

Review

Invasion of the Giant Hogweed and the Sosnowsky's Hogweed as a Multidisciplinary Problem with Unknown Future—A Review

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Abstract: Caucasian hogweeds are plants introduced to Europe from the Caucasus area. This review concerns the two most common ones—the giant hogweed *Heracleum mantegazzianum* and the Sosnowsky's hogweed *Heracleum sosnowskyi*. The first of them was imported as garden decorations from the 19th century, mainly to Western Europe, while the second one was introduced from the mid–20th century to agricultural areas in Eastern Europe. Nowadays, these two species create one of the most problematic invasions in the world. This review aimed to synthesize research on those invaders based on 277 articles selected from the “Scopus” database. Most of the articles concerned their extensive distribution, at least on a continental scale and the rapid dispersal. The reviewed research showed that the complex physicochemical properties of hogweeds tissues and secretions significantly affected insects, aphids, ants, nematodes, fungi, soil microorganisms, plant communities, birds, and many other components of the ecosystems. This knowledge turned out to be disproportionately small to the scale of the problem. The review also showed what ecological traits of hogweeds were responsible for their wide and various role in the environment. Thus far, no effective method to eradicate Caucasian hogweeds has been found. This could be a growing mistake, given that they are probably during the rapid evolutionary changes within the range of their invasion.



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Keywords: *Heracleum mantegazzianum*; *Heracleum sosnowskyi*; dispersal; invasion control; biochemistry; plant ecology; biodiversity; agricultural sciences; genetics

1. Introduction

Biological invasions are one of the most serious environmental problems threatening biodiversity on a global scale. Scientists and environmental practitioners usually agree that invading species should be removed by any method and at any time. Nevertheless, complete removal of invaders is often not feasible or possible at all. Moreover, it was usually not investigated whether the removal of invading species harmed some native organisms that have already adapted to them. Due to the present mass extinction of species, urbanization and environmental degradation, as well as irreversible loss of habitats, the removal of biological invasions need to be discussed when it is carried out without compromises with the fact that invaders can create some new niche opportunities for native organisms. This review showed the example of complex invasion, knowledge of which can fill these gaps and significantly affect invasion science.

Starting from the nineteenth century, some species of the *Heracleum* genus (from the Umbelliferae family) from the south-western regions of Asia (mainly Caucasus) were intentionally introduced to Europe. They were planted as a garden decoration [1], forage for cattle, and as melliferous plants [2]. The most known became the giant hogweed *Heracleum mantegazzianum* Sommier and Levier and the Sosnowsky's hogweed *Heracleum sosnowskyi* Manden. Due to similarities in structure, the same invasive features, and almost identical toxicity [3], those plants were often treated together and commonly called “Caucasian hogweeds.” Both described species reach large sizes, including a height of up

to 4–5 m, a large area of leaf rosettes composed of 2–3 m leaves, stable flowering shoots resembling woody plants, as well as large inflorescences. Due to the significant influence of large hogweeds on many elements of ecosystems, their invasion created a system that integrates environment, agriculture, forestry, land use, hydrosphere, soil system, global change ecology, biodiversity, management, and conservation. It is difficult to find such a multidisciplinary research system. Those plants were the subject of research by specialists from various fields. However, the presenting review emphasized the paradoxically small number of articles on the impact of Caucasian hogweeds on biodiversity. Their distribution on a global scale, including North America [4,5], the significant role of human density in their spread [6], the unpredictability of the invasion dispersal since its beginning [7], and rich chemical composition indicated that this is a big mistake. As plants that cause burns of mammals, including humans, alien hogweeds are especially recommended for removal, and the consequences are unknown. Nobody has yet comprehensively described this invasion. This review aimed to synthesize knowledge about Caucasian hogweeds.

2. Materials and Methods

For this review, the full Latin names of giant hogweed *H. mantegazzianum* and Sosnowsky's hogweed *H. sosnowskyi*, as well as both of them, were written in the scientific database, "Scopus." The choice of Latin names was due to the fact that the English versions could be spelled differently depending on the source (Sosnowsky's hogweed was also called Sosnowski's hogweed or Sosnowskyi's hogweed; giant hogweed was also called Mantegazza or Mantegazzi hogweed). In a few cases, the name of the species could be wrong because sometimes Sosnowsky's hogweed might have been called *H. mantegazzianum* due to diagnostic mistakes, or locally it was its Latin name because *H. mantegazzianum* was also the historical name of this species before its official announcement as a separate one. Nevertheless, the errors mentioned were exceptions to the rule. Their possibility contributed to preparing this review based on a scientific database without supplementing it with articles from more common databases such as Google Scholar. The results of the search in "Scopus" were 232 articles about *H. mantegazzianum*, 139 articles about *H. sosnowskyi*, and 21 articles with both names (on 14 January 2022). None of the articles containing 2 names of Caucasian hogweeds was missing from previous searches. For comparison, the number of articles about *H. mantegazzianum* in the second scientific database, "Web of Science" was 197, the number of articles about *H. sosnowskyi* was 117, while 19 articles contained both names (on 10 February 2022). More articles were available in "Scopus," thus it was chosen to prepare this revision. Of all the articles containing one of the names in the Excel spreadsheet, 27 were duplicated, thus 344 non-duplicated articles were selected (Figure 1). Based on the titles and abstracts of the articles, 63 were rejected, which contained only general information about the species and were related to similar descriptions of human burns resulting from contact with Caucasian hogweeds. Then another 4 articles were removed from the database, which turned out to be non-English versions of the articles already included. Ultimately, this review summarized the knowledge on Caucasian hogweeds based on 277 published articles, of which 160 were about *H. mantegazzianum*, 107 were about *H. sosnowskyi*, and 10 were about both plants. All articles included in this review were matched to the main areas which they concerned (Table 1). Some articles (around 5%) could be matched to 2–3 areas. Articles were classified based on their conclusions, e.g., if it was about distribution and hogweed management and other articles already described distribution in a similar region, then the article was assigned to "invasion control". Some articles concerned the potential effects of hogweeds on biodiversity, but the research was conducted under controlled conditions, thus they fell into "plant ecology."

