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ControlInRoad
Controlling the spread of invasive species with innovative methods in road construction and maintenance

Alternative methods in road construction, operation and maintenance in relation to Invasive Alien Plants (IAPs)

[Deliverable 3.1]

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Executive summary

All standard and alternative methods for the control of invasive alien plants (IAPs) were analyzed based on the current literature and the questionnaire (Deliverable 4.1). In Figure 1 the results are summarized.

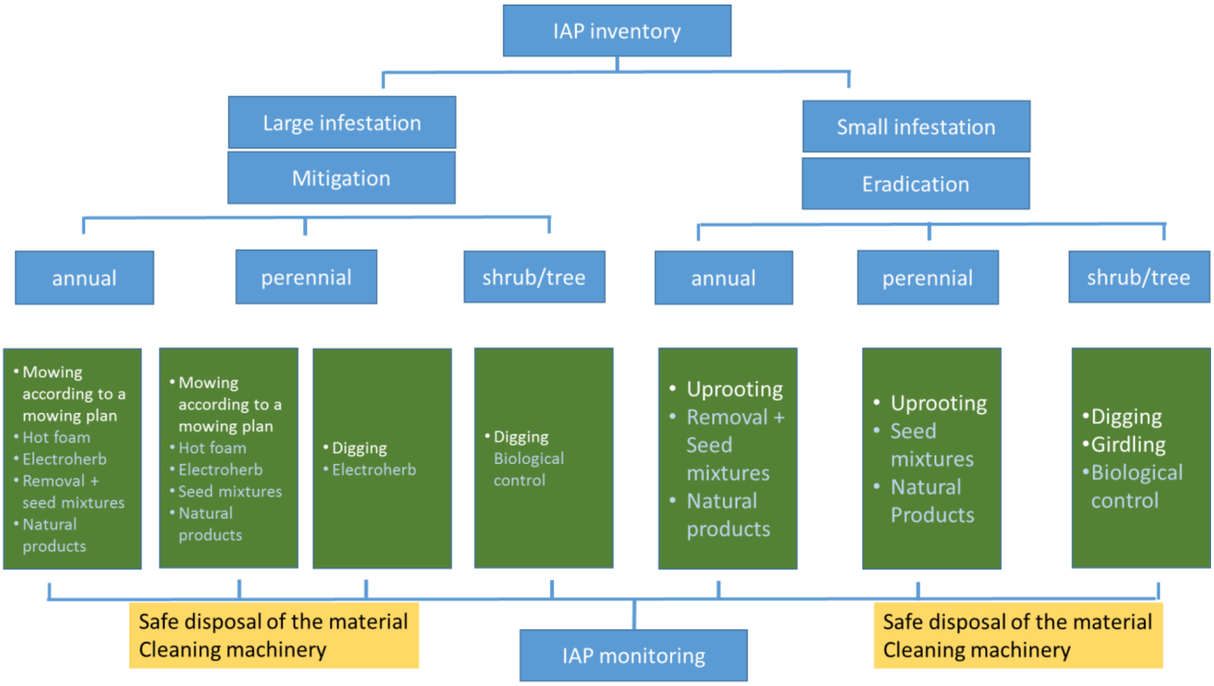

Figure 1: Proposed decision tool for the management of invasive alien plants at current knowledge. The methods in light blue (in the green boxes) are alternative methods that came out as the most promising ones.

There will be no general management guideline for all IAPs. However, one important point in common is the need for IAPs identification (‘IAP inventory’), the elaboration of a management plan (‘blue and green boxes’), the disposal of the plant material, the education of the operating staff and the follow-up control of the success of the eradication or the management (‘IAP monitoring’) (Figure 1).

Alternative control methods are needed because of the glyphosate debate and the general public concern in regards to the application of herbicides along roads. In many European countries, the use of chemicals is already prohibited by national legislation. Until now, alternative methods are not as effective as herbicides, mainly because of higher frequency of application and higher application costs or energy costs to obtain similar results as with herbicides. Therefore, new methods should be selective for the specific invasive alien plant and growth of the native vegetation should by improved. Research studies on biological control agents for weeds are rare and companies for biological control are not willing to register such product, because of the high cost and relative low market size, but for a sustainable management of IAPs biological control is the best alternative. However, the introduction of foreigner organisms has to be validated carefully to no introduce a new pest. Therefore, the control of IAPs be using native organisms which do not kill the target plant completely is maybe safer.

Many alternative methods are currently too expensive, they use non-renewable energy sources or the efficacy is lower compared to standard methods used. Successful eradication in regards to IAPs is currently only possible with man power. The eradication of ragweed and giant hogweed in the Kanton Zürich was mainly attributed through a constant uprooting of the plant and the education of the managing personnel and the general public.

1 Introduction

Roadsides play an important role in facilitating the spread of invasive alien plants (IAPs) by providing habitat for their establishment as well as serving as corridors which allow them to spread. European countries should take action to restrict their distribution and in the best case to eradicate them. With the new EU regulation No 1143/2014 several plants are listed like *Asclepia syriaca Gunnera tinctoria*, *Heracleum mantegazzianum* and *Impatiens glandulifera*, which are related to roads. EU member states shall establish a surveillance system for early detection and rapid eradication of IAPs of Union concern (Article 14), as well as implement effective management measures (Article 19). If justified, Member States shall carry out appropriate restoration measures to assist the recovery of invaded ecosystems (Article 20).

Roadside vegetation managers rely heavily on mechanical and chemical methods to control weeds and IAPs along roadsides. The use of chemicals has been debated for several years. In particular among the public there is a lack of acceptance for the use of chemicals. Moreover, the registration of herbicides is in debate within the European commission and some active ingredients will be most likely withdrawn from the market over the next few years. Some European countries have already regulated the use of herbicides along roadsides, e.g. in Austria, the use of herbicides along roadsides is forbidden. Furthermore, the most widespread standard methods (i.e. mowing, mulching) for the vegetation management along roadsides are often not suitable to achieve adequate control of IAPs. In many cases such methods even tend to spread IAP along roads and e. g. along waterbodies nearby. Distribution of IAPs does not stop at country borders and has the risk to leap into adjacent areas like fields, natural reserves, forests, railway facilities and urban traffic or green areas.

Therefore, there is an urgent need for alternative methods or practices to deal with the problem of IAPs. Most research on the control of weeds (and IAPs) has been done for the use in agriculture and only little information is available for landscape use.
The literature review is separated into widely used methods (standard) and methods in test phase or experimental stage (alternative) (chapter 2 and 3). Each method is briefly described as well as their efficacy to control weeds and IAPs and applicability along roadsides. In chapter 4, current control options and management plans from different European countries for the most important IAPs along roadsides are summarized. Particular focus was put on Invasive Alien Species of Union concern (EU Regulation 1143/2014). The review is based on a combination of scientific papers, online material, personal communications and the case study on the control of three IAPs in 2018 in Austria. The case study included the following species *Fallopia japonica*, *Ambrosia artemisiifolia* and *Robinia pseudoacacia.*

The methods for the management of IAPs mentioned in the questionnaire are also included (chapter 5). All the information in the different chapters has been used to give an overview about available and promising control methods for IAPs (chapter 6).

2 Standard methods

2.1 *Mechanical control*

2.1.1 *Mowing/Mulching*

Mowing and mulching are the most widespread methods for vegetation management (Forman et al. 2003). In many countries, no special care during mechanical control is taken in regards to control IAPs. But different species of IAPs need different time points and different working depth. For all annual plants the control should be done before flowering to avoid the dispersal of the seeds. Some species are able to re-sprout fast (*Ambrosia artemisiifolia*, *Impatiens glandulifera*, *Lupinus polyphyllus* etc.) and therefore, the plants should be cut either in a specific development stage like for *A. artemisiifolia* (i.e.shortly before male flowering; Milakovic & Karrer 2016) or cut as deep as possible below the growing point for *Lupinus polyphyllus* (Brobäck 2015). Special care should be taken to avoid the spread of the IAPs through small plant parts (and seeds), which are able to regrow by cleaning the machinery after working on sites with IAPs infestation. For every infested site a mowing plan should be developed taking into account the special requirements of the plant species.

2.1.2 *Hand removal (uprooting)*

Hand removal is the most effective method for the management of IAPs in areas with a low infestation level. For annual plants hand removal should be done before seeds are set to avoid the spread of the seeds to adjusted areas. This method is very successful for plants like *Ambrosia artemisiifolia* and *Impatiens glandulifera*.
For *Heracleum mantegazzianum* the taproot should be cut 15 cm below ground level in an angel. The advantage of hand removal and digging is the preservation of the natural vegetation and the great success in eradication of IAPs, but it is labor intensive. From the cost benefit analysis, the root cutting is the most promising method to control giant hogweed. The probability of re-infestation is low and the measurement has a positive benefit cost ration in the long term control (Rajmis et al. 2016).

2.1.3 *Digging*

For *Fallopia japonica*, this method is the most effective measurement to eradicate this noxious weed, but it can only be done during road construction where the contaminated soil can be excavated. Any waste containing the species must be disposed properly. It can only be removed to a landfill site which has an appropriate permit and specialized registered carrier should move the waste to a specific safe place. The vehicle must be thoroughly cleaned after use. If the rhizomes can be burned, they first have to be dried. The outcome from the burning should be disposed safely as burned rhizomes may re-sprout again. The same applies for other IAPs with rhizomes like *Asclepias sysriaca*.

2.1.4 *Brushing*

On hard surfaces brushing can be used. The bristles are usually made of polypropylene or steel. The method is not recommended because the bristles damage the surface and the method is less effective (Rask & Kristoffersen 2007).

