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The effect of chemical weed control on growth parameters and biomass of caraway (*Carum carvi* L.)

MASTER'S THESIS

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Declaration

I hereby declare that I have done this thesis entitled "The effect of chemical weed control on growth parameters and biomass of caraway (Carum carvi L.)" independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague

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Maria Munoz Arbelaez

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Abstract

With the increasing demand for the medicinal and aromatic plant products, the cultivation of caraway and its economic importance as a source of essential oil are increasing, together with the scientific interest in the optimization of cultivation techniques for yield improvement. Lack of information on specific agricultural practices make difficult for growers to correctly manage the crop. Adequate practices such as weed control, irrigation, fertilization, and plant protection are particularly important to increase caraway yields. Weed management is one of the crucial factors affecting the production due to the weak root system of caraway plants. The objective of this thesis was to test the effects of different herbicides (registered and not registered) on dicotyledon weeds in caraway fields and on growth parameters of caraway.. Field trial was conducted in the north-eastern part of the Czech Republic, Olomouc region, near the town of Šumperk at the locality of Vikýřovice. The results showed that the use of herbicides did not affect weed diversity and it was found that the weed abundance (i.e. number of weed individuals) was positively correlated to the caraway biomass, which was possibly caused by the low abundance of weeds during the assessments. Both pre-emergent and post emergent herbicides are effective against the control of weeds in general, but Gardorprim Plus Gold 500 SC (S-metolachlor + terbuthylazine) showed symptoms of phytotoxicity on the caraway plants.It is recommended to use herbicides with the lowest rate, taking into account conditions on the field and land history.

Key words: caraway, herbicides, weeds, plant growth

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DAS Days after sowing
EPPO European and Mediterranean Plant Protection organization
RSD Rootstock diameter

The effect of chemical weed control on growth parameters and biomass of caraway (*Carum carvi* L.)

1 Introduction

Caraway (*Carum carvi L*) is an aromatic plant that produces large number of secondary metabolites with therapeutic properties such as antioxidant and anti-inflammatory effects. Caraway has been used since ancient times in Europe and the Middle East as a condiment for flavoring and food preparations. The plant is nowadays grown for its fruits, which are used in food, cosmetics, beverage, and pharmaceutical industries. For its content of the essential oil, caraway is a crop of high economic importance around the world. The annual world production of the essential oil is around 30-40 ton, the fifth largest amount amongst apiaceae species. About 30 t of the essential oil is traded yearly in the world market, (Malhotra 2012). The total world production of fruits is around 15 thousand tones. Nevertheless, it is rather variable and fluctuates from year to year both in quantities and in prices (Malhotra 2012). Therefore, improving the cultivation practices and enhance (and stabilize) crop yield has become a necessity for the production of caraway to meet the increasing demand of essential oils in the global market (Statista 2020).

Adequate agricultural practices such as weed control, irrigation, fertilization, and plant protection are particularly important to increase caraway yields. Caraway plants have a weakly branched root system (Reduron 2020), hence, low competitive ability for water and nutrients, which leads to a common stunted growth of caraway plants and further weed infestation of the caraway fields. Particularly during the period of crop emergence, when the growth is slow, caraway should be kept free of weeds to avoid nutrient competition (Malhotra 2006). Besides the competition for nutrients, the weed population must be suppressed also to maintain the quality at harvest as many weed species belong to the same family and their fruits are difficult to separate from the caraway, which greatly reduces the value of the final harvest.

It is clear that efficient weed control is one of the bottlenecks of the caraway production. As there are only few protection products registered for the use with spices and medicinal and aromatic crops, the growers frequently use herbicides, which are not explicitly formulated for the use in these high-demanding species. Instead, products suitable for all Apiaceae or related plant families are often used. Nevertheless, the most efficient and yet safe weed protection products and the best time of application in caraway.

Many growers successfully use the pre-sowing application of non-selective herbicides to combat weeds in caraway. However, the use of these herbicides can present phytotoxic effects consisting mainly of the inhibition of the emergence of caraway plants or cover crops (Vaculik 2008). Furthermore, these pre-emergence products need excellent preparation of the land without irregularities on the soil, post-harvest residues and enough soil moisture after application. Alternatively, post-emergence herbicides can be applied to reduce weed pressure on caraway. Nevertheless, the use of post-emergence herbicides is more complicated against dicotyledon weeds due to possible problems in terms of product selectivity and the lack of registered products (Vaculik 2020). Little research has been done on integrated crop management in caraway which warrants future studies to increase and stabilize caraway production.

2 Literature Review

2.1 *Carum carvi*

2.1.1 Taxonomy and botanical description

The genus *Carum* belongs to the order Apiales, family Apiaceae and the *Rosidae* subclass of the Dicotyledons.

The species of the Apiaceae family are usually herbs, rarely shrubs. The Carum genus is characterized by 2-4 pinnate leaves and small or absent sepals. Petals whitish, rarely pink, or yellowish, obovate, emarginate. Apex inflexed. The petioles are inflated and sheathing at the base. Flowers are united into an inflorescence forming a compound umbel. Flower is cyclic, with radial symmetry. Calyx is reduced in size and the flowers are epigynous, small, hermaphrodite, or unisexual. The anthers are characterized to have a secretory tapetum. Pollen grains are two or three celled, with bilateral symmetry. Terminal umbels are well developed, and the lateral ones are usually smaller, these umbels, at the end of the flowering period are numerous male flowers. Germination is epigenic. The fruit obovoid-oblong, laterally compressed, dry and indehiscent (Figure 1). The plant has a taproot system and the main root is about 1 cm diameter, weakly branched, of white and yellow colour (Mihalik 1999)

Figure 1. Carum carvi ("Carum carvi Caraway PFAF Plant Database" n.d.)

2.1.2 Composition

The chemical composition of the plant are divided as primary and secondary metabolites, in the case of the caraway, the last ones are the interest for its economic importance (Ruszkowska 1999).Essential oils on plants are usually volatile, odorous, and may contain up to 100 individual components that are composed mainly of monoterpenes, sesquiterpenes, phenylpropanoids, and isothiocyanates (Rasooli & Allameh 2016) .