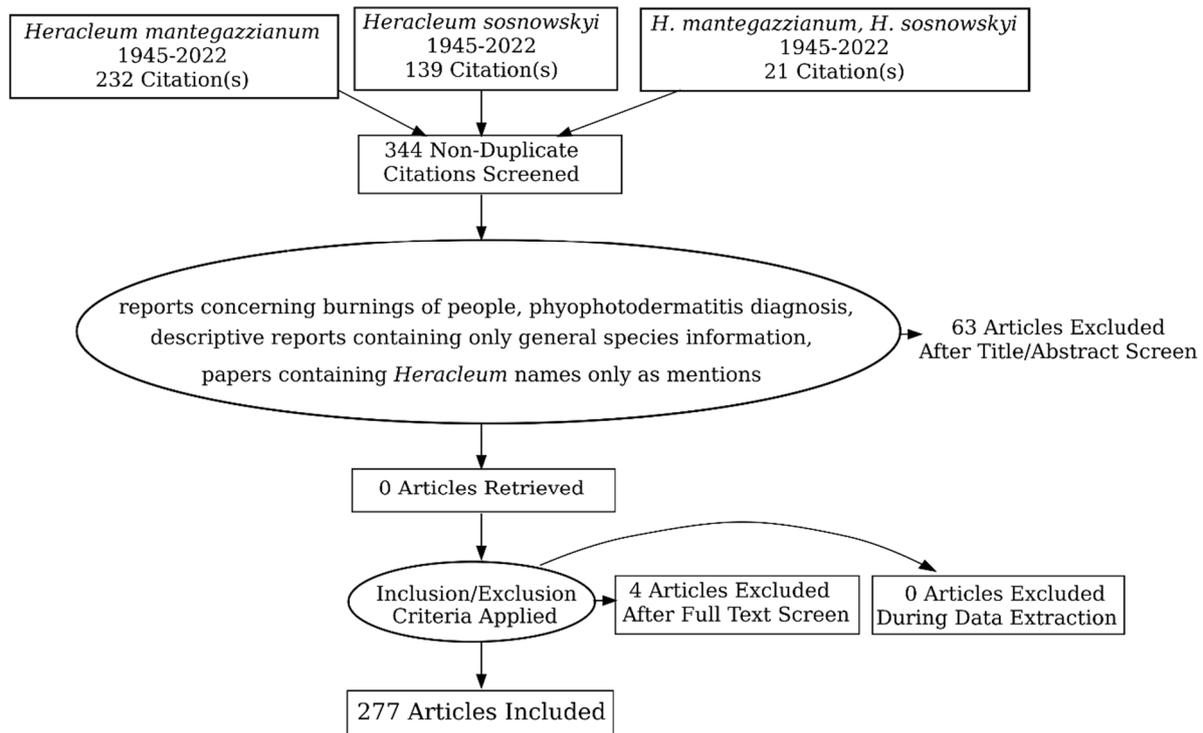


Figure 1. PRISMA flow diagram with the search of articles for this study showing numbers excluded at the particular stages of this review. Only articles retrieved from the “Scopus” (Elsevier) database were presented.

Table 1. List of the research areas used for sorting the articles concerning the giant hogweed and the Sosnowsky’s hogweed found in the “Scopus” database.

Research Areas	Classification Criteria
Agricultural sciences	Agrotechnical research on the importance of hogweeds as crops and their role for biological methods of crops removal and protection.
Biochemistry	Biochemical studies that explained the chemical composition of hogweeds and the possible uses of hogweeds chemicals.
Biodiversity	Research on various community compositions near hogweeds, information on new species appearing on hogweeds, research showing the potential for depletion, and other ecosystem modifications affecting biodiversity associated with Caucasian hogweeds.
Dispersal	Articles describing the distribution, spreading and working with tools enabling detection and dispersal monitoring of invasive hogweeds.
Environmental sciences	The effects of temperature, snow cover, and other elements of the environment on hogweeds.
Genetics	Research on hogweeds genetics—the appearance of hybrids with aliens and natives, genetic differences between aliens from native and invasive ranges.
Invasion control	Articles describing methods of Caucasian hogweeds removal and effects of their eradication.
Mathematics	Analysis used in bioeconomy.
Plant ecology	Mechanisms of the influence of Caucasian hogweeds on other plants explaining details of their allelopathic and similar properties, e.g., conducted in common garden experiments, based on studying fruits and seed production, etc.

3. Results

Despite the larger number of articles concerning *H. mantegazzianum*, it appeared that both selected species of hogweeds were often studied. Research concerning Caucasian

hogweeds was multidisciplinary, one article used this invasion even in the bioeconomy [8]. Nevertheless, giant hogweed has been problematic in Western Europe (Czech Republic, Germany, Great Britain) with greater opportunities for scientific development, which likely contributed to more articles on this species in terms of its dispersal (26.2% of articles on *H. mantegazzianum*), controlling its invasion (13.8%), experimental research contributing to knowledge in plant ecology (17.5%), describing its chemical composition (15%), as well as its impact on biodiversity (13.1%), Figure 2. In the case of *H. sosnowskyi*, the proportion of articles regarding dispersal and plant ecology to the total research on this species was similar to those on giant hogweed (despite a smaller number of articles) and amounted to 23.4% and 15% of research on Sosnowsky's hogweed, respectively (Figure 2). In comparison with giant hogweed, a significantly smaller proportion of articles concerning *H. sosnowskyi* were those on invasion control (7.5% of articles on this species), while there were more articles on agricultural sciences (12.1% research on *H. sosnowskyi* and 6.3% of those concerning *H. mantegazzianum*), as well as articles about *H. sosnowskyi* in the field of biochemistry (25.2%), Figure 2. It was rather *H. sosnowskyi*, not *H. mantegazzianum*, that was the subject of practical agricultural and biochemical science, which was reflected in the state of knowledge from those areas and the proportions of articles from these fields among all research concerning Sosnowsky's hogweed.

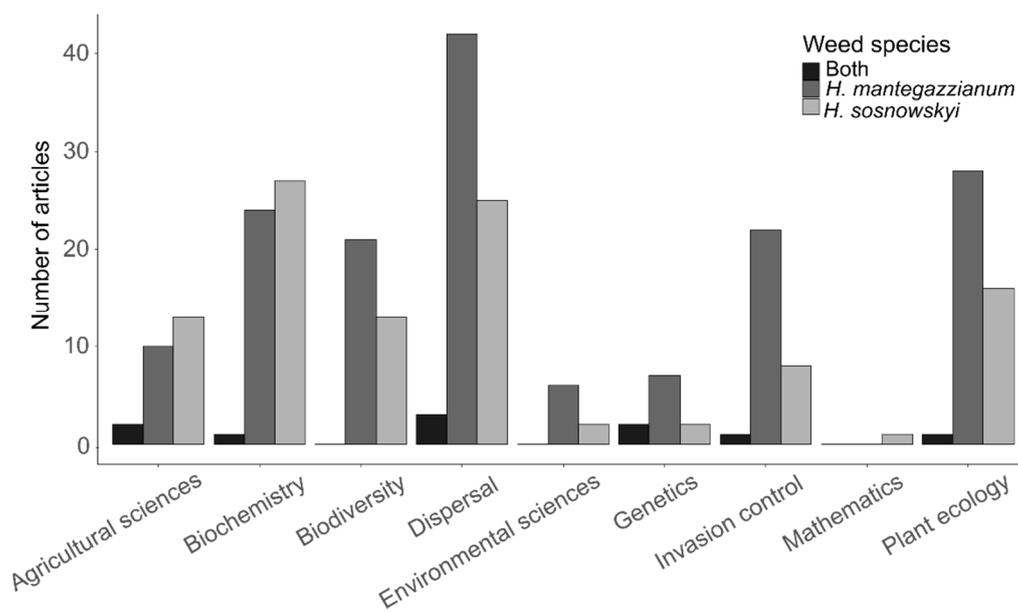


Figure 2. The number of articles included in this review concerning the two described Caucasian hogweeds distinguished into particular research areas.