2.2 *Herbicides*

The application of herbicides is a widely used method to control weeds and IAPs along roadsides. It provides much flexibility and low costs, considering the equipment for application and the spectrum of active substances that are available (Barker & Prostak 2014). In Europe, the most important active substance is glyphosate. It is not selective and can be applied to control a wide variety of annuals, perennials, trees and shrubs. Other selective herbicides can be used to for a targeted control of broadleaf weeds (e.g. auxin herbicides like triclopyr).
Herbicides can be applied in two different ways: foliar application (treatment of individual plants, small and/or large infestations) and stem application (i.e. stem injection). Foliar application is fast and large infestations can be treated. However, in this case, the whole vegetation is destroyed, which makes the treated area suitable for a new infestation. For the stem treatment, the herbicides are injected with a specific equipment directly into the stems or with a specific equipment also into the rhizomes. It is most suitable for inavsive trees, shrubs and perennials. For example, for *Fallopia japonica*, it is proposed to cut the stem and pour the herbicide into the hallow stems (Ford 2004). In that case, the surrounding native species remain largely unaffected. The disadvantage of this method is the time consumed by the injection (labor costs), suffcient experience and permission to work with herbicides is needed.
However, in some European countries the use of herbicides along roadsides is restricted by national laws. In general, their use is viewed critically by the public and also by scientists/ecologists due to environmental concerns. In the last years, herbicides resistance increased. For example, biotypes of *Ambrosia artemisiifolia* developed resistance to several modes of actions of herbicides (Brewer et al. 2009, Bagavathiannan & Norsworthy 2016, HEAP 2018).
Another point is the damage to the native plant community. In the study of the USDA's Agricultural Research Station in Miles City, Montana it was found that after 16 years of a one-time herbicide treatment of leafy spurge the invasive leafy spurge increased due to spraying whereas the native forbs still suffering the effects of spraying 16 years after spraying (http://www.montana.edu/news/7522/study-finds-one-time-herbicide-use-decreased-native-plants).

3 Alternative methods

3.1 *Mechanical control*

3.1.1 *Removal and sowing competitive seed mixture*

Some IAPs are comparably weak competitors in particular during germination and early plant development (e.g. *Ambrosia artemisiifolia*). The resources of light and nutrients are the main drivers for competition. Removal of IAPs and subsequent sowing of native plant species helps to outcompete IAPs and to re-establish native plant communities.

Schuster et al. (2018) conducted a literature review for studies on revegetation after the removal of IAPs. In total, 40 studies were analyzed and 30 studies showed that by revegetation with native species the growth of IAPs was restricted. The review showed that more diverse ecosystems are less prone to invasions. The effect was best seen after a longer period (>3 years). For example, using a seed mixture of *Festuca rubra*, *Lolium multiflorum*, *Lotus croniculatus*, *Poa pratensis* and *Trifolium hybridium* reduced the coverage of *Ambrosia artemisiifolia* by 95% (Gentili et al. 2015).

The selection of native species for revegetation can be achieved by sowing fast grown native plant species in light limited environments. Depending on the landscape different seed mixtures are developed with plants adapted to specific climate and soil conditions. The success of the establishment of native plant species depends also on the time of sowing and on the availability of water resources. Periods with hot and dry weather may prevent a successful establishment of native vegetation (http://198.238.212.152/NR/rdonlyres/0CB59701-542E-4DF2-B8C8-1ACA3CB72172/0/FinalUWReport.pdf).

Some plants produce secondary metabolites, which may reduce the growth of IAPs. *Festuca* ssp. are able to outcompete neighboring plants by the exudation of a phytotoxic compound from the roots. This active compound is *m*–tyrosine (Bertin et al. 2007). Until now, no commercial product exists. However, it may be useful to use seed mixtures with a high percentage of *Festuca* spp. for revegetation of roadsides to outcompete IAPs (see also chapter 3.2.6).

3.1.2 *Stem girdling (ring-barking)*

Stem girdling is the removal of the bark band or strip of bark which contains the cork and cork cambium, phloem and usually the cambium around the entire circumference of a tree. The partial stem girdling was tested on *Ailanthus altissima* and *Robinia pseudacacia* to restrict the re-sprouting (Drescher & Ließ 2006, Böcker & Dirk 2008). In the Caumsett State Park during a period from 2014-2015 57% of the trees died after girdling them twice (http://www.caumsettprojects.org/pdfs/ailanthus-results.pdf). The girdling of *Acer negundo* was the most efficient method compared to cutting and cutting followed by juglone application (Merceron et al. 2016). 65% of the trees died after two years. The applicability for other invasive trees has to be tested. Nevertheless, stem girdling may be used to control (individual) invasive trees along roadsides.

3.1.3 *Drilling machine*

For plants with deep root systems an effective method is the use of a powerful battery operated drilling machine with in auger for soil. This method has already been tested with success on *Heracleum mantegazzianum* instead of cutting the root (https://www.gfg-fortbildung.de/web/images/stories/gfg_pdfs_ver/Hessen/Schwefze/2018/18_schwefze_v3.pdf). With the auger the vegetation point in the root is damaged and thus, preventing the plant from re-growth. In the Netherlands, similar devices were also developed which work by man power (https://www.youtube.com/watch?v=YrXlVZ172T8).

3.1.4 *Suffocation/Smothering*

Mulch, black plastic, carpet or any other impenetrable barriers can be used to cover IAPs for at least one growing season. The coverage with barriers can prevent germination of annual or budding of perennial IPAs. Further materials like Geofabrics (CuTex) and Geosynthetics Knotblock have been developed to prevent the spread into neighboring land. CuTex is a geocomposite root barrier systems consisting of a copper sheet mechanically encapsulated between a woven polypropylene geotextile and a high strength nonwoven polypropylene geotextile (https://www.geofabrics.com/root-barriers/). In general, covering infested sites with such material kills also the native vegetation and re-vegetation is needed to prevent any new invasion (see chapter 3.1.1).
Covering is likely best suited for the control of annual IAPs. For example, it is recommended for the control of *Ambrosia artemisiifolia* by Buttenschøn et al. (2010). In contrast, Jones et al. (2018) demonstrated that among several (physical and chemical) treatments geomembrane covering (high-density polyethylene) was the least effective control treatment for the perennial *Fallopia japonica*.

3.2 ***Natural products***

There are a number of natural products (natural phytotoxic substances) available for weed control in (organic) agriculture (Dayan & Duke 2010). These natural products can also be used for weed and IAP control along roadsides. However, studies in peer-reviewed journals are broadly missing on the efficacy of these active substances on weeds and in particular IAPs along roadsides. The most important natural products, their efficacy and applicability along roadsides are briefly described.

3.2.1 *Organic acids*

Organic acids have a contact action (i.e. they destroy only plant tissue that contacts the herbicide) and they are considered to be non-selective. The foliage of herbaceous plants burns down within a few hours after application. They kill the plant by cell membrane disruption causing loss of cellular function (Dayan & Duke 2010). As a rule, young plants (< 4-leaf stage) are more susceptible than older ones and organic acids provide control of most annual weeds but they were less effective against grass species and perennials. Thus, repeated applications may be necessary for sufficient weed control (Abouziena et al. 2009, Webber et al. 2012).

Acetic acid

Acetic acid is an effective burndown active substance that is applied post-emergence at concentrations ranging from 10 to 30%. In general, efficacy increases as acetic acid content and application volume increase. Naturally, acetic acid is less effective in controlling grasses, perennials and larger weeds (Webber et al. 2012). For example, in greenhouse experiments, Abouziena et al. (2009) showed that acetic acid provided > 90%

control of the tested plant species when applied at 30% in the spray solution at an early stage (2- to 4-leaf stage) except for some of the tested grass species.

Pelargonic acid

Fatty acids (e.g. pelargonic acid, caprylic acid, capric acid) are further non-selective, post-emergent contact herbicides. In a recent experimental study, in Switzerland, Crmaric et al. (2018) showed a high efficacy of pelargonic acid and caprylic acid + capric acid when they were applied on young weeds (natural mixture stand) with a canopy height of 0.05 m. Further studies on the application and efficacy of pelargonic acid (and acetic acid) are mainly available from North America in agricultural and (semi-)natural settings (e.g. Ward & Mervosh 2012, Webber et al. 2014, Johnson & Davis 2014). For example, Webber et al. 2014) demonstrated that pelargonic acid effectively controlled weeds in squash (*Cucurbita pepo*) when applied with a precision directed sprayer. Ward & Mervosh (2012) tested non-chemicals and pelargonic acid and acetic acid against the invasive plant *Microstegium vimineum* (Japanese Stilgrass). Foliar application of acetic acid (5% acidity, early treatment) and pelargonic acid (11.8 kg/ha), reduced *M. vimineum* cover by 58 and 73%, respectively, relative to untreated plots. The authors, however, concluded that both active substances were not sufficiently effective to be recommended.

3.2.2 *Essential oils*

Essential oils are non-selective active substances with a contact action and the main components are clove oil, pine oil and citrus oil. All active substances disrupt the cell membrane. This causes the loss of cellular function and cellular electrolyte leakage followed by the death of green tissue (necrosis) (Bainard et al. 2006, Dayan & Duke 2010). Likewise the organic acids, essential oils, have in general a greater efficacy on younger than larger plant species, and broadleaf weeds are more susceptible than grass weeds. Good coverage is considered crucial, so large volumes of the product are required.

Clove oil
Clove oil is a product of the stem distillation of *Syzygium aromaticum* (clove) leaves. The main active substance is eugenol. Available studies showed inconsistent results as its effectiveness depends largely on the application rate and varies with plant species and their size. Boyd et al. (2006) reported that clove oil controlled the tested broadleaf plants > 95 % at high concentrations, but not grass species. Abouziena et al. (2009) demonstrated that clove oil provided only poor control of most tested plant species (< 35% at 37.5 l/ha, 4 WAT) under greenhouse conditions.