The seed of the caraway plant contain 3-6 % volatile oil, also known as *Oleum Carvi* and it is obtained by steam distillation. Carvone is the main constituent, comprising 50-60 % of the total volatile oil, that also contains oxygenated oil, carvol. After the distillation process, the seed contains protein and fat that can be used for feed. (Shelef 2003).Caraway essential oil is stored and generated in specialized vessels called vittae located in the fruit exocarp and separated by cell layers from the air. The biochemical pathway expresses that limonene is the progenitor of carvone and it is converted into carvone enzymatically (Toxopeus & Lubberts 1999)

2.1.3 Habitat and cultivation

Caraway is indigenous in Europe, India, North Africa and other countries and it is usually cultivated in The Netherlands, Morocco, Germany, Finland, Russia, Norway, Canada and USA (Shelef 2003)

Caraway is cultivated in two forms, annual and biennial form, the differences in morphological and anatomical characteristics are slight and not clear yet.(Mihalik 1999). The biennial form is native of Central Europe, the Alps, the Adriatic peninsula, the Caucasus, and in the Rhine and Danube valleys, extending to Central Asia. Annual form is grown in the Middle East and eastern Mediterranean countries. Winter caraway prefers mainly mountain climates but can also be found in humid coastal ones (Reduron 2020)

It can be cultivated after root and vegetable crops in the crop rotation system. Clover and lucerne are good options and provide high rates of farmyard manure. Cereals are, in contrast, the less recommended forecrops for caraway. Oppositely, caraway is good forecrop for cereals, leaving the field almost weed free, and leaving enough time for pre-sowing practices due to its early harvesting for the case of the biennial caraway (Weglarz 1999)

Agricultural practices such as loosening of the soil, weed control, thinning of cover plants and postharvest residues management are necessary during the caraway cultivation. The seedling emerges normally after two weeks and their initial growth is considered slow. At this point, the plants are sensitive to shading and insufficient aeration and moisture of the soil. These effects can be avoided with the soil loosening as well as by chemical and mechanical weed control.(Weglarz 1999)

2.1.4 Ecological requirements

The production of the essential oil and it yields is highly variable from year to year mainly because of the constant weather variations. Caraway cultivation is affected by ecological factors that influence the production of essential oils on the plant. The main ecological factors include light, temperature, wind, water, soil, and nutrients. These factors affect the essential oil concentration directly through metabolic processes affecting the amount of substances synthetize, and reduced plant growth can affect dry matter production and proportion of different plant organs. Others factors involves the use of pesticides, radioactive rain and other stress factors (Halva 1999)

To produce high yields, caraway requires plenty of light intensity, that increases the bet carbon assimilation rate, thus stimulating the vegetative growth and dry matter production. This also increases the oil concentration. According to Halva (1999), the global radiation, precipitation, and wind during ripening can affect the fruit yield and essential oil content in caraway. The optimum temperature for the growth of caraway depends on the genotype.

Another important feature of the cultivation of the caraway is the length of the vegetation period, that it is based on the type of flower initiation and distinguish two ecotypes, the biennial and annual types. Factors influencing flower induction are described as complex and it is proved in some studies that a certain developmental phase is normally a prerequisite of flowering (Nemeth 1999)

The induction of flowering in the biennial type of caraway requires a cold period for vernalization (Nemeth 1999) and it is said that plants of this type can only be vernalized when the taproot is the size of a pencil or more and it requires also a period of eight weeks of temperatures below 10 °C . The annual type is induced to flower by long days (Toxopeus & Lubberts 1999)

The most suitable soils for growing caraway are deep and warm soils , rich in humus and nutrients (Weglarz 1999)

2.1.5 Uses

Caraway it is usually used as spice on the food industry and culinary purposes. For it contents of essential oil and its properties as carminative, anti-flatulent, antispasmodic, antibacterial antifungal it is also used on the medicinal industry. Also the plant it is used as a popular remedy on the veterinary branch (Malhotra 2012). Caraway extract is also added to cosmetics, toothpaste, and some other pharmaceutical preparations as a source of carvone(Rasooli & Allameh 2016)

It is commercialized as a dried, fallen apart mericarp, as a whole, broken or ground. Actually, the quality standards require a light colored and uniform fruits in size and shape, apparently the darker the fruits are, the lower the price. Also, good quality product consists of not more than 2% of contamination (Dachler 1999)

S-carvone present in caraway has allelochemical properties as a natural sprout inhibitor and antifungal pathogens in potato, extending its dormancy period and quality after storage (Şanlı et al. 2010)

2.1.6 Cultivation of Caraway in the Czech Republic

Medicinal, aromatic, and culinary plants in the Czech Republic are cultivated as a domestic and long tradition, providing opportunities for agricultural diversification. According to the Ministry of Agriculture, caraway is one of the main commodities of this type of plants and annually occupies an area exceeding 2000 hectares. It is also the only crop in the sector that shows a positive external trade balance .Caraway growers use protected Designation of Origin CHAMOMILLA BOHEMICA and ČESKÝ KMÍN for their products (eAGRI 2020).

2.2 Weed management in caraway

Because of its slow initial growth, caraway crop needs to be free of weeds that would otherwise compete with caraway for light, which is essential for a successful development of the plant. In the first vegetation year, caraway forms only a leaf rosette, leaving space for weeds (Vaculik 2020).

Weeds can be controlled mechanically by loosening the soil at shallow deepness to prevent the lifting of weed seeds from lower soil layers. Frequency of this type of practice will depend on the soil and weather conditions and growing season(Weglarz 1999). Nevertheless, use of herbicides remains the most common weed control in the Czech Republic. However only three commercial herbicides, Bandur (Pre-emergent), Butoxone 400 and Laudis (Post-emergent) are currently registered for the use on caraway. With the constant changes on product registration and the increased number of banned pesticides by the European Union it is necessary to find different options on the weed management.

2.3 Active ingredients of the used herbicides

Commercial herbicides can be used for the purpose of weed control in caraway, however they are not registered as specific for this crop. Exploration of the active ingredients and its mechanism of action provides information for the later selection of the appropriate herbicide to be used in the crop, the following active ingredients are described in detail to understand the path on it can be used. They were selected for its common use in crops against dicotyledon weeds.