3.1. Review of Articles Sorted into Research Areas

3.1.1. Dispersal of the Caucasian Hogweeds

Caucasian hogweeds spread very rapidly, starting from the end of the 1980s when agricultural production systems and markets changed because of the fall of communism. With a dramatic decline in agriculture, hogweeds stopped being mowed [9]. The Sosnowsky's hogweed invasion became problematic, especially in countries near the Baltic Sea: Latvia, Lithuania [10,11], Poland [12–15], the European part of Russia [16–25], as well as in Ukraine [26–28] and other parts of Eastern Europe, such as Turkey [29] and Bulgaria [30]. In central and Eastern Europe, two Caucasian hogweeds species, *H. mantegazzianum* and *H. sosnowskyi*, became problematic, e.g., in Poland [14], Ukraine [26,27], Russia [22]. Giant hogweed has been known from the Czech Republic [31–37], Germany [38–40], Austria [41], Great Britain [42], Slovakia [43], Croatia [44], Denmark [45], Norway [46]. The range of Caucasian hogweeds became so wide that they were the subject of many advanced spatial analyses, which were a great contribution of knowledge to the modern invasion ecol-

ogy [47–53]. The analysis of the distribution of both species showed that the regions most affected by the compact invaded areas of Caucasian hogweeds have been located mainly in Eastern Europe, where poorer countries did not have funds to remove the invasion, especially around 30–40 years ago when together with the mentioned fall of communism and modification of the agricultural system, former crops were abandoned. Sometimes the invasion patches became so large that satellite imagery and other spatial analysis tools were used to select where the problem with invasion should be resolved as a priority [54–59]. In connection with the massive spread of *H. sosnowskyi* in Russia, even questions were raised about the need to create a special federal target program to control it. There have been images used from the Sentinel-2 satellite with a resolution of 10 m. Satellite images from space vehicles helped monitor the distribution of Sosnowsky's hogweed [57]. Various spatial analysis tools were also considered useful for assessing the extent of Caucasian hogweeds invasion in central and Western Europe [60–63].

One of the most interesting methods of studying changes in the hogweed range was the comparative analysis of maps and scientific collections from different periods. In the area of the Czech Republic, it was studied how the *H. mantegazzianum* ability to persist affected its distribution. Of the total number of 521 historical sites known from literature and herbaria since the end of the 19th century, it persisted at only 124 (23.8%) ones. The persistence rate differed concerning habitat type and was highest in meadows and forest margins. Factors that best explained persistence were type of habitat, urbanity (higher persistence outside urban areas), proximity to the place of the species introduction, metapopulation connectivity, and distance to the nearest neighboring population [64]. Caucasian hogweeds have been analyzed on various scales (regional, landscape, national, continental) and have been considered a plant invasion of at least continental range [65–67]. It was predicted that the spread of invasive hogweeds might lead to the colonization of other continents [68]. Some studies concerned the rules of plant dispersal and the definition of vectors of this process, including anthropogenic impacts [69–72]. There were also articles about the distribution patterns of Caucasian hogweeds in areas of their native range [73] for comparison with the area of nowadays invasion.

It is worth emphasizing that the current geographical distributions of the giant hogweed and the Sosnowsky's hogweed became different because of their different climatic requirements [2]. Although in some countries both of them co-exist, sometimes might have been mistakenly identified or named (see above), and thus knowledge of their locations (including the former ones) and ranges still needs to be completed.

3.1.2. How Did Caucasian Endemic Plants Become a Widespread Invasion?

The widespread distribution of Caucasian hogweeds and very large problems with their invasion do not indicate that, at first, these endemic plants were respected botanical discoveries. The Sosnowsky's hogweed *H. sosnowskyi* comes from the eastern and central Caucasus, central, eastern and south-western Transcaucasia and north-eastern Anatolia in Turkey [2]. The name "Sosnowsky's hogweed" has its genesis in the name of a scientist and researcher of the Caucasus flora, Dymitr Sosnowsky, and was given in 1944 by the plant finder Ida P. Mandenova. It was introduced to northwest Russia at the end of the 1940s for evaluation in experimental farms as fodder crops. This plant was grown on a mass scale in kolkhozes (cooperatives gathering smaller farms) and sovkhoses (large state-owned farms) in the former Soviet Union as a gift of the All-Union Institute of Plant Cultivation in Leningrad since late 1950. Starting from the 1960s, *H. sosnowskyi* was cultivated over wide areas in Russia, Belarus, Ukraine, Hungary, Poland, Lithuania, Latvia, Estonia, and the former German Democratic Republic [2]. Because plants were not palatable to cattle and the first burns of animals and people were recorded, crops were abandoned in many places. For example, in Bryansk (near the Republic of Belarus), Sosnowsky's hogweed was cultivated as an ensilage plant at some collective farms in the 1970s, but the cultivation was terminated in the 1980s [74]. The real problem with the invasion of this species probably

appeared in the late 1980s and early 1990s, along with agricultural reform, the collapse of collective farms, and the inaccurate liquidation of crops.

The giant hogweed *H. mantegazzianum* is native to the western Greater Caucasus (Russia, Georgia), where it grows in species-rich, tall-herb mountain meadows, clearings, and forest margins. It was introduced as a garden ornamental plant around 1817, and its first naturalized population was documented in Cambridgeshire in 1828 [2]. It was first recorded in the Czech Republic in 1862 in the Bohemia park, where it spread across the country and became invasive [31,32]. In the Czech Republic, for example, the front of the population was advancing at 10 m per year [75]. In Germany, *H. mantegazzianum* became an invader in about two-thirds of districts and occupied 68% of grid cells of the national floristic map, and about one-third of surveyed stands were dominant with its cover-abundances exceeding 50% [40].

Caucasian hogweeds became undesirable invaders due to their large sizes, prolific leading to gross changes in vegetation, obstruction of access to riverbanks, and soil erosion [74]. The plants have been spreading on derelict lands, garden plots, slopes of drainage canals, roadsides, forming arrays ranging from a few square meters to several hectares. The variety of methods for removing *H. mantegazzianum* and *H. sosnowskyi* invasion, as well as the effects of eradication below expectations, were among the aspects that indicated the need to treat these methods in an interdisciplinary manner. Applied ecology scientists have considered many of the properties of hogweeds by testing various techniques to remove invasion, including the fact that those species are neophytes [76] associated with freshwater habitats [77]. The spatial scale of the removed invasion was taken into account [78], as well as the remarkable ability to rapidly regenerate the population [79] and the need to evaluate the results after removal [80–82]. The published methods used to remove the Caucasian hogweeds invasion were diverse and included sheep grazing [83,84], mowing [85], and herbicides [86,87], but also chemical substances, for example, pyrolysis liquids [88] and others [89]. The costs and difficulties of the labor and financial resources required to remove Caucasian hogweeds invasion quickly became so great that there were prepared cost-effectiveness studies [90–92], as well as studies verifying theoretical preparation to eradicate this invasion [93]. Scientists and practitioners agreed that removing invaders from a given area required the development of a special strategy adapted to it [94–96]. Moreover, the pattern of distribution and control of invasion was assumed as being different in the cultural landscape [97] than in the protected area, where environmental degradation associated with the removal of invasions should be avoided [98]. The process of removing Caucasian hogweeds invasion was described as lengthy and requiring monitoring on a large spatial scale [99,100], taking into account aspects such as phenology of invaders [100] and age of invaders [101].