Pine oil

Pine oil is obtained by steam distillation of needles and cones of *Pinus* sp (pine). The main active substances are terpene alcohols and saponified fatty acids (Dayan & Duke 2010). Pine oil requires amounts of 50 to 100 kg of pine oil/ha (newly emerged weeds in freshly cultivated soil) while larger, established weeds required higher rates per hectare to achieve acceptable control (James et al. 2002).

Citrus oil

The main active substance of citrus oil is d-Limone (Erasto & Viljoen 2006). For example, Main et al. (2013) and Shrefler et al. (2011) used successfully d-limonene for weed control in *Daucus carota* subsp. *sativus* (carrots; band application) and *Cucumis melo* var. *Cantalupo* (cantaloupe). Lanini & Roncoroni (2010) conducted greenhouse and field studies using d-limonene for the control of selected species *Brassica nigra*, *Amaranthus retroflexus* and *Echinochloa colona*. In this study, the broadleaf weeds were easier to control than the grass species.

In summary, the costs of using organic acids and essential oils and their comparable low performance are currently most prohibitive for their application along roadsides. In this respect, Boyd et al. (2006) showed that the use of clove oil was 30 to 140 times more costly than the mechanical options for weed control in organic vegetable production. Information on their efficacy IAPs is warranted.

3.2.3 *Plant oils*

The most common plant oils for herbicidal use are rapeseed, flax, grape seed and olive oils. Plant oils seem to have no direct effect on the plants and their phytotoxicity appears to be based on mechanisms that inhibit transpiration and photosynthesis due to stomatal penetration or blocking (Hodge et al. 2018). In a recent study, the authors tested the herbicidal effects of raw and processed culinary oils (rapeseed oil, sunflower oil, olive oil, flax/linseed oils). All tested oils caused a decrease in plant dry matter compared to the control treatment. For example, rapeseed oil caused a reduction in average dry matter from 21% to 90% compared to the control.

Hodge et al. (2018) concluded that plant oils "… can reduce weed biomass in a way that is likely acceptable". Again, repeated applications of oil-based herbicides may be required to maintain satisfactory weed control. Nevertheless, plant oils may be a suitable – in particular environmentally friendly – measure for weed control along roadsides. It may be used as a single option (direct spot spraying) or incorporated into a multi-stage control plan.

3.2.4 *Iron chelate solution*

This selective, broadleaf (turfgrass) herbicide contains the active substance iron chelate. Iron oxidation causes necrosis and the plants die within a few hours of application. A few efficacy studies are available and were summarized by Smith-Fiola & Gill (2014). Basically iron chelate provides sufficient control of annual and perennial turfgrass weeds (e.g. *Taraxacum* sp.). However, repeated applications (up to 3 with an interval of 3 to 4 weeks) are necessary.

In North America, the product Fiesta is on the market with activity against broadleaf weeds on lawns. It contains an iron chelate solution (https://www.nutrilawn.com/fiesta-weed-control). In Europe, this product is not registered. Iron chelate may be used for spot spraying of IAPs along roadsides.

3.2.5 *Crude botanical products*

Corn gluten meal (CGM) and mustard seed meal (MSM) are by-products of the corn wet-milling process and seed oil pressing process, respectively. Both can be used as a non-selective, pre-emergence (should be applied before seed emergence) herbicide (Webber et al. 2012). Phytotoxicity arises from the production of phytotoxins due to microbial degradation of the gluten and seed meal (Dayan & Duke 2010). Webber et al. (2012) give a detailed overview about studies that explored the effectiveness of CGM and MSM against weed species. In the case of CGM, although plant development (plant survival and root development) was reduced for all weeds tested in the studies, the extent of susceptibility differed largely across species and was highest with 80% efficacy. In general, MSM had a greater weed control efficacy than CGM (Webber et al. 2012).

However, very high amounts are needed for a reasonably well weed control limiting its potential use in a roadside setting: up to 4 t/ha CGM were necessary (under field conditions, incorporated into the top 5-8 cm of soil) to reduce weed cover by max. 82% compared to an untreated control (Webber et al. 2012).

3.2.6 *Plant allelopathy*

Several plant species produce exudates, which are phytotoxic to neighboring plants and give them a competitive advantage for resources such as nutrients, light, and water (Duke 2007). Some of these products are potent toxins like juglone from the black walnut and sorgoleaone from sorghum. *Festuca rubra* ssp. *commutata* produces *m*-tyrosine a potent phytotoxin. *m*-tyrosine is a non-protein amino which may have a function in primary metabolism (Bertin et al. 2007). Bertin et al. (2007) evaluated 80 fine fescue cultivars and eight cultivars showed strong weed suppression. Kaur et al. (2009) showed that *m*-tyrosine can be metabolized by the soil microbes and therefore the amount needed for weed suppression under natural condition should be higher as under sterile conditions. In soil *m*-tyrosine is already degraded after 24 hours (Movallan et al. 2014), and has no negative effect on soil microorganism like juglone. However, experiments conducted with different *F. rubra* sp. genotypes in non-sterile pot assays showed a significant reduction in ragweed germination if the seeds of both plants species were sown in the same pot (own results).

3.2.7 *Use of natural products along roadsides*

There are two experimental studies from North America available where natural products have been tested for vegetation control along roadsides.

Young (2004) summarized studies for the control of the vegetation along roadsides using acetic acid, pine oil, essential oil mixture and glyphosate to compare the different methods in terms of efficacy, time and costs. All natural products were less satisfactory in the level of control (despite repeated treatments) and significantly less than the standard treatment of glyphosate. Young (2004) identified three factors likely responsible for their poor performance: no systematic activity, effectiveness decreases rapidly as the growth stage of vegetation progresses and poor spray coverage (due to plant matter/debris inhibiting adequate contact). At that stage of research, Young (2004) noted that “the cost of one or more applications of the natural products was greater than 10 times the cost of using one or two applications of glyphosate”. The author concluded that the tested natural products were not suitable for the use along roadsides.

In a more recent study, Barker and Prostak (2014) tested CGM, clove oil, pelargonic acid and glyphosate as well as glufosinate. Results were broadly similar to Young (2004). The efficacy lasted for no more than 6 weeks, and the difference between no treatment and clove oil and pelargonic acid was minimal whereas glyphosate reduced the biomass significantly. No suppression of growth of roadside vegetation was observed with the use of CGM. Again, the costs (material, labour) for the natural products were substantially higher than for the conventional herbicides used in this study.

In summary, natural products in particular organic acids and plant oils may be still an option for IAPs control along roadsides in certain situations (e.g. direct spot spraying of specific IAPs, band application along the central reservation). At present, the high costs of the natural products are most prohibitive and further information on their efficacy on specific IPAs is necessary.

3.3 *Physical control*

3.3.1 *Thermal control*

3.3.1.1 Direct flame

With this method the plants are directly burnd by flames. Machines were developed to work on agricultural land and on hard surfaces. Flames can kill also plants which are resistant to herbicides. Flames are produced by propane/butan mixtures. Flaming generates combustion temperature of up to 1900°C. The energy needed for this method is 60 kg/ha to have a 95% reduction in zero to two leaf stage (Ascard 2010). For bigger plants the consumption increases. In agriculture, the method was developed to kill the weeds between the roads, crop plants were not damaged. Because of the high potential for a fire risk, the method can only be applied where no risk of fire exists. Plants with a thick cuticula or vegetation points and rhizomes below soil level are protected from the flame and can regrow. The soil microorganisms biomass at <5 mm decreases, but between 5-10 mm flaming had little effect on the microbial biomass. The soil temperature rased by 4°C at 5 mm and at 10 mm by 1.2°C (Rahkonen et al. 2012). As a rule, grasses are more resistant to direct flames compared to broadleaf weeds and plant species are most susceptible to flaming when small (2-4 leaf stage) compared to larger plants (> 6-leaf stage) and significantly more heat energy is needed to control larger plants (e.g. Ascard 1995).

3.3.1.2 Infrared

Infrared burners also use a mixture of propane/butan to produce red brightness temperature of about 900°C. The burner heats ceramic or metal surfaces that then radiate heat toward the plant. The infrared burners are not affected by wind like direct flames. On trials the infrared burner weeder were as effective as flaming (Ascard 2010). Infrared burners show similar short weed suppression for all plants which can regrow fast from subsoil organs. Main reason for the high energy need is the limited thermal transfer capacity through air to the plant.

3.3.1.2 Hot plant oil

A current development is the application of hot plant oils for thermal weed control. This system has recently been developed by Peukert et al. (2017). Oil is significantly more effective for thermal weed control because it can be heated to temperatures up to 300°C. First experiments have shown that the application of hot oil to dicotyledonous weeds caused lethal plant damages.

3.3.1.3 Hot water

The hot water method uses 600 liters water per hour at a temperature of 90°C. De Cauwer et al. (2015) studied the efficacy of hot water treatments to reduce the fuel used. Different growth stages and time of application at different dosages were tested. The treatments were repeated in different intervals. They concluded that young plants should be treated in the afternoon in a 3 week interval.
A study carried out on hot water treatment of the common broad-leaved dock (*Rumex obtusifolius*) showed 80% success in eradicating the weeds and 1 year after treatment

there was no evidence of lasting damage to the soil structure on the site, neither did the treatment stimulate the germination of any great number of seeds of *Rumex obtusifolius* found in the soil (Latsch et al. 2017).

3.3.1.4 Hot Foam

The method uses hot water in combination with foam made from natural, non-toxic ingredients including plant oils and sugars. When the solution is applied to a weed, the hot solution acts as a thermal blanket, keeping the heat on the weed long enough to kill it. Several machines from the company weedingtech (FoamStream) are on the market from small handheld devices to small and medium machines. No efficacy data is available but the manufacturer claim that their technique needs 50% fewer applications compared to hot water and thereof the cost is lower compared to other methods like hot water, steam and vinegar (acetic acid).