2.3.1 Aclofinen

It is a primary amino compound that is aniline in which the phenyl group has been substituted at positions by chlorine, phenoxy, and nitro groups (Figure 2). A protoporphyrinogen oxidase (PPO) inhibitor, it is used as an herbicide against a broad range of weeds in a wide range of crops. The major target of this class of herbicides is protoporphyrinogen oxidase (Protox), located in the pathway leading from α-amino-levulinic acid to chlorophyll inhibited by the aclofinen (PubChem 2020h).

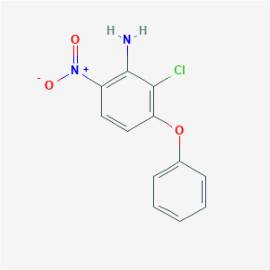

Figure 2. Chemical structure of Aclonifen. Source: (PubChem 2020h)

Mode of action

Aclonifen, acts on two different biochemical pathways including carotenoid synthesis on the one hand, as well as protoporphyrinogen oxidase, in the chlorophyll synthesis pathway. This herbicide has a photo dependent mode of action (Kilinc et al. 2009).

Target crops and weeds

In the Czech Republic Aclofinen is recommended for beans, sunflowers, peas, potato and maize and it is registered against some susceptible weeds: *Apera spica-venti*, *Alopecurus myosuroides*, *Poa annua*, *Thlaspi arvense*, *Sinapis arvensis*, *Spergula arvensis*, *Viola arvensis*, *Amaranthus spp*, *Brassica napus*, *Veronica spp.* ,*Fumaria officinalis*, *Galinsoga spp.*, *Chenopodium spp.*, *Lapsana communis*, *Capsella bursa-pastoris*, *Urtica urens*, *Galium aparine*, *Persicaria sp.* , *Senecio vulgaris*, *Atriplex sp.*, *Lamiun spp*, *Stellaria spp. and Euphorbia spp.* Some less sensitive weeds are also target of Aclonifen: *Galium aparine* on highly humus-rich soil, and *Fallopia convolvulus* (Agromanual 2020a).

2.3.2 Pendimethalin

Pendimethalin is a member of the class of substituted anilines that is N-(pentan-3-yl) aniline bearing two additional nitro substituents and two methyl substituents (Figure 3). It is used to control most annual grasses and many annual broad-leaved weeds. It is also, an environmental contaminant and an agrochemical (PubChem 2020a)

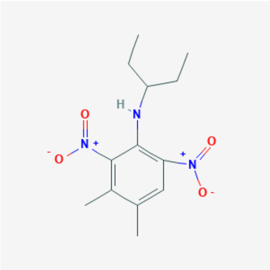

Figure 3.Chemical structure of Pendimethalin. Source: (PubChem 2020a)

Mode of action

According to the Herbicide Resistant Action Committee (HRAC), pendimethalin belongs to the Inhibition of Microtubule Assembly group in its mode of action, meaning that it inhibits cell division and cell elongation (HRAC 2020)

Target crops and weeds

The herbicides containing Pendimethalin are recommender in the Czech Republic for weed control in corn, sunflower, peas, beans, lupine, soybeans, carrots, onions, some winter cereals, and it has minor registration in gooseberry, currant, raspberry, blackberry, and winter oilseed rape. Pendimethalin is effective against *Mercurialis annua, Setaria sp., Hyoscyamus niger, Anagallis arvensis, Matricaria spp., Lamium spp., Sinapis arvensis, Arabidopsis thaliana, Capsella bursa-pastoris, Viola spp., Veronica spp.,* among others. (Agromanual 2020b)

2.3.3 S-Metolachlor

(S)-metolachlor is the (S)-enantiomer of 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(1-methoxypropan-2-yl) acetamide. It is an enantiomer of a (R)-metolachlor (Figure 4).It is part of the Chloroacetamide herbicides (PubChem 2020,Mann 2017).

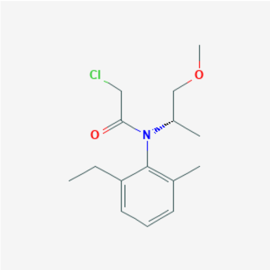

Figure 4. Chemical Structure of S-Metolachlor. Source: (PubChem 2020)

Mode of action

The active substance is taken in by means of a coleoptile, sprouts, and roots, where it inhibits the elongation and division of cells in the youngest parts. It inhibits the synthesis of long chain fatty acids. S-metolachlor penetrates the tissues mainly through the coleoptile. It slows down germination.

Target crops and weeds

S-Metolachlor is intended for the control of some grasses and certain dicotyledonous weeds in sugar beet, peas, sunflowers, maize, and potatoes. It has minority registration in the lupine crop as well. Highly sensitive weeds include *Echinochloa crus-galli, Apera spica-venti, Setaria spp., Digitaria spp., Alopecurus spp., and Bromus spp.* Sensitive are *Capsella bursa-pastoris, Chamonille, Lamium purpureum, Stellaria media, Portulaca oleracea, Lolium spp., Avena spp., Poa annua.* And others less sensitive as *Chenopodium spp., Solanum nigrum and Persicaria* (Agromanual 2020c)

2.3.4 Terbuthylazine

Terbutylazine is a is a member of the chloro-s-triazine group characterized by ethylamino and tert-butylamino side chains. It is a diamino-1,3,5-triazine that is N-tert-butyl-N'-methyl-1,3,5-triazine-2,4-diamine substituted by a chloro group at position (Figure 5). It has a role as an herbicide, an environmental contaminant, and a xenobiotic.

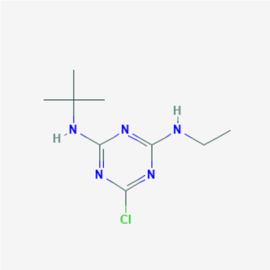

Figure 5. Chemical structure of Terbuthylazine. Source:(PubChem 2020c)

Mode of action

Terbuthylazine is a triazine selective systemic herbicide absorbed principally through the roots, but also through the foliage, translocated acropetally in the xylem and accumulated in the apical meristems and leaves. This compound binds to the plastoquinone-binding protein in photosystem II, inhibiting electron transport (Oxon 2020) The active ingredient terbuthylazine is ingested by weed roots and leaves and inhibits photosynthesis.