The following section of this review concerning Caucasian hogweeds showed that these plants have nevertheless also been the subject of scientific research worth systematizing for two reasons: (1). Described wide distribution and high costs or difficulties in the eradication. Perhaps past research has shown some phenomena that could be helpful in finding a solution to the problem using more developed techniques. (2). The attractiveness of plants for declining pollinators or other species and their complex ecology, which resulted in the past interest of scientists and may influence the modern invasion science.

3.1.3. Biochemistry of Invasive Caucasian Hogweeds

It turned out that Caucasian hogweeds had a high concentration of biologically active compounds in tissues [102] that might have been among the reasons for their invasiveness. The total phenols content in *H. sosnowskyi* was mainly in leaves, and *H. mantegazzianum* also in seeds, stem, and roots [103]. The content of phenolic compounds was similar in these two invasive species. The determined allelochemical phytotoxicity of both aliens should be addressed to the partial explanation of the high aggressiveness of those species [103,104]. The essential oils were collected from the seeds of two hogweed species. The major groups of compounds in the seed extracts were coumarins, furanocoumarins, hydrocarbons,

alcohols, esters, and aldehydes. The only difference observed on the chromatograms was signal intensity (higher for *H. sosnowskyi*) and few compounds individual for each species [3]–Table 2. A total of 62 compounds were identified and constituted 96% of the total oil. Aliphatic esters (82.9%) were the main constituents of the oil, followed by aliphatic alcohols (11%). Octyl acetate (39.5%), hexyl 2-methylbutanoate (14.4%), hexyl 2-methylpropanoate (6%), hexyl butanoate (5.4%), and octanol (8.6%) predominated in the oil, while other components were: octyl 2-methylbutanoate (4%), hexyl 3-methylbutanoate (2.6%), octyl 2-methylpropanoate (2.4%), hexanol (1.3%), hexyl acetate (1%) and octanal (0.7%) [103]. Other study concerning only oil of *H. sosnowskyi* [105] identified: octyl acetate (29.5%), hexyl 2-methylbutanoate (7.4%), and octanol (16.2%). Many other articles confirmed the rich content of various oils in Caucasian hogweeds [106–113].

Given the importance of the chemical composition, oils showed antimicrobial activity towards Gram-positive and Gram-negative bacterial strains. Oils were also more active against some fungi: *Penicillium funiculosum*, *Fusarium oxysporium* (especially *n*-octanol). While *n*-octanol shared responsibility for the antimicrobial activity, octyl acetate determined its antifungal action. Hogweed essential oils were more toxic to normal than cancer cell lines in mammals. *n*-octyl acetate also showed a significant inhibitory effect against some plant pathogenic fungi [111]. A 9.5% oil yield was found from *H. mantegazzianum* seeds and identified 21 constituents, with the main ones being octyl acetate (59.1%), octanol (8.8%), hexyl butanoate (7.9%), and anethole (6.6%) [112]. *n*-octyl butyrate (32%), *n*-octyl acetate (18%), and *n*-hexyl butyrate (9.2%) were dominant in plants from Russia [113]. According to other studies, the composition of the extracts of *H. sosnowskyi* and *H. mantegazzianum* seeds did not differ in their qualitative chemical compositions [3].

In all parts of the Caucasian hogweeds was juice containing coumarin derivatives, esters, alcohols, and long-chain hydrocarbons, and thus both were confirmed as toxic to vertebrates, invertebrates, fungi, bacteria, and viruses [114]. Many furanocoumarins have been produced by plants as a defensive mechanism against various types of predators, ranging from bacteria to insects and mammals. Various lists of furanocoumarins in different places suggested that habitat conditions had a significant role in their composition. In Poland, pimpinellin, isopimpinellin, psoralen were in both hogweed species and also bergapten and methoxalen in seeds [3]. In *H. mantegazzianum* fruits, there was revealed the presence of 8 coumarins, and 7 of them were identified: xanthotoxin, angelicin, isopimpinellin, bergapten, pimpinellin, imperatorin, and phellopterin [115], Table 2. The microbial activity of the mixture of bergapten and angelicin was evaluated. Bergapten alone showed moderate activity against Gram-positive bacteria and fungi, while the mixture had a much stronger ability to inhibit the growth of microorganisms and yeasts. Synergism of action was also suggested for some furanocoumarins [115]. In general, the composition of furanocoumarins of Caucasian hogweeds responsible for their hazardous toxic properties has been the subject of many detailed studies [116–124].

Other important chemical compounds were polysaccharides that were, for example, mixtures of arabinogalactan proteins and pectic polysaccharides that might be linked to pectin [125]. Other works concerned the structures of polysaccharides and pectins of Caucasian hogweeds [126–134]. Studies on *H. sosnowskyi* allowed expanding the knowledge of the structural diversity of polysaccharides of plant origin. Pectic polysaccharides predominated in the aboveground parts of plants [125]. The water-alcohol supernatants from the obtained fractions contained several classes of polysaccharides and consisted of branched arabinan-rich pectic polysaccharides, cross-glycans in the classes of glucomannans and arabinoxylans, as well as much of proteins. The aboveground parts of *Heracleum* consisted mainly of arabinogalactan proteins [133]. The hogweed organs, e.g., leaves, phloem, xylem, have been used to isolate specific chemical compounds in many biochemical studies that have provided an insight into the diverse properties of extracts obtained from invaders, including the potential of substances as inhibitors and toxins affecting various processes in studied invaders [135–147]. Some biochemical studies were closely related to histology and cell biology explaining the mechanisms of physiological processes in Caucasian

hogweeds at the level of tissues and cell structures [148–154]. It has been elucidated what hogweeds chemicals might be responsible for the phenomenon of allelopathy and what was the composition of the soil at the site of invading hogweeds [155–157]. Careful research described the chemical emission potential of different morphological structures of hogweeds [158] also in the context of environmental factors such as temperature [159]. The chemical contents of invaders were tested as stimulants for plant growth [160]. In addition, the toxic effect of Caucasian hogweeds on mammals [161] has been extensively studied as a biochemical process [162,163].

Table 2. Examples of the research results from Poland that showed the most important differences in the crucial chemical compounds of the two described Caucasian hogweeds. In the case of essential oils, only compounds individual for each weed were shown.