3.3.1.5 Steaming

The steam raises the plant shoot and soil temperature to 70-100 °C killing most weed seeds to a depth of at least 10 cm. It is also possible to use jets of steam to kill emerged weeds. Steam is more efficient at conducting the heat and has a better penentration. The machines are also effective in windy and wet conditions. The test of steam in a strawberry field showed a reduction of weeds equal to commercial standard procedures (Miller & Fennimore 2014).

3.3.2 *Other physical methods*

3.3.2.1 High cold water pressure

A system that uses high cold water pressure has been developed for weed control in vineyards and orchards (Bravin & Kuster 2016). The machine removes weeds with rotational nozzles up to 5 cm soil depth. Water consumption is approximately 1000 L/ha depending on the speed. Certainly, the applicability and efficacy along roadsides needs to be determined. It may be useful to control IAPs along the road verge, however further experiences are needed.

3.3.2.2 Microwave

Several patents dealing with microwave treatment of weeds and their seeds have been registered. However, none of these systems has been commercially developed (review Brodie et al. 2012). Several advantages are seen compared to other methods, for instance microwaves are not affected by wind and the age of the plant. Microwave treatment wilted the leaves and may have ruptured internal structures within the marshmallow plants quite fast in a prototype (Brodie et al. 2007). Microwave treatment needs a time to heat weed plants to a sufficiently high temperature to kill the plant. The travel speed of the microwave equipment during weed treatment depends on the energy send to the plant (Brodie et al. 2012). The energy requirements are an important bottleneck in the development of machines for the use in weed management. Focused energy applications together with sensor technology may open the way for novel microwave technologies.

3.3.2.3 Electroherb

The use of high-voltage electric power is a new method offering the possibility to destroy plants systemically by touching the upper part of the plants. Electric power is directed to the root system mainly mechanically destroying the water supply lines of plants without relevant thermal heating. As a result plants dry down and remain fixed to the ground without need to move soil or open soil surfaces. Experiments with different plant species showed root destruction down to a depth of 10-15 cm. This is in many cases sufficient to destroy the vegetation points or rhizomes sufficiently to lead to no or very slow regrowth of plants. Depending on the amount of available electric power, treatment speed, stem density and woodiness of plants, many weeds up to 1 m of height can be controlled. The company Zasso/Germany develops systems for agricultural and urban applications. First results within the present project showed that annual plants (*Ambrosia artemisiifolia*) were destroyed completely and they were not able to re-sprout. Specific application plans for Japanese Knotweed are under development within the current project. Results after two treatments per year showed significant reduction in shoot density. For optimised procedures and weed control at least a 2-year treatment and observation period is necessary.
The technique is still under the development and new insights will be obtained during the present project. Specific aspects of high voltage energy on or near road infrastructure are considered as well as safety aspects fur humans and the environment. Results from the two-year experiment including best application times and modes will provide information about the efficacy, the selectivity and the costs of high-voltage electric power systems.

3.3.2.4 UV radiation, freezing or laser radiation

The energy of the UV radiation is absorbed by the plant and results in heating of the plant tissue. Because of the potential to cause mutation to living organisms (including humans) this method may not be futher investigated.
Different freezing media, such as dry ice and liquid nitrogen were used (Fergedal 1993) and compared to flaming. But none of the freezing medium was better than flaming.
Laser delivers high energy to selected plant material, raising the temperature of water in the plant cells and thereby destroying the plant cells. The biological efficacy of the laser control method is related to wavelength, exposure time, spot size and laser power. The efficacy also varies between the weed species (Mathiassen et al. 2006). Laser applications were tested on plant heights between 30 and 60 cm of *Amaranthus retroflexus*. For higher plants more energy is needed to have a 100% lethal damage. However, the energy demand for laser weed control was 20% lower compared to flaming (Kaierle et al. 2013).
Researchers from the Geodesy and Geoinformation at the University of Bonn developed a system combining the weed recognition with the laser technique (https://www.sciencedaily.com/releases/2017/06/170607094152.htm). A start-up was established in 2017 with the name ESCARDA technology. At present, no data on efficacy is available. JÄTI developed by Unkrautfrei in Rei(he)nkultur) is another machine for the use in agriculture which is equipped with an imagine processor and a laser to kill small weed plants.

3.3.2.5 Use of physical methods along roadsides

In general, there is a growing interest and research in physical weed control methods. However, such methods are currently hardly used for vegetation control along roadsides to our knowledge. Thermal methods (direct flame, hot water) suffer from the difficulty to achieve adequate damage to the plant, because thermodynamic limitations (heat transfer,

especially systemic and directed) and costs (labour, energy) are still prohibitive. Due to the temporal increase of soil temperature of these methods which affect the soil, seeds in the soil may start to germinate, which makes a subsequent treatment necessary. However, further development may improve this situation. Certainly, the applicabilty of some of the mentioned methods along roadsides is limited (fire hazard and infrastructure damage due to direct flame), others have not been developed any further.
Some new methods can potentially be used for the control of IAPs along roadsides (e.g., electroherb, hot plant oil, hot foam), but further development steps are necessary. This includes specific application procedures, machinery and time-logistic aspects as well as a consideration of costs to deal with the specific needs of roadside plant management.

3.4 ***Biological control***

3.4.1 *Classical and inundative biological control*

The classical biological control methods generally use non-indigenous organisms to control non-desirable species, disease and pest. Within the invasive plant context, it is therefore often considered to utilize predators, herbivores or microorganism from the native range of the invasive species to control its population. In Europe such methods are not common and the registration of such an agent is very costly or impossible. The biocontrol agent is released once into the new environment and with time, the biocontrol organism builds up a population size that is able to reduce the invasive species, disease or pest. The introduced population is maintained over very long periods of time (Bale et al. 2008). This type of biological control has been most successful with perennial crops (fruit plantations and forests), where the long-term nature of the ecosystem enables the interactions between the invasive and its natural enemy to become fully established over a period of time (Bale et al. 2008). The called augmentation or inundative control refers to all forms of biological control in which natural enemies are applied periodically in high concentrations at the time when the non-desirable species, disease and pest cause the problem, analogous to the use of a pesticide. In this approach, the biological agent is not expected to be self-sustaining (Boyetchko 1997) and the control is usually transient, and sometimes re-releases are required more than once per year (Bale et al. 2008). The advantage of this strategy is that no species from other regions are introduced. For the application against weeds several products for the application in agriculture were developed and some are commercially available, but only outside of Europe (review in Harding et al. 2015). The so called bioherbicides are still underexploited to control IAPs. They may not eradicate the target plant completely but can reduce the growth and the spread. However, the development and registration of such agents are expensive and manufacturers are not willing to bear the costs, if the turnover is too small from such a product. Although, the results for controlling *Prunus serotina* with the fungus *Chondrostereum purpureum* were very successful, the product never reached the market because of the high cost for the registration (de Jong 2000).

CABI has several projects dealing with classical biocontrol agents to control *Impatiens glandulifera* (rust fungi *Puccinia koarovii*), *Buddleja davidii* (*Chondrostereum purpureum*) and *Fallopia japonica* (psyllid *Aphalara itadori*) (Shaw et al. 2011). The researchers used control agents from the place of origin. If such agents can be established in Europe without any effect on the native vegetation, the agent keeps the plant at low level, as is the case in their original range and no management cost are needed anymore. However, the research on biological agents needs time and resources. Still the acceptance in Europe is not as in other countries like US, South Africa, New Zealand and Australia, where many biological agents had a great success in the control of invasive plantsThe work on the *Ailanthus altissima* and *Verticilium nonalfalfae,* which is a naturally found plant pathogen

(Maschek & Halmschlager 2017), or *Ophrella communa* against ragweed (Müller-Schärer et al. 2014), both with a very narrow host range, show the possibility to restrict the growth of IAPs with biological organisms. This approach is the most sustainable method with a long lasting effect.

3.4.2 *Grazing*

Using goats and sheep in pasture for weed control is well established (Firn et al. 2013, Willard 2016). Most of the young plants are eaten by goats or sheep like *Fallopia japonica*, *Impatiens glandulifera* and *Heracleum* spp. Grazing is not possible for plants which produce secondary metabolites which are toxic to livestock like *Senecio* species. The set-up of fences to keep the animals in place is cost intensive, however for long term use, it is the most cost efficient method. The method can only be applied on specific sites, were no risk for road traffic and animals exist.

4 Case studies of management strategies for IAPs along roadsides

To give an overview of research done in regards to the management of IAPs a summary of selected plant species is presented. Particular focus was put on Invasive Alien Species of Union concern (EU Regulation 1143/2014). The summary includes literature research but also online material from management plans for IAPs from different countries like Ireland and the US. The case studies show, that management plans for each IAPs have to be elaborated for each species to consider their biology.

4.1 *Ailantus altissima (Mill.) (Tree-of-heaven)*

The effect of hand pulling and mulching, cut stump and glyphosate treatment was evaluated in the Carolinian Life Zone, Rondeau Provincial Park, Canada (Meloche & Murphy 2006). Cutting the stump and glyphosate treatments was the most effective method in regards to control young trees of heaven. Cutting the stump without further procedure increased the young shouts. Injection of glyphosate to mature trees showed to be effective.
In the field guide for managing tree-of-heaven in Southwest US (USDA) several control methods are listed (http://www.envirothonpa.org/documents/tree-of-heaven.pdf). The time for successful control of *A. altissima* requires a management regime for up to 5 years. All the control methods should start in early summer when the root reserves are at lowest and repeated application is necessary to keep the root reserve at low levels. The tree is relatively shade intolerant and by establishing competitive shrubs, *A. altissima* may respond with reduced growth. Young trees can easily be pulled out from the soil, if the soil is moist enough to remove the entire root. Several broadleaf herbicides are recommended such as triclopyr. Care should be taken, because these herbicides are non-selective and affect also the surrounding vegetation.
The use of *Verticilium nonalfalfae* to control the tree of heaven is very effective. The fungus only affects *Ailanthus altissima* and none of the other tested trees showed symptoms (Maschek & Halmschlager 2018). After two weeks of inoculation, the leaves show first symptoms. A complete defoliation occurs after 6 to 8 weeks. Depending on weather conditions, water, and nutrient resources, the tree can respond with restricted re-sprouting, but the sprouts are not frost protected and the tree dies in the following year (Maschek pers. communication).