Target crops and weeds

This herbicide is recommended for the control of weeds in maize, sorghum, sunflower, legumes, oilseed rape and cotton. It is effective against *Echinochloa crus-galli, Galium aparine, Chenopodium album, Fallopia convolvulus, Stellaria media, Polygonum aviculare, Urtica urens, Solanum nigrum* and *Chamonille* among others.

2.3.5 Isoxaflutole

It is a member of the class of isoxazoles. It is a 4-hydroxyphenylpyruvate dioxygenase inhibitor which is used as an herbicide for weed control (Figure 6). It has a role as a 4-hydroxyphenylpyruvate dioxygenase inhibitor, and an agrochemical. It is a member of cyclopropanes, a member of isoxazoles, an aromatic ketone, a member of (trifluoromethyl) benzenes and a sulfone.

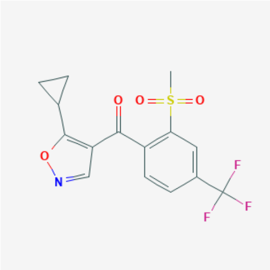

Figure 6. Chemical structure of Isoxaflutole. Source:(PubChem 2020d)

Mode of action

Isoxaflutole causes characteristic bleaching of newly developed tissues of susceptible species followed by growth inhibition and necrosis. The inhibitors target the enzyme phytoene desaturase, which catalyzes the first two desaturation steps in the conversion of the colorless carotenoids into colored carotenoids. Isoxaflutole inhibits 4- hydroxyphenylpyruvate dioxygenase (Pallett et al. 1998). It is absorbed mainly by roots and emerging plants. Weeds are destroyed during emergence, emerging plants after treatment grow with a lack of chlorophyll.

Target crops and weeds

This herbicide is recommended in the Czech Republic for the use in Maize and Poppy crops against some sensitive weeds as *Echinochloa crus-galli, Setaria, Datura stramonium, Panicum miliaceum, Lamium, Sinapis arvensis, Capsella bursa-pastoris, Amaranthus retroflexus, Solanum nigrum, Chenopodium album, Thlaspi arvense, Stellaria media, Persicaria lapathifolia, Persicaria maculosa, Portulaca oleracea* and some less sensitive weeds: *Sorghum bicolor, Anagallis arvensis, Galium aparine, Viola, Helianthus annuus*(Agromanual 2020d)

2.3.6 MCPB

It is an aromatic ether, a member of monochlorobenzenes and a monocarboxylic acid (Figure 7). It has a role as a xenobiotic, an environmental contaminant and a phenoxy herbicide.

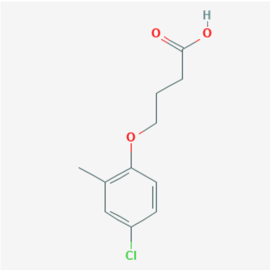

Figure 7. Chemical structure of MCPB. Source:(PubChem 2020e)

Mode of action

The phenoxy herbicides are systemic growth regulating hormones that act at multiple sites in a plant to disrupt hormone (auxin) balance and protein synthesis. The result is plant growth abnormalities. Uptake of phenoxy herbicides is said to be primarily through the foliage, but root and seed uptake are also said to occur(Janson 2005).

Target crops and weeds

MCPB in the Czech Republic is intended for the control of seed weeds and other dicotyledonous weeds in peas and cumin. Registered against susceptible weeds: *Capsella bursa-pastoris, Chenopodium album, Thlaspi arvense, Cirsium arvense, Rape and less sensitive weeds: Galeopsis ladanum, Polygonum convolvulus, Galeopsis tetrahit, Stellaria media, Persicaria maculosa* and *Viola arvensis.* (Agromanual 2020e)

2.3.7 Tembotrione

Tembotrione is an aromatic ketone that is 2-benzoylcyclohexane-1,3-dione in which the phenyl group is substituted at positions 2, 3, and 4 by chlorine, (2,2,2-trifluoroethoxy) methyl, and methylsulfonyl groups, respectively (Figure 8. Chemical structure of Tembotrione. Source: (PubChem 2020f)Figure 8).

It is a sulfone, a cyclic ketone, an aromatic ketone, a member of monochlorobenzenes, an organofluorine compound, an ether and a beta-triketone (PubChem 2020f)

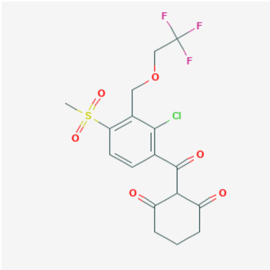

Figure 8. Chemical structure of Tembotrione. Source: (PubChem 2020f)

Mode of action

Tembotrione inhibits the activity of the 4 hydroxy-phenyl-pyruvate-dexygenase (4 HPPD) enzyme. The formation of carotenoid (plant pigments) is disrupted by the blockage of the enzyme. Depletion of carotenoids deprives chlorophyll - where photosynthesis takes place - of its protection against an over dose of light and this results in chlorophyll bleaching (BAYER 2020)

Target crop and weeds

It is recommended in the maize and poppy seed crops. It is used together with the chemical compound isoxadifen-ethyl against sensitive weeds: *Echinochloa crus-galli*, *Chenopodium album*, *Amaranthus retroflexus*, *Galium aparine*, *Stellaria media*, *Thlaspi arvense*, *Lamium purpureum*, *Capsella bursa-pastoris* and less sensitive weeds: *Tripleurospermum*, *Fallopia convolvulus*, *Veronica persica* and *Viola arvensis* (Agromanual 2020f) .

