effect of EO isolated from H. sosnowskyi seeds on two dicots and four monocot species [24]. Different susceptibilities to H. sosnowskyi EO was evaluated in seeds germination as well as in radical length. The most susceptible were Bromus secalinus and Avena fatua (both monocots). Other comparable study was done by cotton swab method to characterize the effect of volatiles from H. sosnowskyi fruits on Lactuca sativa. The radicle and hypocotyl growth of lettuce seedlings were significantly inhibited while the germination of lettuce seeds was not affected by volatiles from the H. sosnowskyi fruits [27].

The chemical composition of essential oil varies greatly among species. While aliphatic esters dominate in Heracleum species, the compositions of the majority of known EOs generally contain terpenes. Many of the species in which terpenes dominated have been tested for potential phytotoxic effect [28–31]. Some scientific study of phytotoxic activity of EO reflects the different impact on monocot and dicot plant species. Different studies reported that monocot species are more resistant to EOs from plants belonging to different families (Cupressaceae, Asteraceae, Anacardiaceae, Cardiopetiridaceae, Lamiaceae, Polygonaceae, Rutaceae) comparing to dicot species [28,32,33]. On the other hand, evaluation of phytotoxic activity of S. terrae-albae (Asteraceae) EO on a dicot plant Amaranthus retroflexus and a monocot plant Poa annua revealed that the monocot plant, P. annua, was more sensitive to essential oil than dicot one [34].

4. Materials and Methods

4.1. Plant Material

Plant material was collected during the vegetative season 2017 at Lekárovce (GPS 48.608129 E 22.140227) in the eastern part of Slovakia. Collection was done in July when the plant was fully maturated. There were collected aboveground parts (whole stems with leaves, flowers and seeds) from different individuals which presented fresh plant material. Plant material was placed on thin layer on filter paper and was left in room temperature approximately 14 days, until all plant material was possible to crumble.

4.2. Essential Oil Isolation

The dried plant material were cut into small pieces and divided into three proportionally similar samples. Then plant material was subjected into the flasks to hydrodistillation in a Clevenger-type
apparatus (Kavaliergalss, Sáza, Czech Rep.). Distillation lasted 3 h. Isolated EO was placed in dark vials at +4 °C until other analysis. The plant material yielded pale-yellow oils with strong floral odor.

4.3. Chromatographic Analysis

Essential oil was analyzed by GC-MS-FID. The analysis was performed on a Trace GC Ultra coupled with DSQII mass spectrometer (Thermo Electron, Waltham, MA, USA). A simultaneous GC-FID and MS analysis was performed using a MS-FID splitter (SGE Analytical Science, Ringwood Victoria, Australia). Mass range was 33–550 amu, ion source-heating: 200 °C, ionization energy: 70 eV. One microliter of essential oil solution (80% v/v) diluted in pentane-diethyl ether was injected in split mode at split ratios (50:1). Operating conditions for capillary column Rtx-1 MS (60 m × 0.25 mm i.d., film thickness 0.25 µm), and temperature program: 50 (3 min)–300 °C (30 min) at 4 °C/min. Injector and detector temperatures were 280 °C and 300 °C, respectively. Carrier gas was helium (constant pressure: 300 kPa).

4.4. Identification of Compounds

The identification of compounds was based on a comparison of their mass spectra (MS) and linear retention indices (RIs, non-polar column), determined with reference to a series of alkanes C8–C24, by comparing with those in MassFinder 3 [21], Adams [22] as well as with computer mass libraries NIST 2012 and the Wiley Registry of Mass Spectral Data 8th edition.

4.5. Model Plants

Evaluation of potential phytotoxic effect of EO was evaluated on seeds of four species. There were chosen three dicotyledonous species as Raphanus sativus L. (radish), Lepidium sativum L. (garden cress) and Lactuca sativa L. (lettuce) and one monocotyledonous species Triticum aestivum L. (common wheat) as a model plants. R. sativus var. radicula Pers. (cv. ‘Duo’), L. sativum L. (cv. ‘Dánska’), and L. sativa (cv. Král Máje I.) seeds were purchased from Zel Seed (Slovakia). Common wheat was obtained from the Research Center in Malý Šariš.