4.2 *Asclepias syriaca (Common milkweed)*

Until now only very little research has been conducted in regards to the management of common milkweed. The results from the literature recommend different broadleaved herbicides. Mechanical control is not recommended and can be contra-productive. Because of the rhizomes similar methods may be applied as for Japanese knotweed (Zalai et al. 2017).

4.3 *Ambrosia artemisiifolia (Common ragweed)*

Guidelines for the control of ragweed were elaborated within the frame of the project: Strategies for *Ambrosia* control (AMBROSIA) (Buttesnchøn et al. 2010). The prevention practices should include initiatives to limit unintentional spreading of seeds by implementation of hygiene and prevention practices together with regulation of habitat quality in areas prone to common ragweed invasion. The dispersal of seeds should be prevented along transport corridors. Apart from awareness programs the survey and monitoring of invested areas and adjusted land is important for fast eradication actions. After the measures, treated areas need to be monitored to follow up the success of the actions.

For the control of ragweed several methods are summarized in the report. For small populations uprooting is possible before flowering. The operating people should wear protective clothing and sensitized people susceptible to allergies should not work with ragweed uprooting.

Hoeing is possible in agriculture land, but not on road verges. Mowing or cutting is an alternative on large sites, were herbicides are forbidden. The cutting should be as close to the ground as possible, without disturbance of the soil surface to minimize re-growth. The time of cutting is crucial as it greatly influences the plant's re-growth and flowering (Milakovic et al. 2014). It was recommended that a first cut should be performed shortly before male flowering followed by subsequent cuts before the onset of new flowers on re-sprouted lateral shoots (Karrer 2016). Chemical treatments in large infested areas are depending on national regulation, however ragweed has developed some resistances against specific herbicides. In the USA, ragweed plants were found that are 10 times more resistant to the normal rate of glyphosate (Buttenschøn et al. 2010). Mulching can be used to limit seed germination on small areas. Mulch cover can prevent seeds to germinate and prevent seedling from growing. Also covering the infested area with plastic reduces the seedling growth. After any eradication method, it is important to re-green the site with native seed mixtures to reduce the risk of new infestations.

In frame of the cost action FA1203 SMARTER the effectiveness of the biological control with *Ophrella communa* was analyzed. The beetle is used in China for ragweed control. The beetle also occurs in Northwestern Italy and southern Switzerland. The insect preferentially feeds on ragweed and severe defoliation is observed. Plants which are exposed to the beetle produce fewer male flowers and little amount of pollen but no increase in allergenicity of the pollen grains was observed (Lommen et al. 2017). Moreover, pollen-monitoring studies in the Milano area revealed that since the introduction of the beetle the pollen counts have dropped by approximately 80% (Bonini et al. 2018).

Tests with seed mixtures containing a high percentage of *Festuca* spp. within the frame of the project showed that the germination of ragweed seeds was reduced. In pots were ragweed and *Festuca* spp. were sown together less than a half of the ragweed seeds germinated compared to pots with only ragweed.

4.4 *Fallopia japonica (Japanese knotweed)*

At present, the most effective method to reduce populations of knotweed is the application of glyphosate at the maximum growing stage until the flowering period when there is a strong sink towards the rhizomes. However, herbicide application is not allowed in all European countries and the approval of glyphosate for the next years is debated. Frequent mowing is possible, but it was observed that the number of stems increased over time, although the stems were thinner. Alternative methods like freezing with liquid nitrogen is possible, but the costs are too high.

Biological control with *Aphalara itadori* showed promising results and should be evaluated as an economical alternative to prevent future spread and keep the population at an acceptable size. However, the rate of overwintering of the psyllid is low. The use of the rust fungi *Puccinia polygoni-amphibii* var. t*ovariae* is tested as bioherbicide in the UK. The success of the fungi depends on the biotype of *Fallopia japonica* (pers. Communication Marion Seier).

In the future, alternative methods are urgently needed. The main target to control Japanese knotweed is the removal of rhizomes with the save disposal of the plant material. This is the most effective but cost intensive way for its control.

4.5 *Gunnera tinctoria (Giant rhubarb)*

The management of giant rhubarb takes several years. As the most effective method, a combination of physical and chemical control measures is recommended in Ireland. The plant is able to regrow from small fragments of rhizomes. Therefore, the plant material has to be treated as hazard waste to prevent future spread. Tools, machines, shoes and clothes have to be cleaned on site. Physical removal can be done with spades for small plants or where a small number of plants is present. Plants missed in a first attempt can be treated in subsequent years. The burial of the plants with large machines is under investigation.

Open land should be re-naturalized to prevent future invasion of giant rhubarb.

The use of chemicals like glyphosate can be used if no restrictions by legislation exist. The timing of the treatment is an important factor, because early herbicide treatments had no impact in preventing the growth of giant rhubarb. The treatment in the later season (August-September) resulted in no regrowth of the plant in the next year, but in regrowth after two years, which indicate that the rhizomes can survive in the soil. Therefore, it is necessary to observe the treated size several years with repeated application of herbicides.

In Ireland, the cut and paint method was applied in Achill Island. This method involves the cut of petiole at the bases and applying the herbicides directly to the cut surface. The methods is cost effective as only small quantities of herbicides are applied, and the results were better as with spraying. The third tested application of herbicides was the injection into the rhizomes. Several holes should be made along the rhizome as translocation can be slow and the herbicide may only penetrate small sections of the rhizome. The method is labor intensive but the effects on the neighboring environment are minimized. It was tested in the Achill Island with the same success rate as the cut and paint method (https://invasivespeciesireland.com/wp-content/uploads/2011/01/Gunnera_tinctoria_ISAP.pdf)

In the Azores and New Zealand, trials indicate that triclopyr, butoxyethyl and metsulfuron-methyl are also effective to kill the entire plant, including the rhizomes. The eradication plan takes several years and requires continues inspection. It is recommended that trained and experienced personnel should carry out the control of giant rhubarb.

4.6 *Heracleum mantegazzianum (Giant hogweed)*

Nielsen et al. (2005) evaluated different mechanical control methods like root cutting, cutting the plant, mowing and umbel removal. Only by root cutting an immediate death of the plant is achieved and it should be done in early spring by cutting the root at least 10 cm below soil level. The cut parts of the plants need to be pulled out.

Mechanical mowing can be done for larger stands, but it has to be repeated 2-3 times during the growing season. Cutting the umbels fails often because of the fast regeneration and production of new flowers.

Grazing has been shown very effective to control large stands, if the grazing starts early in the season. Animals like goats and sheeps remove most of the young plant parts.

Giant hogweed is sensitive to herbicides like glyphosate and triclopyr. This active substance of triclopyr is only effective against broad-leaved plants and does not harm grasses. However, national legislation can restrict the use of herbicides outside from

agricultural land. Other methods like salt, household ammonia, heating oil and others were tested, but without success.
The authors recommend different combinations of methods depending on the stand size. To prevent future establishment and soil erosion native grass species are recommended at high density. After the treatments, a yearly inspection is needed to prevent the regrowth of the plant.

4.7 *Impatiens glandulifera (Himalayan balsam)*

Several herbicides have been shown to be effective against Himalayan Balsam and one application is usually sufficient. The treatment should be done in the active growing stage, before flowering of the plant. The best time in the UK is May/June. Populations that have been controlled by hand pulling, can be treated in the following year with herbicides. Because Himalayan balsam is mostly found close to water reservoirs, the use of herbicides has to be carefully evaluated to prevent the contamination of ground water resources. However, seeds in the soil will not be killed by herbicides.
Hand pulling, strimming and mowing are recommended. Hand pulling should be done several times (every 4 to 5 weeks) before the flowers are set up. The mowing of populations should be repeated several times and it is recommended to cut the plants as deep as possible, because Himalayan balsam is able to regrow from the stem.
If hand pulling or mowing are done only once a year before the flowering period, the population size is reduced in the first years, but in the following years a relative dense stand will be obtained again.
Used machineries should be cleaned after work to prevent future spread.
Where immediate eradication is required for example for road buildings, the plants can be excavated. After the excavation the contaminated soil should be treated as special waste. During the storage, it is important to monitor the growth of plants and to take Himalayan balsam out before plants set seeds.
For all treatments, a management plan should include also the monitoring of the treated stands for at least four consecutive growing seasons to ensure a successful eradication and actions have to be taken if regrowth is observed.
After the eradication of Himalayan balsam a plan for revegetation should be elaborated. Bare ground is often left after the removal of Himalayan balsam. This soil is exposed to erosion and re-invasion by **Himalayan balsam and other IAPs.** Plants have to be carefully selected to reestablish the natural biodiversity.