2.3.8 Isoxadifen-ethyl

Isoxadifen-ethyl is an isoxazoline that is the ethyl ester of isoxadifen (Figure 9). It is used as an herbicide safener (PubChem 2020g)

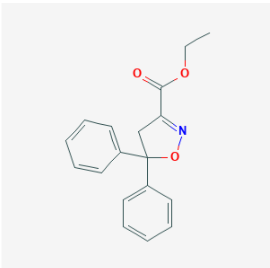

Figure 9 Chemical structure Isoxadifen-ethyl. Source: (PubChem 2020g)

Mode of action

As a safener, it enhances the degradation of the herbicides to inactive metabolites in the crop. The speed of these transformations is the main reason for crop selectivity and weed control. Safeners, such as isoxadifen-ethyl and mefenpyrdiethyl, can enhance sulfonylurea herbicide tolerance in cereal crops by effectively inducing cellular xenobiotic detoxification mechanisms (Sun et al. 2017)

Target crop and weeds

It is recommended in the maize and poppy seed crops. It is used together with the chemical compound tembotrione against sensitive weeds: *Echinochloa crus-galli, Chenopodium album, Amaranthus retroflexus, Galium aparine, Stellaria media, Thlaspi arvense, Lamium purpureum, Capsella bursa-pastoris* and less sensitive weeds: *Tripleurospermum, Fallopia convolvulus, Veronica persica* and *Viola arvensis* (Agromanual 2020f) .

3 Objectives

The main objective of this thesis is to test the effects of commercial herbicides differing in active compounds, application rates and times of application (pre-emergent and post-emergent) on the weed populations in caraway fields and growth parameters of caraway crop. Specifically, I aimed to determine the most suitable herbicide treatment for weed control in caraway and to improve our understanding of the problematics of weed control in caraway.

4 Hypothesis

Herbicides application reduces the weed abundance in the caraway fields, which leads to improved caraway growth parameters and biomass production

4.1 Specific hypothesis

H1: Pre-emergent herbicide application is more effective in weed control

H2: Herbicides will reduce weed abundance and diversity

H3: Caraway biomass production is inversely related with the number of weeds

H4: Applied herbicides have no phytotoxic impact on the vegetative growth of the caraway plants

H5: The role of cell differentiation (inflorescence primordia) is not affected by the use of herbicides

5 Materials and Methods

5.1 Study site

The experiment was carried out in the north-eastern part of the Czech Republic, Olomouc region, near the town of Šumperk at the locality of Vikýřovice (coordinates: 49.9652603N, 17.0147031E).

Meteorological data were obtained from the climate station located in the area and is shown in Figure 10, where both long-term average (2014-2019) and the date from the period of this experiment (2020-2021) can be found.

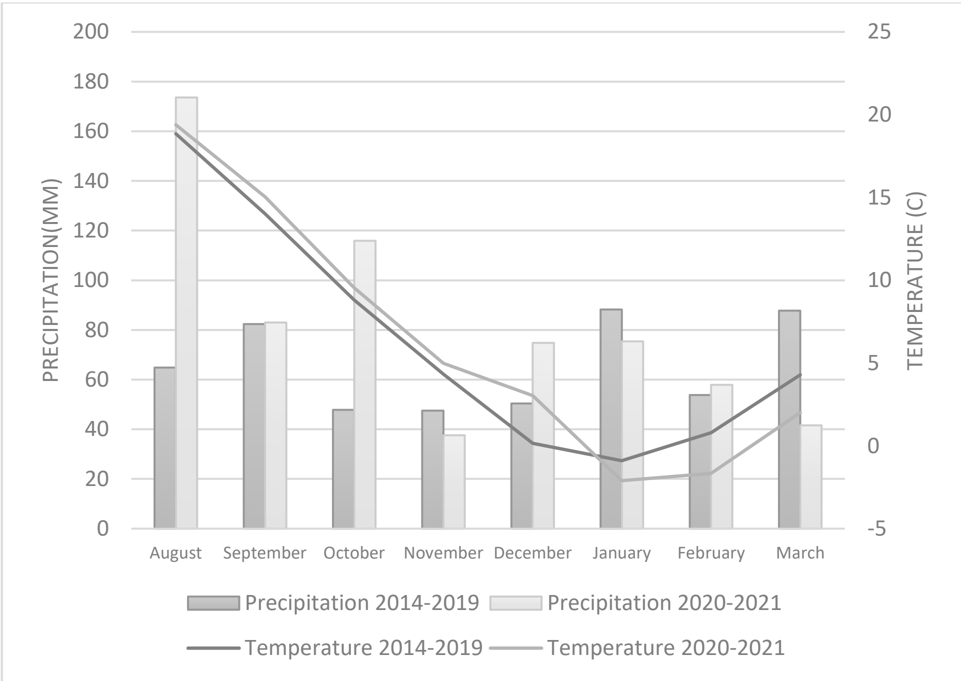

Figure 10. Average monthly temperatures and precipitations on the study site in the growing season 2020-2021 and the long-term means (2014-2019)

5.2 Experimental design

The experiment was established as a completely randomized block design with four repetitions. In total, there were 13 treatments corresponding to 12 herbicide treatments and control without herbicide application (Table 1). Thus, 52 plots were established, each with an area of 12.5 m^2 (1.25 x 10 m).

Caraway (*Carum carvi* var. Aprim) was sown on September $4^{th,}$ 2020 at a rate of 15g of seeds $10m^{-2.}$ Before seeding, the plots were fertilized twice: (i) in August 25^{th} 2020, urea (100 kg ha^{-1}) was applied to increase the C:N ratio and stimulate the mineralization of the straw from the previously grown barley, and (ii) in August 26^{th} 2020 NPK was applied (100 kg ha^{-1}).

The used herbicides are recommended for the control of dicotyledon weeds and some of them also monocotyledon (See Appendix 1). The pre-emergent application was made with a HEGE sprayer and for the post emergent application a dorsal sprayer was used. The complete description of the herbicide treatments can be seen on table 1. A uniform application of herbicide for the control of monocotyledon weeds was made on October 26$^{th, 2020}$ in all plots using Targa super 5 (Quizalofop-P-ethyl) at a rate of 1 l/ha of the herbicide.