4.6. Phytotoxic Activity Assay

Phytotoxic assay followed previously used method [35]. Two factors were taken into account in the experimental treatment: (i) four test plants: [radish (R. sativus L.), garden cress (L. sativum L.), lettuce (L. sativa L.) and common wheat (T. aestivum L.)] and (ii) six different H. mantegazzianum essential oil concentrations: (2.5, 1.25, 0.625, 0.25, 0.125, and 0.062 µg/mL). The essential oils were dissolved in distilled water/acetone 99.5:0.5 and diluted to prepare the desired concentrations. Distilled water/acetone 99.5:0.5 was used as control. Test seeds were surface sterilized in 95% EtOH for 15 s and rinsed thrice in distilled water. Ten sterilized seeds were sown into each Petri dish (90 mm dia) containing 5 layers of Whatman filter paper. In each Petri dish 7 mL of essential oil solutions of different concentration or distilled water/acetone 99.5:0.5 was added. Each treatment was triplicated. The Petri dishes were kept in growth chamber (20 ± 1 °C, natural photoperiod, Sanyo, MLR-351H). Evaluation of germination and the radicle length (cm) was measured after 120 h.

4.7. Statistical Analysis

Data from the experiment were subjected to analysis of variance (ANOVA) by Least Significant Difference’s Test. Statistical analyses were performed using the PlotIT ver. 3.2 program (Scientific Programming Enterprises, Haslett, MI, USA).

5. Conclusions

The aims of the study were based on the novel weapon hypothesis. The present study evaluated phytotoxicity of volatiles produced by alien species H. mantegazzianum to model plants. According to
our findings, we can conclude that EO hydrodistilled from the alien plant species presented biological activity on the dicot and monocot plant species. The most sensitive was *Lactuca sativa* comparing to *Lepidium sativum* and *Raphanus sativus* in seed germination as well as in root length evaluation. Stimulation effect was visible in both root length and root number at two or one highest doses, respectively in monocot species. *Triticum aestivum* L.

Composition of EO is characteristic for the genus *Heracleum* where the dominant compounds are aliphatic esters which differ from dominant terpenoids in different plant groups. Regardless the EO composition, the volatile components presented similar biological effect.

**Author Contributions:** M.M., J.J., V.S. and Z.G. performed essential oil isolation, established phytotoxic activity experiment and its evaluation; A.W.-B. performed GC-MS analysis; M.R. analyzed the data and performed statistical analysis; D.G. and J.P. conceived and designed the experiments, evaluated data and wrote the paper, D.K. provided project administration, consult data and wrote paper.

**Funding:** This research was funded by Grant Agency for PhD. students and young researchers and pedagogical workers of University of Presov, grant number GaPU 52/2018 (0.2); by Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic, grant numbers VEGA 1/0783/18 (0.2); VEGA 2/0013/16 (0.2); and by the ERDF-funded operational program Research and Development, the project code IMTS: 2622022116 (0.2) and ITMS: ITMS 2622012041 (0.2).

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Pergl, J.; Perglová, I. *Heracleum mantegazzianum*. Delivering Alien Invasive Species Inventories for Europe. DAISIE 2006. Available online: [www.europe-aliens.org/pdf/Heracleum_mantegazzianum.pdf](http://www.europe-aliens.org/pdf/Heracleum_mantegazzianum.pdf) (accessed on 3 March 2018).

2. Balezentiene, L.; Renco, M. Phytotoxicity and accumulation of secondary metabolites in *Heracleum mantegazzianum* (Apiaceae). *Allelopathy J.* 2014, 33, 267–276.

3. Reinhardt, F.; Herle, M.; Bastiansen, F.; Streit, B. *Economic Impact of Spread of Alien Species in Germany*; Environmental Research, Federal Ministry of Environment, Nature Conservation and Nuclear Safety, Research Report 201 86 211, UBA-FB 000441e; Federal Environmental Agency (Umweltbundesamt): Berlin, Germany, 2003; 229p.

4. Starfinger, U.; Kowarik, I. *Heracleum mantegazzianum* Sommier & Levier (Apiaceae), Riesen-Barenklau. *NeoFlora*. Bundesamt f. Naturschutz, Ed.; 2003. Available online: [www.neophyten.de](http://www.neophyten.de) (accessed on 30 October 2017).