4.8 *Lupinus polyphyllus (Lupine)*

For the management of this plant is important to minimize the seed production by mowing the plant before seed setting. Regular mowing can prevent seeds to get mature. Mowing is recommended twice a year for 3 to 5 years, before flowering and two month later. Individual plants can be hand pulled out in stands with low numbers of plants. The plants with seeds or rhizomes should be treated as hazard waste and burned to prevent future spread. Machines contaminated with seeds or rhizomes must be cleaned.
Commercial distribution of L. polyphyllus should be prohibited to avoid the escape to nature.
Brobäck (2015) tested different cutting times for the control of Lupinus polyphyllus in Sweden. Plants cut early at flowering stage re-sprout better as plants cut later in the season. The early cut plants produced new flowers and fruits. If the lupine is cut in a height of 15 cm above the ground, regrowth is pronounced. It was found that seeds from cut plants germinated earlier, but they were also more susceptible to mold.

The use of lime to increase the pH in the soil is another method to control of lupines (Sjölund & Brobäck 2018).

5 Control methods – results from the questionnaire

Based on the questionnaire send out to people working in road construction, maintenance or related fields we obtained an overview on current practices and possible alternatives (Figure 2). The majority of the participants indicated that the most important measure is the identification of the IAPs before road construction to avoid future spread of the species which also includes specific soil management. Therefore, participants see a need in the involvement of well-educated personnel in the field of invasive biology. The movement of contaminated soil should be strictly forbidden and prosecuted. The increase of public awareness, prohibition of selling invasive species and the mapping of infestation are often mentioned in regards to minimize the spread of IAPs.

Up-rooting of the plants is the most effective method for eradication, whereas mulching and mowing are seen as not useful for the control of IAPs. One participant stated that for an effective eradication man power is indispensable. The cleaning of the machinery was seen by 73% of the participants as a useful method to control IPAs. Alternative methods like hot water treatment or electrical treatment are seen as important or very important by 60% and 68%, respectively. The use of special seed mixtures are rated by 79% of the participants as important and very important and the same was seen for the chemical control with herbicides. Mowing and mulching have been regarded as the least effective method in regards to the control of IAPs, however one participants proposed repeated mowing and mulching, following a management plan. Several participants mentioned to invest more in biological control methods and research on more ecofriendly weed killers. The combination of different methods was proposed from one participant. One idea was to change the soil pH or to heat the soil with chemicals which has to be tested at small scale.

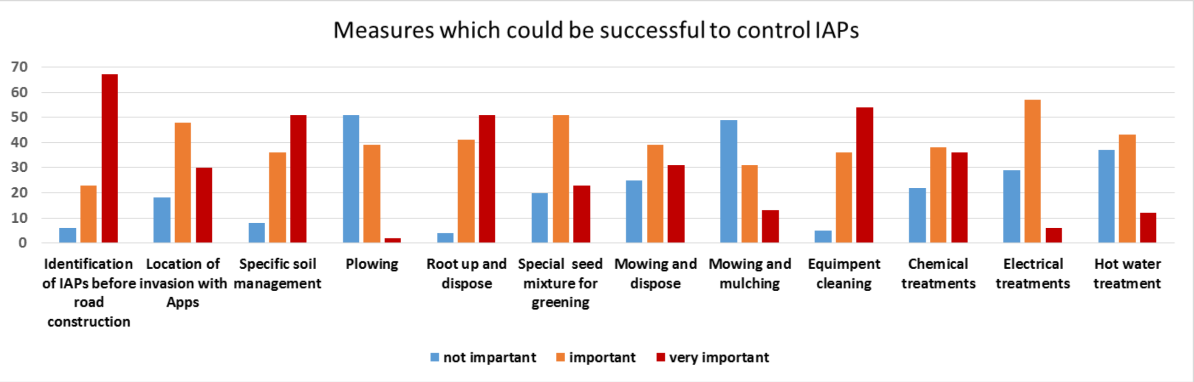

Figure 2: Response from the questionnaire send out to people working in road maintenance, construction or similar fields.

6 Summary

In Table 1, all mentioned standard and alternative methods are briefly summarized to provide a quick overview.

Table 1: Overview about standard and alternative methods to control invasive alien plants (IAPs) along roadsides. Their advantages and disadvantages and applicability for life forms (annuals, perennials, shrubs, and trees) are shown as well as a selection of IAPs where the methods have already been applied to as a common practice or experimentally. Main references are outlined. In the last column, currently most applicable methods (*) for the control of IAPs along roadsides are indicated based on the literature and the questionnaire.

Method	**Advantage**	**Disadvantage**	**Plant species**	**IAPs (selection)**	**Main references**	**Most applicable**
Standard methods						
Mechanical control						
Mowing/Mulching	Comparable low cost to other mechanical control options, for medium to large-sized populations, standard measure	High frequency needed, to prevent seed production the timing is very important, some IAPs (*Fallopia* sp.) sprout from stem fragments, high rate of resprouting, only short term effect	Annuals, perennials	*Ambrosia artemisiifolia*, *Lupinus polyphyllus*, *Asclepias syriaca, Heracleum mantegazzianum, Impatiens glandulifera*	Pyšek et al. (2007), Brobäck (2015), Zalai et al. (2017), Lommen et al. (2017) G. Gebhard (road maintenance unit, Burgenland, Austria), pers. com.	*
Hand removal (uprooting)	Effective, highly targeted, surrounding native species unaffected	High cost, labour intensive, only suitable in areas with low infestation (small stands)	Annuals	*Impatiens glandulifera*, *Ambrosia artemisiifolia*	Howell (2002), D. Fischer (Zürich), pers. com	*
Digging	Effective, highly targeted, surrounding native species remains largely unaffected	High cost, labor intensive, only suitable in areas with low infestation, requires good access	Annuals, perennials	*Fallopia* sp., *Asclepias syriaca, Gunnera tinctoria, Heracleum mantegazzianum*	Pyšek et al. (2007), D. Fischer (Zürich), per. com.	*
Brushing	Effective	Only used on hard surfaces, negative effect on the pavement	Annuals, perennials	Experimental and/or field tests available, not yet tested on relevant IAPs	Rask & Kristoffersen (2007)	
Chemical control						

Herbicides	Effective, flexible, low costs	Environmental problems, herbicide resistance	Annuals, perennials, shrubs, trees	Experimental and/or field tests available, tested on relevant IAPs	Jones et al. (2018)	*
Alternative methods						
Mechanical control						
Mowing (removal) competitive seed mixture (cultural competition)	Sustainable method	Restoration of native vegetation is critical	Annuals and biannuals	*Ambrosia artemisiifolia*	Schuster et al. (2018)	*
Stem girdling ring-barking)	Effective to prevent re-sprouting, surrounding native species unaffected	High cost, labour intensive, only suitable in areas with low infestation	Shrubs and trees	*Robinia pseudoacacia*, *Ailanthus altissima* *Acer negundo*	Böcker & Dirk (2008) Merceron et al. (2016)	*
Suffocation/Smothering (Geofabrics, CuTex Root Barrier, Knotblock)	Effective (inhibits germination and budding). Prevent the spread into neighboring sites, used during road construction	Less effective against rhizome perennials (e.g. *Fallopia japonica*), maintenance effort, difficulty of removal, disposal management Alternative: biodegradable mulch film,	Annual, perennials	Practical use in agriculture (vegetables), experimental and/or field tests available, tested on relevant IAP (e.g. *Fallopia japonica, Heracleum mantegazzianum, Impatiens glandulifera*)	Jones et al. (2018), http://www.geosyn.co.uk/product/knotblock-knotweed-barrier	*
Natural products						
Organic acids (e.g. acetic acid, pelargonic acid, caprylic acid, capric acid)	Effective against (young) annual broadleaf plants	Not very effective against grass species and perennials, only “burndown effect”, high dosages needed, high costs	Annuals	Experimental and/or field tests available (along roadsides), not yet tested on relevant IAPs	Young (2004), Abouziena et al. (2009), Barker & Prostak (2014), Crmaric et al. (2018)	*

Essential oils (e.g. clove oil, pine oil, citrus oil)	Effective against (young) annual broadleaf plants, positive image of the product ("natural")	Not very effective against grass species and perennials, only "burndown effect", high dosages needed, high costs	Annuals	Experimental and/or field tests available (along roadsides), not yet tested on relevant IAPs	Young (2004), Boyd et al. (2006), Abouziena et al. (2009), Barker & Prostak (2014)	
Plant oils (rape oil, sunflower oil)	Reduces biomass of plants, environmentally friendly	Herbicidal activity appears low (depends on plant species), more treatments necessary, quantities required may not be economically viable	Annuals, perennials	Experimental and/or field tests available, not yet tested on relevant IAPs	Hodge et al. (2018)	
Iron chelate solution	Selective, for broadleaf plants, no residuals	Repeated treatments necessary, product not available in Europe yet	Annuals, perennials	Not yet tested on IAPs	Smith-Fiola & Gill (2014)	
Corn gluten meal (crude botanical product)	Pre-emergence herbicidal activity, positive image of the product ("natural")	Grasses and perennial weeds are less sensitive, applicability along roadsides questionable (e.g. high quantities needed)	Annuals	Experimental and/or field tests available (along roadsides), not yet tested on relevant IAPs	Barker & Prostak (2014), Dayan & Duke (2015)	
Plant allelopathy (*Festuca rubra*, *Festuca arundinacea straw/mulch* (crude boatnical product)	Can be effective	Effectiveness depends largely on the weed spectrum, applicability along roadsides questionable (e.g. high quantities needed), more experiments necessary	Annuals, perennials	Experimental and/or field tests available, not yet tested on relevant IAPs	Bertin et al. (2007), Recasens et al. (2018)	*
Physical methods						