Table 1. Herbicides and application rates used in each treatment during the trial

Treatment	Commercial Name	Active Ingredient	Mode of Action	Application Rate	Type of application and Date of Spraying
Ban	Bandur	aclonifen	Inhibition of Solanesyl Diphosphate Synthase	3 l/ha	preemergent application: 7 DAS
Stom2.6	Stomp AQUA	pendimethalin	Inhibition of Microtubule Assembly	2.6 l/ha	
Stom3.0	Stomp AQUA			3.0 l/ha	
Stom3.5	Stomp AQUA			3.5 l/ha	
Gar2.0	Gardoprim Plus Gold 500 SC	S-metolachlor, terbuthylazine	Inhibition of Very Long-Chain Fatty Acid Synthesis	2.0 l/ha	
Gar3.5	Gardoprim Plus Gold 500 SC			3.5 l/ha	
Gar5.0	Gardoprim Plus Gold 500 SC		D1 Serine 264 binders	5.0 l/ha	
Mer0.08	Merlin 750 WG	isoxaflutole	Inhibition of Hydroxyphenyl Pyruvate Dioxygenase	0.08 kg/ha	
Mer0.13	Merlin 750 WG			0.13 kg/ha	
Stom3.0Pos	Stomp AQUA	pendimethalin	Inhibition of Microtubule Assembly	3.0 l/ha	post emergent: 45 DAS
But3.0	Butoxone 400	MCPB	Auxin Mimics	3 l/ha	
Lau2.25	Laudis	tembotrione, isoxadifen-ethyl	Inhibition of Hydroxyphenyl Pyruvate Dioxygenase	2.25 l/ha	

DAS: days after sowing

5.3 Data collection and analyses

The time and activities made during the trial are recorded on Table 2

Table 2. Timeline of the operations in the trials

Operation	Time
Seeding	0 DAS (September 4th, 2020)
Pre-emergent herbicides application	7 DAS (September 11th, 2020)
1st weed assessment (weed abundance and diversity)	40 DAS (October 14th, 2020)
Post-emergent herbicides application	45 DAS (October 19th, 2020)
Monocotyledon herbicide application	52 DAS (October 26th, 2020)
2nd weed assessment (weed abundance, diversity, and biomass)	62 DAS (November 5th, 2020)
Caraway assessment: phytotoxicity evaluation (visual observation on caraway plants)	105 DAS (December 18th, 2020)
Caraway assessment: growth parameters (number of leaves, rootstock diameter, flower primordia stage)	181 DAS (March 3rd, 2021)
3rd weed assessment (weed abundance and diversity)	206 DAS (March 19th, 2021)
Caraway assessment: biomass	217 DAS (April 9th, 2021)

5.3.1 Weed performance

The weed individuals were counted and determined three times during the trial at 40,62 and 206 DAS (days after sowing). Each count was made in five randomly laid quadrats (55 × 35 cm) within each plot and all dicotyledon weeds were identified to species level. The first assessment (40 DAS) was performed on 2-4 true leaves stage, after the pre-emergent herbicide application. The second assessment was performed two weeks after the post -emergent application (2-8 true leaves stage) and the third assessment was made after the winter season.

Weed diversity was evaluated using the Simpson index of diversity according to Equation 1 for every treatment and control in all three assessments.

Equation 1. Simpson's Diversity Index

$$D = 1 - \frac{\sum n(n-1)}{\sum N(N-1)}$$

$$Where: \quad n = number\ of\ individuals\ of\ each\ species,$$
$$N = total\ number\ of\ individuals\ of\ all\ species$$

Weed biomass was measured 63 DAS. For this purpose, all weed individuals inside a quadrat of 25 cm^2 were collected with their root systems. Three such quadrats were taken in each plot and both fresh and dry weight (three hours at 108°C) were noted.

The effectiveness of used herbicides was evaluated following the protocols of the European and Mediterranean Plant Protection organization (EPPO) and Abbotts Formula (Abbott 1925) was used to calculate the effectiveness of the herbicides against weeds (Equation 2). This was made for each repetition on the treatments for later statistical analysis.

Equation 2. Abbott's formula to test effectiveness

$$\% \, Effectiveness = \left[1 - \left(\frac{Number\ of\ weed\ individuals\ after\ the\ treatment}{Number\ of\ weed\ individuals\ \ in\ control}\right) * 100\right]$$

5.3.2 Caraway performance

The caraway biomass was assessed at 63 and 217 days after sowing as described for weed biomass. All caraway plants with roots were collected inside three 25 cm^2 quadrats in each plot. Both fresh and dry weight (108°C for three hours) were noted.

After the winter season (181 DAS), ten caraway plants were randomly sampled in each plot with their root system, then taken to the laboratory where the number of leaves, rootstock diameter (RSD) and the stage of development of the flower primordia were measured as shown in Figure 11 and Figure 12

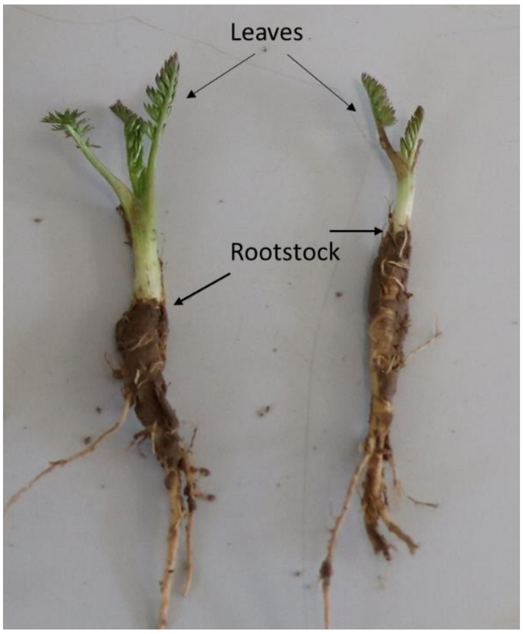

Figure 11. Caraway plant sample, measured parameters: Rootstock diameter(mm) and number of leaves

For the determination of the stage of the flower primordia on the caraway plants, a pre-sampling was made on the field, then observing and classifying the development into five stages (0-4) based on Procházka & Vrzalová (1988).