5. Thiele, J.; Otte, A. Impact of *Heracleum mantegazzianum* on invaded vegetation and human activities. In *Ecology and Management of Giant Hogweed (Heracleum mantegazzianum)*; Pyšek, P., Cock, M.J.W., Nentwig, W., Ravn, H.P., Eds.; CABI International: Wallingford, UK, 2007; pp. 144–156.

6. Csiszár, Á.; Korda, M.; Schmidt, D.; Šporcic, D.; Súle, P.; Teleki, B.; Tiborcz, V.; Zagyvai, G.; Bartha, D. Allelopathic potential of some invasive plant species occurring in Hungary. *Allelopathy J.* 2013, 31, 309–318.

7. Jakubksa-Busse, A.; Śliwiński, M.; Kobyłka, M. Identification of bioactive components of essential oils in *Heracleum sosnowskyi* and *Heracleum mantegazzianum* (Apiaceae). *Arch. Biol. Sci.* 2013, 65, 877–883. [CrossRef]

8. Tschiedel, K. *Wenn Neophyten zum Problem Werden (Invasive Pflanzenarten in Ostschlesien)*; Naturschutzbehörde des Landeskreis Löbau-Zittau: Zittau, Germany, 2005.

9. Callaway, R.M.; Ridenour, W.M. Novel weapon: Invasive success and the evolution of competitive ability. *Front. Ecol. Environ.* 2004, 2, 436–443. [CrossRef]

10. Becerra, P.I.; Catford, J.A.; Inderjit; McLeod, M.L.; Andonian, K.; Aschehoug, E.T.; Montesinos, D.; Callaway, R.M. Inhibitory effects of *Eucalyptus globulus* on understorey plant growth and species richness are greater in non-native regions. *Global Ecol. Biogeogr.* 2018, 27, 68–76. [CrossRef]

11. Wang, H.; Zhou, Y.; Chen, Y.; Wang, Q.; Jiang, L.; Luo, Y. Allelopathic Potential of Invasive *Plantago virginica* on Four Lawn Species. *PLoS ONE* 2015, 10, e0125433. [CrossRef]

12. Del Fabbro, C.; Güsewell, S.; Prati, D. Allelopathic effects of three plant invaders on germination of native species: A field study. *Biol. Invasions* 2014, 16, 1035–1042. [CrossRef]
13. Grul'ová, D.; Baranová, B.; Ivanova, V.; de Martino, L.; Mancini, E.; de Feo, V. Composition and biological activity of essential oils of Solidago species and the possible impact on their invasions. *Allelopathy J.* 2016, 39, 129–142.

14. Wille, W.; Thiele, J.; Walker, E.A.; Kollmann, J. Limited evidence for allelopathic effects of giant hogweed on germination of native herbs. *Seed Sci. Res.* 2013, 23, 157–162. [CrossRef]

15. Jandová, K.; Dostál, P.; Cjatham, T.; Kameník, Z. Intraspecific variability in allelopathy of *Heracleum mantegazzianum* is linked to the metabolic profile of root exudates. *Ann. Bot.* 2015, 115, 821–831. [CrossRef] [PubMed]

16. Loydi, A.; Donath, T.W.; Eckstein, R.L.; Otte, A. Non-native species litter reduces germination and growth of resident forbs and grasses: Allelopathic, osmotic or mechanical effects? *Biol. Invasions* 2015, 17, 581–595. [CrossRef]

17. Walasek, M.; Grzegorczyk, A.; Malm, A.; Skalicka-Woźniak, K. Bioactivity-guided isolation of antimicrobial coumarins from *Heracleum mantegazzianum* Sommier & Levier (Apiaceae) fruits by high-performance counter-current chromatography. *Food Chem.* 2015, 186, 133–138. [CrossRef] [PubMed]

18. Skalicka-Woźniak, K.; Grzegorczyk, A.; Świątek, Ł.; Walasek, M.; Widelski, J.; Rajtar, B.; Polz-Dacewicz, M.; Malm, A.; Elansary, H.O. Biological activity and safety profile of the essential oil from fruits of *Heracleum mantegazzianum* Sommier & Levier (Apiaceae). *Food Chem. Toxicol.* 2017, 109, 820–826. [CrossRef]

19. Szumny, A.; Adamski, M.; Winska, K.; Maczka, W.; Nowakowski, P. Chemical composition of volatile oils of giant-hogweed. *Przem. Chem.* 2012, 91, 1024–1027.