Direct flame	Can be effective (on a hard surface 100% reduction of weed cover)	Effectiveness depends on plant age and species, weather conditions; less effect on perennials; high energy consumption (6.82 kg/h, working width 1 m), fire hazard	Annuals	Experimental and/or field tests available (along roadsides), not yet tested on relevant IAPs	Ascard (1995), Rask & Kristoffersen (2007), Barker & Prostak (2014)	
Hot water	Can be effective, moderate environmental impact	Effectiveness depends in particular on plant age and species, weather conditions, less effect on perennials	Annuals	Experimental and/or field tests available, not yet tested on relevant IAPs	Kurfess und Kleisinger (2000), Rask & Kristoffersen (2007) HEATWEED Technology (http://heatweed.com/about-the-company/)	
Hot foam made from plant oils and sugar	Can be used on any surface, low energy consumption, keep heat on the plant	Very high impact on environment because palm oil and avocado oil is used.	Annuals	Experimentally tested	Foamstream available at the US market (https://www.benziecd.org/uploads/1/1/5/2/11522077/invasive_plant_treatments_alt_to_herb.pdf)	*
Steaming	Can be effective, less water use as for hot water, higher heat transmission	Effectiveness depends in particular on plant age and species, weather conditions, less effect on perennials; higher risk of energy loss during application	Annuals	*Erigeron annuus*, *Senecio* sp. Experimental and/or field tests available, not yet tested on relevant IAPs	Rask & Kristoffersen (2007)	
Hot air	Effect similar to other thermal control	Effectiveness depends in particular on plant age and species, weather conditions, less effect on perennials; High energy	Annuals	Experimental and/or field tests available, not yet tested on relevant IAPs	Rask & Kristoffersen (2007)	

		needed, only small machines are available				
Cold water (under high pressure)	Can be effective, machine for practical use available	Cost intensive	Annuals	Experimental and/or field tests (orchards) available, not yet tested on relevant IAPs	Bravin & Kuster (2016)	
Infrared/Radiant	Can be effective	Effectiveness depends in particular on plant age and species, weather conditions, less effect on perennials; high cost, low area output	Annuals	Experimental and/or field tests available, not yet tested on relevant IAPs *no machine available*	Ascard (1995), Rask & Kristoffersen (2007)	
Microwaves	-	High energy consumption (1000 to 3400 kg diesel/ha), no machine for practical use available, experimental stage	Annuals	Experimental and/or field tests available, not yet tested on relevant IAPs	Sartorato et al. (2006), Rask & Kristoffersen (2007)	
Laser radiation	Lower energy cost compared to other thermal control	Does not kill plants, only retards plant growth, no machine for practical use available, experimental stage for direct targeting the specific plant species	Annuals	Experimental and/or field tests available, not yet tested on relevant IAPs	Rask & Kristoffersen (2007) Mathaissen et al 2006 Kaierle et al 2013	
Freezing (i.e. liquid nitrogen and carbon dioxid)	-	Only destroys upper part of the plants, no machine for practical use available. Treatment is time and cost intensive, can damage road infrasturcture	Annuals, perennials	Experimental and/or field tests available, not yet tested on relevant IAPs, except *Fallopia* sp.	Rask & Kristoffersen (2007), Report LIFE12 NAT/AT/000321	

Electroherb	Effective against (young) annual grass and broadleaf plants,	The deep root system of perennials, seems to be not affected sufficiently, experimental stage	Annuals (perennials)	*Ambrosia artemisiifolia*		*
Biological control (examples)						
Chondrostereum purpureum	Effective	Cultivated and native *Prunus* sp. are also affected, commercially developed (BioChon), but not on the market	Trees (*Prunus* sp.)	*Prunus serotina*	De Jong (2000), Hamberg et al. 2017 https://neobiota.bfn.de/handbuch/gefaesspflanzen/prunus-serotina.html	*
Verticillium nonalfalfae	Effective, commercially developed (Ailantex) and temporary authorized (in AT),	Labor intensive (stem inoculation), follow-up host range studies are needed	Tree (*Ailanthus altissima*)	*Ailanthus altissima*	Maschek & Halmschlager (2017), Maschek & Halmschlager (2018)	*
Puccinia komarovii var. *glanduliferae*	Effective, already released in the UK, (establishment phase)	Biotypes of *Impatiens glandulifera* seem to be less sensitive	Annuals (*Impatiens glandulifera*)	*Impatiens glandulifera*	Varia et al. (2016)	*
Grazing (e.g. goats)	Viable option for specific right of way situations (e.g. reclaiming overgrown roadside sites)	High cost (e.g. fence needed), not widely applicable, security concerns	Annuals, perennials, shrubs and trees	*Robinia pseudoacacia, Ailanthus altissima, Fallopia* sp., *Heracleum mantegazzianum, Impatiens glandulifera*	Popay & Field (1996), Willard (2016)	

7 References

Abouziena H.F.H., Omar, A.A.M., Sharma S.D., Singh M. (2009). Efficacy comparison of some new natural-product herbicides for weed control at two growth stages. Weed Technology 23, 431-437.

Ascard J. (2010). Comparison of flaming and infrared radiation techniques for thermal weed control. Weed Research 38, 69-76.

Ascard J. (1995). Effects of flame weeding on weed species at different developmental stages. Weed Research 35, 397-411.

Bagavathiannan M.V., Norsworthy J.K. (2016): Multiple-herbicide resistance is widespread in roadside Palmer Amaranth populations. PLoS ONE 11(4), e0148748. doi:10.1371/journal.pone.0148748.

Bale J.S., van Lenteren J.C., Bigler F. (2008). Biological control and sustainable food production. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 761-776.

Bainard L.D., Isman M.B., Upadhyaya M K. (2006). Phytotoxicity of clove oil and its primary constituent eugenol and the role of leaf epicuticular wax in the susceptibility to these essential oils. Weed Science 54, 833–837.

Barker A.V., Prostak R.G. (2014). Management of vegetation by alternative practices in fields and roadsides. International Journal of Agronomy 12, https://doi.org/10.1155/2014/207828.

Bertin C., Weston L.A., Huang T., Jander G., Owens T., Meinwald J. Schroeder F.C. (2007). Grass roots chemistry: meta-Tyrosine, an herbicidal nonprotein amino acid. PNAS 104, 16964-16969.

Böcker R., Dirk, M. (2008). Development of an effective girdling method to control *Robinia pseudoacacia* L.: First results and outlook. Neobiota 7, 63-75.

Bonini M., Šikoparija B., Skjøth C.A., Cislaghi G., Colombo P., Testoni C., Smith M. (2018). Ambrosia pollen source inventory for Italy: a multi-purpose tool to assess the impact of the ragweed leaf beetle (*Ophraella communa* LeSage) on populations of its host plant. International Journal of Biometeorology 62, 597-608.

Boyd N.S., Brennan E.B., Fennimore S.A. (2006). Stale seedbed techniques for organic vegetable production. Weed Technology 20, 1052-1057.

Boyetchko, S.M. (1997). Principles of Biological Weed Control with Microorganisms. HortScience 32, 201-205.

Bravin E., Kuster T. (2016). Kosten der Baumstreifenpflege. Schweizer Zeitschrift für Obst- und Weinbau *22/*17, 8-12 [in German].

Brewer C.E., Oliver L.R. (2009). Confirmation and Resistance Mechanisms in Glyphosate-Resistant Common Ragweed (*Ambrosia artemisiifolia*) in Arkansas. Weed Science 57, 567-573.

Brobäck D. (2015). Preventing the spread of the invasive *Lupinus polyphyllus*. Master thesis, University of Uppsala, Sweden. http://www.diva-portal.org/smash/get/diva2:893657/FULLTEXT01.pdf.

Brodie G., Ryan C. Lancaster C. (2012). Microwave Technologies as Part of an Integrated Weed Management Strategy: A Review. International Journal of Agronomy, article ID 636905, doi:10.1155/2012/636905.

Brodie G., Hamilton S., Woodworth J. (2007). An assessment of microwave soil pasteurization for killing seeds and weeds. Plant Protection Quarterly 22, 143-149.

Burch P.L., Zedaker, S.M. (2003). Removing the invasive tree *Ailanthus altissima* and restoring natural cover. Journal of Arboriculture 29,18-24.

Buttenschøn R.M., Waldispühl S., Bohren C. (2010). Guidelines for management of common ragweed, *Ambrosia artemisiifolia*. EUPHRESCO project AMBROSIA 2008-09. http:/www.EUPHRESCO.org.

Crmaric I., Keller M., Krauss J., Delabays N. (2018). Efficacy of natural fatty acid based herbicides on mixed weed stands, doi 10.5073/jka.2018.458.048

Dayan F.E., Duke S.O. (2010). Natural Products for Weed Management in Organic Farming in the USA. Outlooks on Pest Management, doi 10.1564/21aug02.

De Cauwer B., Bogaert S., Claerhout S., Bulcke R., Reheul D. (2015). Efficacy and reduced fuel use for hot water weed control on pavements. Weed Research 55, 195-205.

De Jong M.D. (2000). The BioChon story: deployment of *Chondrostereum purpureum* to suppress stump sprouting in hardwoods. Mycologist 14, 58-62.

Drescher A., Leiß N. (2006). Control of alien woody species in the Danube National Park (Austria). The example of *Ailanthus altissima* (Mill.) Swingle. BfN-Skripten, 184, p. 106.

Duke S.O. (2007). The emergence of grass root chemical ecology. Proceedings of the National Academy of Sciences 104, 16729.

Erasto P., Viljoen A.M. (2008). Limonene – A review: Biosynthetic, ecological and pharmacological relevance. Natural Products Communications 3, 1193-1202.

Fergedal S. (1993). Weed control by freezing with liquid nitrogen and carbon dioxide snow; a comparison between flaming and freezing. Communications of the 4th International Conference I.F.O.A.M. Non Chemical Weed Control, Dijon, France, 163-166.

Firn J., Price J.N., Whalley R.D. (2013). Using strategically applied grazing to manage invasive alien plants in novel grasslands. Ecological Process 2, 26. https://doi.org/10.1186/2192-1709-2-26.