Chemical Compounds	<i>H. mantegazzianum</i>	<i>H. sosnowskyi</i>	References
Phenol contents	Leaves, seeds, stem, roots.	Mainly in leaves.	Synowiec and Kalemba, 2015 [103]
Essential oils from seeds	4-Hexen-1-ol, acetate; Hexyl 3-methyl-2-butenate; Octyl butyrate; Octyl valerate; Octadecanoic acid; 1-Tetracosanol.	Acetic acid, octyl ester; Butanoic acid, 3-Methyl-, hexyl ester; 1,11-Dodecadiene.	Jakubska-Busse, Śliwiński and Kobyłka, 2013 [3]
Furanocoumarins from fruits	Angelicin; pimpinellin; imperatorin; phellopterin; xanthotoxin; isopimpinellin; bergapten [115].	Isopimpinellin; isobergapten; pimpinellin; bergapten; angelicin; imperatorin; psoralen; methoxsalen [109].	Politowicz, Gebarowska, Proćków, Pietr and Szumny, 2017 [109]; Walasek, Grzegorzczak, Malm and Skalicka-Woźniak, 2015 [115]

3.1.4. The Properties of Caucasian Hogweeds in the Life of Animals

The rich chemical composition of the organs, tissues, and secretions of Caucasian hogweeds could not be neutral to the organisms that appeared on them or in their surroundings. Although toxic substances were identified in the oil of hogweeds, aphids, for example, were often observed on those plants [164]. Using fruits and roots of invasive *Heracleum*, albino mice were used as test animals, and the toxicity of oils was evaluated by oral treatment. The essential oils from *Heracleum* demonstrated antiviral activity; the more active essential oil came from the roots as opposed to the fruits [165]. Many chemicals isolated from Caucasian hogweeds were used in studies showing their antibacterial properties [166,167]. Those plants rich in chemical substances affected the surrounding animals in various ways—positive, negative, or neutral—depending on their resistance and adaptation to life in their vicinity.

Much of the research linking the Caucasian hogweeds influencing the environment to native fauna focused on insects. The flowers of invasive hogweeds were described as unspecialized, insect-pollinated, attractive to a variety of unspecialized pollinators, and visited by a wide range of insects, including many Hymenoptera, Diptera, Coleoptera, and Hemiptera [168–170]. In Moscow oblast, at least 49 insect species of five orders (Coleoptera, Diptera, Hemiptera, Lepidoptera, Hymenoptera) were detected on *H. sosnowskyi* specimens, and at least 29 insect species of the same order were found on the neighboring plants, moon carrot *Seseli libanotis*, which suggested that Caucasian hogweeds might have been an attractant for insects [171]. The activity of bees on *H. sosnowskyi* was also high, especially the European honeybee *Apis mellifera* and bumblebee *Bombus lucorum* [171], although Caucasian hogweeds could also negatively affect pollinators, e.g., solitary bees [172]. In another study, the native fauna of invasive *H. mantegazzianum* and native *H. sphondylium* was compared. A total of 42 phytophagous arthropod species was found; 34 on *H. sphondylium* and 34 on the giant hogweed. The arthropod guilds of 26 phytophagous species being common to both plant species were very similar. Nine species were specific to Apiaceae (including all *Heracleum* species). The remaining species were polyphagous [173]. The presence of

Caucasian hogweeds affected the local fauna in many ways, from creating a niche for specific species associated with them [174], being a food plant for larvae [175], to creating a parasitoid threat [176].

During other research, the authors gathered information on 358 insect species occurring on 16 different *Heracleum* species in Europe. About 162 species were herbivores on *H. mantegazzianum*, of which 123 were polyphagous. The number of insect specialists was lower in invaded areas. Authors found fewer herbivore species per biomass on the stem and roots and more on the leaves. Most herbivores were polyphagous generalists, and only a few had *Heracleum* species as host plants [164]. It was demonstrated that the defense systems (furanocoumarins and trichomes) of giant hogweeds were developed to different degrees in the native and invaded regions, which affected the composition of herbivore species or herbivore biomass on *H. mantegazzianum* in native and invaded areas [177].

As complex and difficult to control plants, Caucasian hogweeds have contributed to agrotechnology research on insects with new insights into their use in biological weed control. The weevil *Nastus faustii* (Coleoptera, Curculionidae) was evaluated for its potential in the biological control of invasive giant hogweeds because sampling suggested that its high population density could have some negative impact on the above-ground part of the plant. However, these insects foraged also on important crops: carrot, parsnip, celeriac, thus they could not be considered as a potential agent for biological control of invasive *Heracleum* species [178]. In the Moscow region, five insect species intensively foraged on the Sosnowsky's hogweed: *Lixus iridis*, *Epermenia chaerophyllella*, *Dasypolia templi*, *Depressaria radiella*, *Phytomyza pastinacae*. Those insects, however, were oligophagous and also lived on other plants, thus it was not recommended to use them for biological control. Especially promising were, however, two lepidopteran species: *Dasypolia templi* and *Depressaria radiella* [179]. The weevil *Liophoeus tessulatus* caused root damage of invasive *Heracleum* and was assumed as a species deserving further investigations in the research on the potential biological control of invaders [173]. In other research conducted on giant hogweeds in the Russian Caucasus, authors estimated plant vigor before and after herbivore attacks under natural conditions. Endophagous herbivores on the giant hogweeds were dominated by the weevil species *Lixus iridis*, *Nastus fausti*, *Otiorynchus tatarchani* (Coleoptera: Curculionidae), and the fly *Melanagromyza heracleana* (Diptera: Agromyzidae). None of the insects, however, caused serious damage to plants. The occurrence of root-feeding weevils was associated with weak plants [177]. Since scientists have long ago recognized the value of the chemicals released by Caucasian hogweeds and have linked them to the selective effects of those invading plants on local fauna, research using chemical compounds isolated from invaders as biological pest control agents [180–183] paradoxically advanced agrotechnical science.

An interesting issue was the species composition and diversity of soil animals under the Caucasian hogweeds. For example, the composition of the soil nematode communities was studied in three different habitats invaded or uninvaded by *H. sosnowskyi*: abandoned land, grassland on a roadside slope, and the edge of afforested land. Nematode abundance and species diversity were lower in the invaded habitats [184]. Invasion of *H. sosnowskyi* caused significant shifts in plant species composition, which modified nematode assemblages. Stress-sensitive omnivores, fungivores, and root-biomass-dependent obligate plant parasites best-reflected changes in soil nematode communities under the influence of *H. sosnowskyi* invasion [185]. Near *H. sosnowskyi* in an abandoned land and road-side slope were more bacterivorous, fewer fungivores, and plant parasites belonging to nematodes [184]. This type of research has been continued for many years, bringing new information to applied science [186,187].