20. Kaur, S.; Singh, H.P.; Mittal, S.; Batish, D.R.; Kohli, R.K. Phytotoxic effects of volatile oil from *Artemisia scoparia* against weeds and its possible use as a bioherbicide. *Ind. Crop. Prod.* 2010, 32, 54–61. [CrossRef]

21. Hochmuth, D. MassFinder 3: GC/MS Visualisation, Interpretation and Library Administration. *Mass Spectral Library “Terpenoids and Related Constituents of Essential Oils”,* (C) 1999–2006 Dr. Detlev Hochmuth: Hamburg, Germany.

22. Adams, R.P. *Identification of EssentialOil Components by Gas Chromatography/Mass Spectrometry;* Allured: Carol Stream, IL, USA, 2007.

23. Tkachenko, K. Constituents of essential oils from fruits of some *Heracleum* L. species. *J. Essent. Oil Res.* 1993, 5, 687–689. [CrossRef]

24. Synowiec, A.; Kalemba, D. Composition and herbicidal effect of *Heracleum sosnowskyi* essential oil. *Open Life Sci.* 2015, 10, 425–432. [CrossRef]

25. Calabrese, E.J. Hormesis: A conversation with a critic. *Environ. Health Persp.* 2009, 117, 1339–1343. [CrossRef]

26. Hideg, E.; Jansen, M.A.; Strid, A. UV-B exposure, ROS, and stress: Inseparable companions or loosely linked associates? *Trends Plant Sci.* 2013, 18, 107–115. [CrossRef]

27. Mishyna, M.; Laman, N.; Prokhorov, V.; Maninang, J.S.; Fujii, Y. Identification of octanal as plant growth inhibitory volatile compound released from *Heracleum sosnowskyi* fruit. *Nat. Prod. Comun.* 2015, 10, 771–775.

28. Amri, I.; Hamrouni, L.; Hanana, M.; Jamoussi, B. Herbicidal potential of essential oils from three Mediterranean trees on different weeds. *Curr. Bioact. Compd.* 2012, 8, 3–12. [CrossRef]

29. Angelini, L.G.; Carpanese, G.; Cioni, P.L.; Morelli, I.; Macchia, M.; Flamini, G. Essential oils from Mediterranean lamiaceae as weed germination inhibitors. *J. Agric. Food Chem.* 2003, 51, 6158–6164. [CrossRef]

30. Cavalieri, A.; Caporali, F. Effects of essential oils of cinnamon, lavender and peppermint on germination of Mediterranean weeds. *Allelopathy J.* 2010, 25, 441–451.

31. Taban, A.; Saharkhiz, M.J.; Hadian, J. Allelopathic potential of essential oils from four *Satureja* spp. *Biol. Agric. Hortic.* 2013, 29, 244–257. [CrossRef]

32. Almarie, A.A.; Mamat, A.S.; Wahab, Z.; Rukunudin, I.H. Chemical composition and phytotoxicity of essential oils isolated from Malaysian plants. *Allelopathy J.* 2016, 37, 55–70.

33. Shao, H.; Zhang, Y.M.; Nan, P.; Huang, X.L.; Zhang, C. Chemical composition and phytotoxic activity of the volatile oil of invasive *Xanthium italicum* Moretti from Xinjiang, China. *J. Arid Land* 2013, 5, 324–330. [CrossRef]
34. Shao, H.; Hu, Y.; Han, C.; Wei, C.; Zhou, S.; Zhang, C.; Zhang, C. Chemical composition and phytotoxic activity of *Seriphidium terrae-albae* (Krasch.) Poljakov (Compositae) essential oil. *Chem. Biodivers.* **2018**, *15*, e1800348. [CrossRef] [PubMed]

35. Mancini, E.; Camele, I.; Elshafie, H.S.; De Martino, L.; Pellegrino, C.; Grulova, D.; de Feo, V. Chemical composition and biological activity of the essential oil of *Origanum vulgare* ssp. Hirtum from different areas in the Southern Apennines (Italy). *Chem. Biodivers.* **2014**, *11*, 639–651. [CrossRef]

**Sample Availability:** All samples of the compounds are available from the authors.

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).