Ford S. (2004). Cut and inject herbicide control of Japanese knotweed *Fallopia japonica* in Cornwall, England. Conservation Evidence 1, 3-5.

Forman R.T.T., Sperling D., Bissonette J.A., Clevenger A.P., Cutshall C.D., Dale V.H. et al. (2003). Road Ecology. Science and Solutions. Island Press, Washington, D.C. (US).

Gentili R., Gilardelli F., Ciappetta S., Ghiani A., Citterio S. (2015). Inducing competition: intensive grassland seeding to control *Ambrosia artemisiifolia*. Weed Research 55, 278-288.

Hamberg L., Lemola J., Hantula J. (2017). The potential of the decay fungus *Chondrostereum purpureum* in the biocontrol of broadleaved tree species. Fungal Ecology 30, 67-75.

Harding D.P., Raizada M.N. (2015). Controlling weeds with fungi, bacteria and viruses: a review. Frontiers in Plant Science 6, 659.

Heap I. (2018). The International Survey of Herbicide Resistant Weeds. Online. Internet. Monday, November 26, 2018, Available from http://www.weedscience.org.

Hodge S, Merfield C.N., Bluon A., Berry N.A., O'Connell D.M. (2018). The potential of culinary vegetable oils as herbicides in organic farming: the effect of oil type and repeated applications on plant growth. Organic Agriculture, https://doi.org/10.1007/s13165-018-0208-z.

Howell B. (2002). Control and eradication of Himalayan balsam. Quarterly Journal of Forestry 96, 125-127.

James T.K., Rahman A., Trolove M., Frith H. (2002). Efficacy of a certified organic herbicide based on pine essence. New Zealand Plant Protection 55, 207-212

Johnson III W.C., Davis J.W. (2014): Pelargonic acid for weed control in organic Vidalia® sweet onion production. HortTechnology 24, 696-701.

Jones D., Bruce G., Fowler M.S., Law-Cooper R., Graham I., Abel A., Alayne Street-Perrott F., Eastwood D. (2018). Optimising physiochemical control of invasive Japanese knotweed. Biological Invasions 20, 2091-2105.

Karrer G. (2016). Control of common ragweed by mowing and hoeing. Julius Kühn Archiv 455, 118-124.

Kaur H., Kaur, R., Kaur S., Baldwin I.T., Inderjit (2009). Taking Ecological Function Seriously: Soil Microbial Communities Can Obviate Allelopathic Effects of Released Metabolites. PLoS ONE 4, e4700.

Kaierle S., Marx C., Rath T., Hustedt M. (2013). Find and irradiate — lasers used for weed control. Laser Technik Journal 10, 44-47.

Kurfess W., Kleisinger S. (2000). Wirkung von Heißwasser auf Unkrautpflanzen. Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz, Sonderheft XVII, 473-477.

Lanini W.T., Roncoroni J.A. (2010): Field testing of organic herbicides. Proceedings of the Western Society of Weed Science 63, 13.

Latsch R., Anken T., Herzog C., Sauter, J. (2017). Controlling *Rumex obtusifolius* by means of hot water. Weed Research 57, 16-24.

Lommen S.T.E., Ciappetta S., Ghiani A., Asero R., Gentili R., Müller-Schärer H., Citterio S. (2017). Defoliation of common ragweed by *Ophraella communa* beetle does not affect pollen allergenicity in controlled conditions. Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology 151, 1094-1100.

Main D.C., Sanderson K.R., Fillmore S.A.E., Ivany J.A. (2013). Comparison of synthetic and organic herbicides applied banded for weed control in carrots (*Daucus carota* L.). Canadian Journal of Plant Science 93, 857-861.

Maschek O., Halmschlager E. (2017). Natural distribution of *Verticillium* wilt on invasive *Ailanthus altissima* in eastern Austria and its potential for biocontrol. Forest Pathology 47, e12356-n/a.

Maschek O., Halmschlager E. (2018). Effects of *Ailanthus altissima* wilt caused by *Verticillium nonalfalfae* on indigenous and invasive tree species in Eastern Austria. European Journal of Forest Research 137, 197-209.

Mathiassen S.K., Bak T., Christensen S., Kudsk P. (2006). The Effect of Laser Treatment as a Weed Control Method. Biosystems Engineering 95, 497-505.

Meloche C., Murphy S.D. (2006). Managing tree-of-Heaven (*Ailanthus altissima*) in parks and protected areas: A case study of Rondeau Provincial Park (Ontario, Canada). Environmental Management 37, 764-772.

Merceron N.R., Lamarque L.S., Delzon S., Porté A.J. (2016). Killing it softly: Girdling as an effective eco-friendly method to locally remove invasive *Acer negundo*. Ecological Restoration 34, 297-305.

Milakovic I., Fiedler, K., Karrer G. (2014). Management of roadside populations of invasive *Ambrosia artemisiifolia* by mowing. Weed Research 54, 256-264.

Milakovic I., Karrer G. (2016): The influence of mowing regime on the soil seed bank of the invasive plant *Ambrosia artemisiifolia* L. NeoBiota 28, 39-49.

Miller T.C., Fennimore S.A. (2014). Evaluation of an automatic steam applicator in strawberry. Book of Abstracts, 10th European Weed Research Society Symposium, p. 9.

Movellan J., Rocher F., Chikh Z., Marivingt-Mounir C., Bonnemain J.-L., Chollet J.-F. (2014). Synthesis and evaluation as biodegradable herbicides of halogenated analogs of L-meta-tyrosine. Environmental Science and Pollution Research 21, 4861-4870.

Müller-Schärer H., Lommen S.T., Rossinelli M., Bonini M., Borianim M., Bosio G., et al. (2014). *Ophraella communa*, the ragweed leaf beetle, has successfully landed in Europe: Fortunate coincidence or threat? Weed Research 54, 109-119.

Peukert J., Schulze Lammers P., Damerow L. (2017). Development of an application system for selective, thermal weed control in row crops with vegetable oil. Landtechnik 72, 202–212.

Popay I., Field R. (1996). Grazing Animals as Weed Control Agents. Weed Technology 10, 217-231.

Pyšek P., Cock M.J.W., Nentwig W., Ravn H.P. (2007). Ecology and Management of Giant Hogweed (*Heracleum mantegazzianum*). CAB International.

Rahkonen J., Pietikäinen J., Jokela H. (1999). The Effects of Flame Weeding on Soil Microbial Biomass. Biological Agriculture & Horticulture 16, 363-368.

Rajmis S., Thiele J., Marggraf R. (2016). A cost-benefit analysis of controlling giant hogweed (*Heracleum mantegazzianum*) in Germany using a choice experiment approach. NeoBiota 31, 19-41.

Rask A.M., Kristoffersen P. (2007). A review of non-chemical weed control on hard surfaces. Weed Research 47, 370-380.

Recasens J., Mas, N., Amadeo A., Valencia, F. (2018). Effect of different mulches and bio-herbicides on weed flora in organic vineyards. Book of Abstracts, 18th European Weed Research Society Symposium, p. 267.

Sartorato I., Zanin G., Baldoin C., De Zanche C. (2006). Observations on the potential of microwaves for weed control. Weed Research 46, 1-9.

Schuster M.J., Wragg P.D., Reich P.B. (2018). Using revegetation to suppress invasive plants in grasslands and forests. Journal of Applied Ecology 55, 2362-2373.

Shaw R.H., Tanner R., Djeddour D., Cortat G. (2011). Classical biological control of *Fallopia japonica* in the United Kingdom – lessons for Europe. Weed Research 51, 552-558.

Shrefler J., Webber III C.L., Taylor M.J., Roberts B.W. (2011). Weed management options for organic cantaloupe production. Proceeding of the Weed Science Society of America. Portland, OR, USA. Feb. 2011.

Sjölund M.P.A., Brobäck D. (2018). Kill the killer. Book of abstracts, IENE 2018 International Conference 10-14 September 2018, p. 213.

Smith-Fiola D., Gill S. (2014). Iron-based herbicides: alternative materials for weed control in landscapes and lawns. University of Maryland Extension.

Varia S., Pollard K., Ellison C. (2016). Implementing a novel weed management approach for Himalayan balsam: progress on the biological control in the UK. Outlooks on Pest Management 27, 198-203.

Ward J., Mervosh T. (2012). Nonchemical and herbicide treatments for management of Japanese Stiltgrass (*Microstegium vimineum*). Invasive Plant Science and Management 5, 9-19.

Webber III C.L., Shrefler J.W., Brandenberger L.B. (2012). Organic Weed Control. In: Herbicides - Environmental Impact Studies and Management Approaches (ed. R. Alvarez-Fernandez). Available from: http://www.intechopen.com/books/herbicidesenvironmental-impact-studies-and-management-approaches/organic-weed-control

Webber III C.L., Taylor M.J., Shrefler J.W. (2014). Weed control in yellow squash using sequential postdirected applications of pelargonic acid. HortTechnology 24, 25-29.

Willard R. (2016). The Use of Grazing Animals in Integrated Roadside Vegetation Management Washington State Department of Transportation Maintenance Operations Division May 2016.

Young S.L. (2004). Natural product herbicides for control of annual vegetation along roadsides. Weed Technology 18, 580-587.

Zalai M., Poczok L., Dorner Z., Körösi K., Pálinkás Z., Szalai M., Pintér O. (2017). Developing control strategies against common milkweed (*Asclepias syriaca* L.) on ruderal habitats. Herbologia 16, 69-84.

Websites retrieved
https://heatweed.com/wp-content/uploads/2017/01/20170602_Leaflet-A5-ISRP-web-EN.pdf
https://dnr.wi.gov/topic/invasives/control.html
https://www.benziecd.org/uploads/1/1/5/2/11522077/invasive_plant_treatments_alt_to_herb.pdf
http://www.ijabe.… final section…

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