It is worth emphasizing that the state of knowledge regarding the influence of Caucasian hogweeds on biodiversity was relatively small based on the reviewed articles (Table 3). For some animals, these plants were very attractive, such as ants [188]. In contrast, recent studies indicated that in vertebrates, the impact of described invasion was negative even if some signs of adaptation were shown, as seen in birds [189,190]. However, researchers were interested in tailoring removal strategies of invaders to complex

relationships in particular ecosystems. Firstly, sometimes it was impossible to remove invading hogweeds, thus there was suggested a need to study the associated biodiversity. Secondly, removing the invaders by all methods might have contributed to the degradation of the environment, in which some animals, due to the lack of natural habitats, might not be able to recreate relationships already established with Caucasian hogweeds. It turned out that the decision to remove invaders should have been supported by the results of interdisciplinary research, not just the group-specific one.

3.1.5. The Meaning of Caucasian Hogweeds for Habitats and Soil Science

In the native range, the Sosnowsky's hogweed has been known as growing in mountain areas alongside streams, in forests and alpine meadows. The climate in its natural habitat is continental, with hot summers and cold winters. Outside its native range, this invasive plant has spread rapidly, infesting grasslands, forests, wetlands, riverbanks, canal sides, rails, roadsides, urban areas, as well as abandoned agricultural land [191,192], see Figure 3 with an example from Poland. In Russia, the light use efficiency of upper leaves was significantly higher than that of middle and lower layers, and the canopy of *H. sosnowskyi* captured approximately 97% of the light, preventing the development of other plant species in the monostad [193]. Low habitat requirements of hogweeds within the range of invasion and homogenization of the habitat resulted in their negative impact on native plants communities [194–198], Table 3. Communities more vulnerable to *H. mantegazzianum* invasion were composed of species with similar ecological requirements (at least for nitrogen) and different life forms and/or strategies compared to the invader [32]. In the Bryansk oblast (Russia, near the Republic of Belarus), the density of *H. sosnowskyi* in natural communities was related to anthropochorous dispersal and damage of the vegetative cover. In the “alluvial abandoned meadow” the described alien formed a monoculture and was positively correlated with soil moisture and *Urtica dioica* plant species [185]. Much research to date in the field of plant ecology has focused on the plant communities with invading Caucasian hogweeds [199–206], pointing to the modification of both such habitats as steppes [203] and riverside vegetation [204], as well as the role of anthropogenic disturbances favoring invasion [206].

One of the most important ways the Caucasian hogweeds could have influenced their surrounding habitats was by releasing chemicals into the substrate. The phenomenon of allelopathy involving the interaction with other organisms through specific chemical compounds has been the subject of numerous studies on those invaders [207–210]. On the other hand, root exudates of *H. mantegazzianum* contained allelopathic compounds, which were not likely to be furanocoumarins, but other yet unidentified molecules. Thus, allelopathy by producing unique compounds by the invader was probably not a principal driver of the invasion success of at least the giant hogweed [209]. Other works also treated Caucasian hogweeds' release of substances into the soil as more complicated than just chemical allelopathy [210,211].

It was not surprising that the example change in plant communities caused by hogweeds was associated with a change in soil properties. The giant hogweed presence also reduced red/far-red light ratios but increased soil pH [212], which sometimes could be crucial for the soil organisms. Hogweed invasion significantly modified the composition of soil microbial communities, but the exception was the fungal/bacterial ratio [212]. In the soil under Sosnowsky's hogweed, the share of the ascomycetes was much lower than in the control. However, in the vicinity of hogweeds were also more fungi with high hydrolytic activity [213]. Active colonization of meadows by *H. sosnowskyi* led to a decrease in the biodiversity of microorganisms through the disturbance of the developed biotic cycle [214]. Several other studies identified the impact of hogweed invasion on soil organisms and other soil components important for biodiversity [215–225], Table 3. While most of these studies indicated a negative impact of invaders on soil organisms, few studies showed a positive impact for some fungi [213,217,222]. An example of a possible explanation was

that hogweed, unlike most meadow grasses, does not hibernate with green leaves that do not gradually die out with the formation of semi decomposed plant residues [213].



Figure 3. An example of a severely invaded area with Sosnowsky's hogweeds growing in a monostad covering about 5 ha on the research site in south-eastern Poland (former crop near Koniecpol); invaders on the photograph were before flowering (date: 10 June 2020—author of photograph: E. Grzędzicka).

Table 3. List of studies that identified impact of Caucasian hogweeds on biodiversity (weeds: HS—Sosnowsky's hogweeds *Heracleum sosnowskyi*, HM—giant hogweed *Heracleum mantegazzianum*). Articles were sorted according to the genera and systems they have concerned, arranged from the ground, through the herbaceous part of hogweeds, to the invaders' effects on the elements of ecosystems at the highest trophic levels.

Study Group, Attribute	Description	Weed	References
Nutrient pools in the topsoil and the standing biomass	<i>H. mantegazzianum</i> contributed to soil homogenization through enhanced nutrient uptake.	HM	Dassonville, Vanderhoeven, Vanparys, Hayez, Gruber and Meerts, 2008 [216]
Soil properties	<i>H. mantegazzianum</i> slowed down soil organic matter.	HM	Koutika, Vanderhoeven, Chapuis-Lardy, Dassonville and Meerts, 2007 [219]
Soil chemical and biological characteristics	<i>H. mantegazzianum</i> affected the composition of soil microbial communities, soil conductivity, and light availability of sites.	HM	Jandová, Klinerová, Müllerová, Pyšek, Pergl, Cajthaml and Dostál, 2014 [212]
Microbial community	Activity of soil microbial community decreased in soils under the invasive <i>H. mantegazzianum</i> .	HM	Bobulská, Demková, Cerevková and Renčo, 2019 [215]
Actinomycetes in the soil	An increase in genus and species diversity of actinomycetes in soil under <i>H. sosnowskyi</i> was noted along with intensive organic matter mineralization.	HS	Tovstik, Shirokikh, Soloveva, Shirokikh, Ashikhmina and Savinykh, 2018 [225]

Table 3. Cont.