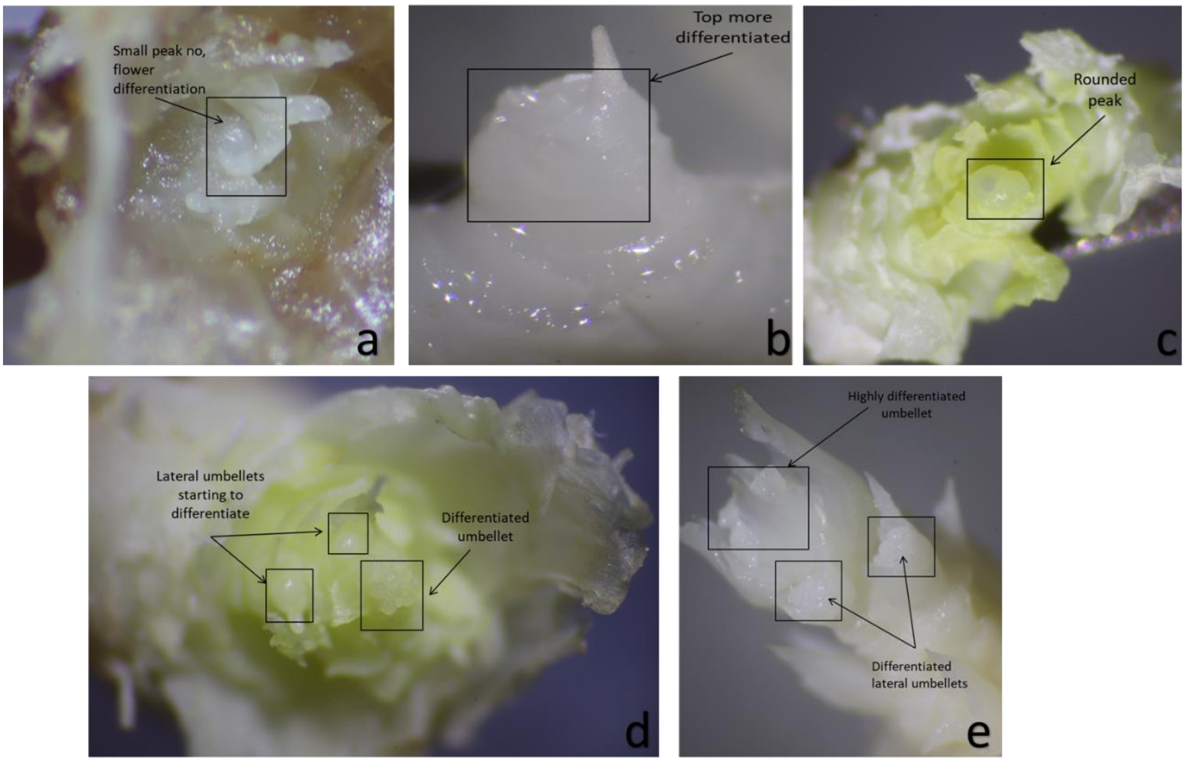

Figure 12. Stage of floral development. a. Stage 1 b. Stage 2 c. Stage 3 d. Stage 4

Field observations of the caraway plants were made for each treatment and compared with control to visualize possible symptoms of phytotoxicity during the trial.

5.3.3 Statistics analyses

The effects of the herbicides on the weeds abundance and caraway plants parameters were evaluated for each assessment using one-way ANOVA and poshoc Tukey's HSD in case the assumptions for parametric testing were fulfilled (normality of distribution with Shapiro-Wilk test, and homogeneity of variances with Levene's test). Otherwise, non-parametric test was applied (Kruskal-Wallis) and the differences between individual means were considered significant at $p < 0.05$. Additionally, paired t-test or non-parametric Wilcoxon 's paired test was used to determine the differences between assessments. The *Statistica TIBCO Software version 13.5* was used to perform the analyses. Correlations between the plant growth parameters and weed parameters (abundance, biomass, and diversity) were determined using the Pearson's correlations.

6 Results

6.1 Weed performance

6.1.1 Total weed abundance, diversity and biomass

The total number of weed individuals at 40 DAS in the plots treated with pre-emergent herbicides was lower that the number of weed individuals in control plots. The plots corresponding to post-emergent herbicides application did not differ from control($p<0.05$) (Figure 13).

After the application of the post emergent herbicides (applied 45 DAS), the abundance was different between pre-emergent and post-emergent herbicides and the control (Figure 13). The number of weed individuals was lower only on Ban and Lau2.25, 62 DAS($p<0.05$).

After the winter (206 DAS), no difference between the control and the plots treated with the post-emergent herbicides were observed. However, at this time there was also no difference ($p<0.05$) between all the pre- emergent herbicides and Lau2.25 (post) and no differences between Stom2.6, Stom3.0, Stom3.5, Mer0.08 and the post-emergent Stom3.0Pos. The pre-emergent herbicides did not have difference within them (Figure 13). The untreated control and the treatments Stom2.6, Gar2.0, Mer0.08, Mer0.13 as well as all the post-emergent treatments, presented lower number of weeds in spring in comparison with the abundance of weeds 62 DAS. ($p<0.05$)

None of the studied treatments had effect ($p<0.05$) on species diversity (Appendix 2) and no differences ($p<0.05$) were detected in weed biomass Figure 14.