Study Group, Attribute	Description	Weed	References
Soil microbial properties, nematode communities	Soil microbial and nematode communities were altered by the invasion of <i>H. sosnowskyi</i> .	HS	Čerevková, Ivashchenko, Miklisová, Ananyeva and Renčo, 2020 [187]
Soil nematode communities	Nematode abundance and species diversity were lower in habitats with <i>H. sosnowskyi</i> .	HS	Renčo and Baležentienė, 2015 [184]
Soil nematode communities	Invasion, although not a single <i>H. sosnowskyi</i> changed plant species composition and negatively affected nematodes.	HS	Renčo, Kornobis, Domaradzki, Jakubská-Busse, Jurová and Homolová, 2018 [185]
Plants and soil nematodes in the riparian habitats	<i>H. mantegazzianum</i> increased soil pH, decreased carbon and nitrogen content, reduced the coverage of the native plants, and negatively influenced nematodes.	HM	Renčo, Jurová, Gömöryová and Čerevková, 2021 [186]
Soil yeast communities	Under <i>H. sosnowskyi</i> were less ascomycetes <i>Candida vartiovaarae</i> , <i>Wickerhamomyces anomalus</i> , although more yeast-like fungi with high hydrolytic activity: <i>Trichosporon moniliforme</i> , <i>T. porosum</i> .	HS	Glushakova, Kachalkin and Chernov, 2015 [213]
Soil yeast	The share of yeast-like <i>Trichosporon</i> fungi with high hydrolytic activity was higher in the soil under <i>H. sosnowskyi</i> .	HS	Glushakova, Kachalkin and Chernov, 2015 [214]
Mycobiota: e.g., <i>Phloeospora heraclei</i> , <i>Septoria heracleicola</i> , <i>Ramularia heraclei</i>	<i>H. mantegazzianum</i> was related to specific fungal pathogens.	HM	Seier and Evans, 2007 [224]
Mycobiota	Remarkable mycodiversity of different genera and species on dead stems of <i>H. mantegazzianum</i> .	HM	Feige and Ale-Agha, 2004 [217]
Mycobiota: ascomycetes, genus <i>Periconia</i>	A new species <i>Periconia pseudobyssoides</i> was collected on dead <i>H. sosnowskyi</i> stalks.	HS	Markovskaja and Kačergius, 2014 [222]
Soil ecosystem, plant community	<i>H. sosnowskyi</i> contributed to the preservation and maintenance of soil fertility due to the annual return of fast mineralized plant material.	HS	Lapteva, Zakhozhiy, Dalke, Smotrina and Genrikh, 2021 [221]
Soil seed bank communities	Seed banks containing <i>H. mantegazzianum</i> were dominated by seeds of a few agricultural weed species.	HM	Gioria and Osborne, 2010 [218]
Seed bank, vascular plants	<i>H. mantegazzianum</i> decreased the diversity of seed bank communities.	HM	Gioria and Osborne, 2009 [196]
Plant community	<i>H. sosnowskyi</i> used its allelochemicals to inhibit germination of perennial ryegrass (monocots) and winter rapeseed (dicots).	HS	Baležentienė, 2013 [194]
Plant community	<i>H. sosnowskyi</i> is an agriophyte species and a minor flora component under the conditions of Middle Urals.	HS	Tretyakova, 2011 [198]
Plant community	<i>H. mantegazzianum</i> became a dominant in invaded ecosystems.	HM	Callaway and Hierro, 2006 [195]
Plant community	<i>H. mantegazzianum</i> decreased species diversity of plants in riparian habitats.	HM	Pyšek and Prach, 1993 [197]
Insecta: Hemiptera, aphids	Positive relationship between the relative <i>H. mantegazzianum</i> growth, ant activity, and the number of myrmecophilic aphids, although negative impact of hogweeds on non-myrmecophilic aphids.	HM	Hansen, Hattendorf, Nentwig and 2006, [164]
Insecta: Hymenoptera, Formicidae	<i>H. mantegazzianum</i> was found to be attractive to ants.	HM	Stukalyuk, Zhuravlev, Netsvetov and Kozyr, 2019 [188]
Insecta: Lepidoptera, Depressariidae, <i>Agonopterix caucasiella</i>	It lives in Caucasus, the larvae feed on <i>H. mantegazzianum</i> .	HM	Karsholt, Lvovsky and Nielsen, 2005 [175]
Insecta: Hemiptera, Lepidoptera, Hymenoptera, Coleoptera, Diptera	Specific herbivorous insects were related to <i>H. mantegazzianum</i> .	HM	Hansen, Hattendorf, Nielsen, Wittenberg and Nentwig, 2007 [169]
Insecta: Diptera, Psilidae, <i>Chamaepsila rosae</i> *	<i>H. mantegazzianum</i> was described as a new host of the carrot fly.	HM	Hardman and Ellis, 1982 [174]
Insecta, Diptera, Drosophilidae	<i>Drosophila</i> species, <i>Scaptomyza pallida</i> , used the petioles of <i>H. mantegazzianum</i> with the parasitoid <i>Leptopilina australis</i> .	HM	van Alphen, Nordlander and Eijs, 1991 [176]
Insecta: pollinators	<i>H. mantegazzianum</i> sites had a lower abundance of solitary bees and hoverflies.	HM	Davis, Kelly, Maggs and Stout, 2018 [172]

Table 3. Cont.

Study Group, Attribute	Description	Weed	References
Insecta: pollinators	Very few insects carried both native and alien pollen from <i>H. sphondylium</i> or <i>H. mantegazzianum</i> , suggesting species barrier to gene flow.	HM	Grace and Nelson, 1981 [168]
Insecta: pollinators	Pollinators' visitation of <i>Mimulus guttatus</i> was enhanced close to <i>H. mantegazzianum</i> .	HM	Nielsen, Heimes and Kollmann, 2008 [170]
Insecta: pollinators	Sixty-nine species of anthophilous insects visiting inflorescences of <i>H. sosnowskyi</i> were identified.	HS	Ustinova, Savina and Lysenkov, 2017 [171]
Bird community	Ground dwellers and farmland birds responded negatively to <i>H. sosnowskyi</i> towards open habitats, while a more negative response towards forest habitats was observed in birds associated with bushes.	HS	Grzędzicka and Reif, 2020 [189]
Bird guilds	<i>H. sosnowskyi</i> decreased the abundance of insectivorous, granivorous and omnivorous birds.	HS	Grzędzicka and Reif, 2021 [190]
Biodiversity, ecosystems	<i>H. mantegazzianum</i> negatively impacted biodiversity and ecosystems.	HM	Koutika, Rainey and Dassonville, 2011 [220]

* current name, not from the cited paper.

The reproductive capacity and specific ecology of Caucasian hogweeds in their invasive range undoubtedly contributed to their significant impact on plant communities and soil components. Firstly, the large size of those plants should be emphasized once again, as well as the rapid growth of large green biomass [226,227], much larger than that of the relative native plants [228] and larger than the size of describing plants from the same species growing in the range of their native distribution [229]. Caucasian hogweeds showed the enormous ability of regeneration [230]. Their large biomass has resulted in several studies of its use as a biofuel [231–234]. Secondly, the success of invaders was determined by their enormous reproductive abilities, where propagation was exclusively by seeds. Seed germination under laboratory conditions was very high: 71–94% in different temperature regimes [235]. Having a huge reproductive capacity, one plant produced 5–20 thousand seeds per year and occasionally even 50,000 [236], which could germinate for 5–6 years, showing seasonal dynamics [237–240] and long survival in soil despite unfavorable factors [241–243]. Seeds were easily spread by wind, the surface of water, birds, and vehicles [244,245]. The distribution of fruits on inflorescences and the structure of the fruit itself was of considerable importance for reproductive ability [246–248]. Reproductive characteristics of *H. mantegazzianum* were studied at seven sites in the Czech Republic. Fruits from terminal inflorescences were heavier than those from satellites, while those produced in the center of an umbel were heavier than those from the margin. Neither umbel size nor time of flowering had a significant effect on germination characteristics [248]. Terminal umbels were the main seed suppliers for the population [236]. Moreover, the accompanying quick response of giant hogweed to tissue removal might have affected its reproduction and invasion success [249]. Both described features of invaders huge biomass and productivity made them resistant to harsh environmental conditions, as well as they have been considered as aggressive plants [250–253]. Caucasian hogweeds were classified as neophytes, introduced species that rapidly colonized new habitats in their new range [254,255]. Due to the specific biology and ecology of those invaders, despite over a dozen studies on the possibility of using biological methods of controlling their populations, including herbicides, insects, fungi, and parasites [256–262], none of them gave any chance of success in the fight against the invasion of Caucasian hogweeds.

4. Discussion

4.1. The Unknown Future of Caucasian Hogweeds

Invasive hogweeds were not the same plants as the large endemic specimens growing in their native range. Samples of *H. mantegazzianum* and *H. sosnowskyi* were collected from the native ranges in Asia and invaded ranges of both described species in Europe and

then analyzed using amplified fragment length polymorphism. Within each species, plants collected in the invaded range were genetically close to those from their native ranges. However, a high overall genetic variability detected in the invaded range suggested that the majority of invading populations were affected by rapid evolution, drift, or hybridization, which played a role in the genetic structuring of invading populations. More within-taxon variation was detected in the invaded range (Europe) than in the region of native distribution [1]. At various sites within the invasion range, the Caucasian hogweeds were described as still evolving [263–267], and their genetic resources may develop [268]. Large genetic diversity resulted from numerous sites of former introductions [264]. Invasive hogweeds formed hybrids with native species of the same genus studied [269,270], including the example research on hybrids' unknown epidermal features [271]. It seemed difficult to predict what genotoxins [272] and genotoxic carcinogens [273] the evolving hogweeds have produced and will produce in the future. These chemicals could already affect organisms living in their vicinity. Caucasian invaders also showed other properties of which knowledge was little, such as bioelectric potential in soil-plant systems [274], photosensitivity [275], native species richness recovery after about 30 years of hogweed invasion after the occurrence of stabilizing processes [276] or the possibility of inactivating the ability of invaders' seeds to germinate during the year under certain laboratory conditions [277]. The hogweeds invasion is, therefore, not only complicated, but it is difficult to predict in which direction it will develop.

4.2. *The Need for Further Studies*

Among the future research needed to better understand and react to the invasion of Caucasian hogweeds are the following:

1. This review showed how little research has been available on the impact of Caucasian hogweeds on biodiversity. It is a serious oversight that the author would like to emphasize and suggest this research direction for scientists interested in conservation biology and invasion science. Possible adaptations of native organisms to invasive Caucasian hogweeds are worth studying.
2. Nowadays, pollinators decline is observed, which concerns the mass extinction of species, of particular importance for food security and the future of humanity. Caucasian hogweeds stand out from other invasive plants as species especially attractive for pollinators. In the case of high costs and difficulties with the removal of those invaders, it seems that instead of incurring endless losses for this process, it is worth starting to research the importance of hogweeds for local pollinator communities, with particular emphasis on the European honeybees. Although Caucasian hogweeds were once used as valuable melliferous plants, there is no research on the properties of honey prepared from products collected by pollinators on these plants.
3. Eastern Europe is a mainstay of farmland birds that are legally protected in the European Union, and this group also includes many endangered and protected species. Research on the effects of invasive hogweeds on birds only began a few years ago, which may be a very serious oversight. There is an urgent need to start long-term research based on large-scale analyses at the level of at least the European continent, which would compare the spreading process of invaders with the trends of changes in the abundance and distribution of farmland birds over the same period. In recent years, ornithologists have become interested in the significance of environmental elements remaining after the communist era, such as military areas, abandoned farms, or the way land was partitioned at that time. No research has shown the role of Caucasian hogweeds occurring in these areas.
4. The history of the Caucasian hogweeds invasion has lasted for at least 80 years, assuming that the real problem of invasion, at least on a continental scale, began with the fall of communism and the abandonment of widely distributed former crops. Thus far, research has shown native organisms facing this invasion to react at the phenotypic level. In the coming decades, research should be planned to check whether

the described invasion already causes variability in organisms at the genotypic level. For comparison, the phenomenon of urbanization, which has lasted for 200 years, has already caused many changes in organisms at the genotypic level. The very large ranges of invasive hogweeds have the potential for the research of geneticists dealing with large-scale genetic variation in organisms.

5. There is a lack of research on the effects of global warming and extreme weather events on the dispersal of invaders and their reproductive success. It is not known what effect mild winters have on Caucasian hogweeds populations and seed survival in soil. Increasingly frequent floods potentially favor the dispersal of hogweeds, thus it seems that especially in river valleys, management of this invasion requires a specific strategy supported by scientific research, e.g., large-scale dispersal modeling in the context of the water flow rate in the particular river and the extent of the floods. The high temperatures during increasingly hotter summer periods on the European continent may favor the more intense release of hogweeds chemicals into the environment, thus far not explored.
6. There is a lack of experimental studies showing what the main drivers of the Caucasian hogweeds invasion are. It should be emphasized that sometimes birds are considered to be one of the drivers facilitating the invaders' spread. This has not been tested experimentally, and it is not known if any bird species have invasive hogweeds seeds in their diets. It is not known whether and how the birds contribute to the dispersal of Caucasian hogweeds.
7. One of the unexplored invasion drivers may be habitat degradation that lowers the local biodiversity and potentially facilitates the spread and development of invasive plants. On the one hand, invaders may appear in disturbed habitats, and on the other hand, procedures related to their removal may have a negative impact on the surrounding environment, paradoxically facilitating invaders. It is not known what the balance between habitat disturbance and native biodiversity should be kept to prevent the development of invaders.
8. The complex attractiveness of Caucasian hogweeds to certain groups of organisms requires further research. An example is the interest of ants in those plants. Ants perform many useful functions in nature, e.g., sanitary. It is worth carefully examining the relationship of ants with hogweeds and checking whether other organisms appearing in the invasive hogweeds indirectly benefit from it.
9. Research on the influence of Caucasian hogweeds on ecosystems has been related to soil science. The unique composition of communities of soil organisms in the substrate of growing invaders seems to be an interesting research topic for environmental biologists interested in soil ecology. The influence of hogweeds on soil organisms goes beyond the phenomenon of only chemical allelopathy, which requires further experimental studies.
10. The dispersal of Caucasian hogweeds related to linear features such as rivers and roads is worth exploring on a landscape scale. Today, roadless areas are becoming rarer. There are no spatial analyses showing what this means for the Caucasian invaders' dispersal.

5. Conclusions

To summarise, Caucasian hogweeds are one of the most problematic plant invasions in the world, extending across the European continent to North America and possibly even other continents in the future. While they have already had a significant impact on biodiversity, this issue was disproportionately poorly researched concerning the scale of the problem. The rich physicochemical properties of invaders' tissues and secretions in the face of the rapid evolution of plants combined with the progressing global changes and degradation of the environment can form a system for testing hypotheses in the field of applied evolutionary ecology. Finally, it is worth adding that this review did not exhaust the topic. The most important issues may require significant updates even in a decade.

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