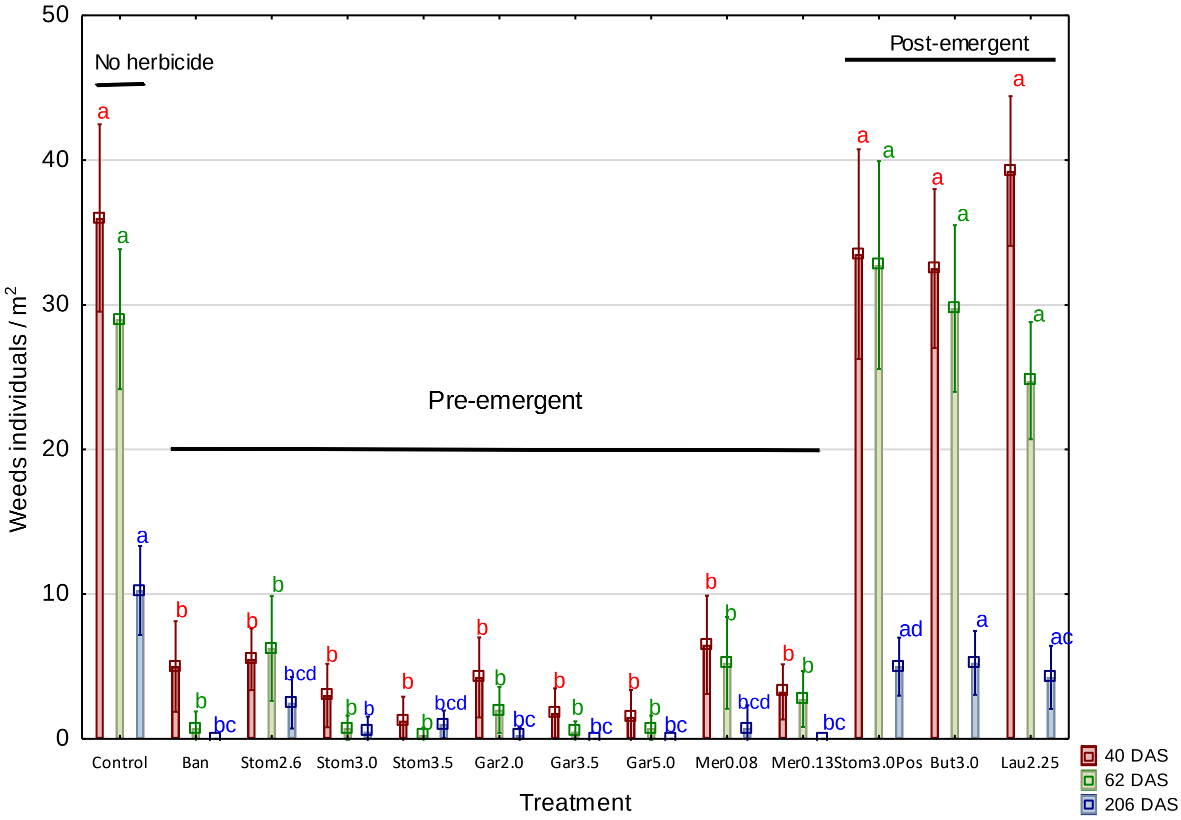

Figure 13. Number of weed individuals in all treatments per m2. Mean ± standard deviation of the mean. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. DAS: days after sowing. Same letter in the same color indicates no difference (p<0.05) between the treatments on the corresponding date. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

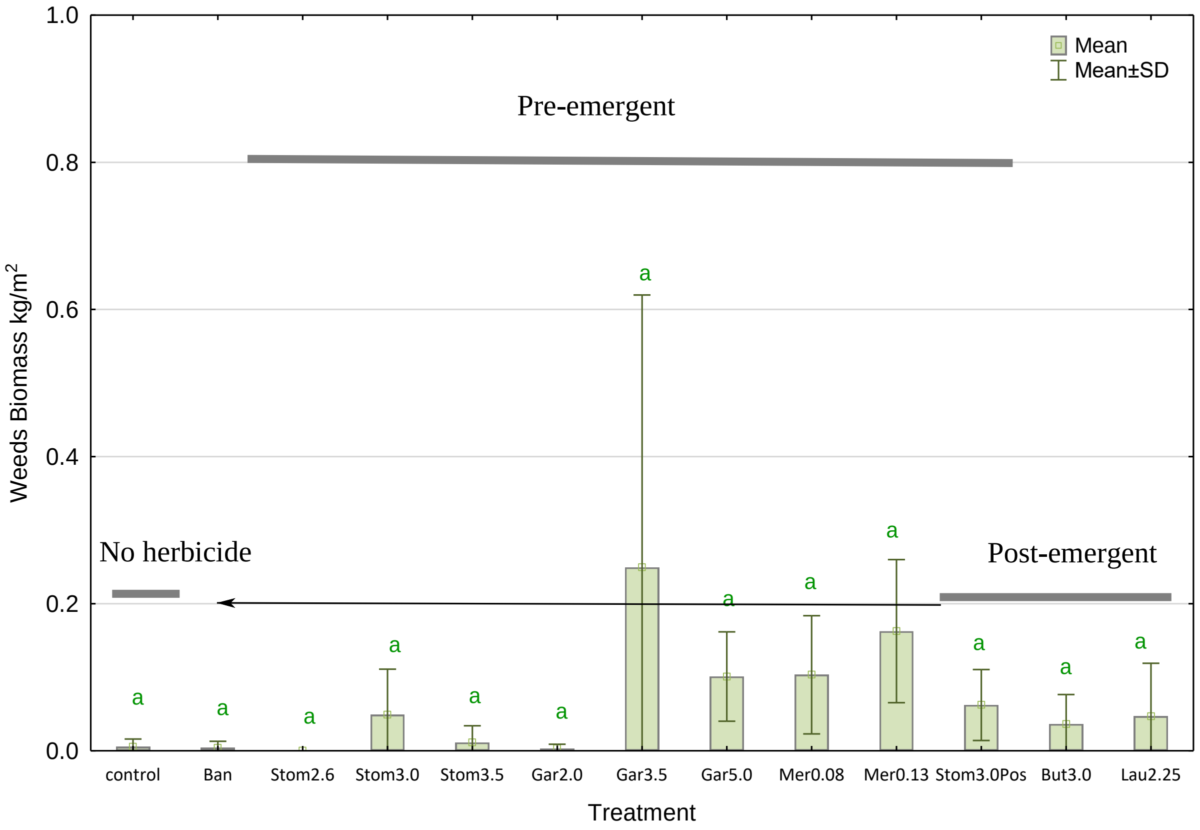

Figure 14. Weeds Biomass expressed in kg/m2. Measured 62 DAS. Mean ± standard deviation of the mean Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25 Same letter indicates no difference (p<0.05) between the treatments. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

6.1.2 Abundance and diversity of the most common weed species

The most frequently encountered species were *Lamium purpureum, Veronica persica and Viola arvensis* (Figure 15). Less frequent species were *Chenopodium album*, *Thlaspi arvense Brassica napus* and *Fumaria officinalis*.

Figure 15. Most frequently encountered species on the field trial.

Lamium purpureum: 40 DAS the number of weed individuals was the same in control and the herbicide treatments. Differences were found between all the treatments with pre-emergent application and But3.0 and Lau2.25 (post-emergent) (Figure 16). During the second assessment (62 DAS), statistical significative difference was found between all the treatments with pre-emergent application and the treatments with post-emergent application. After winter, 206 DAS, no significative differences were found within the control and all the other treatments (Figure 16)

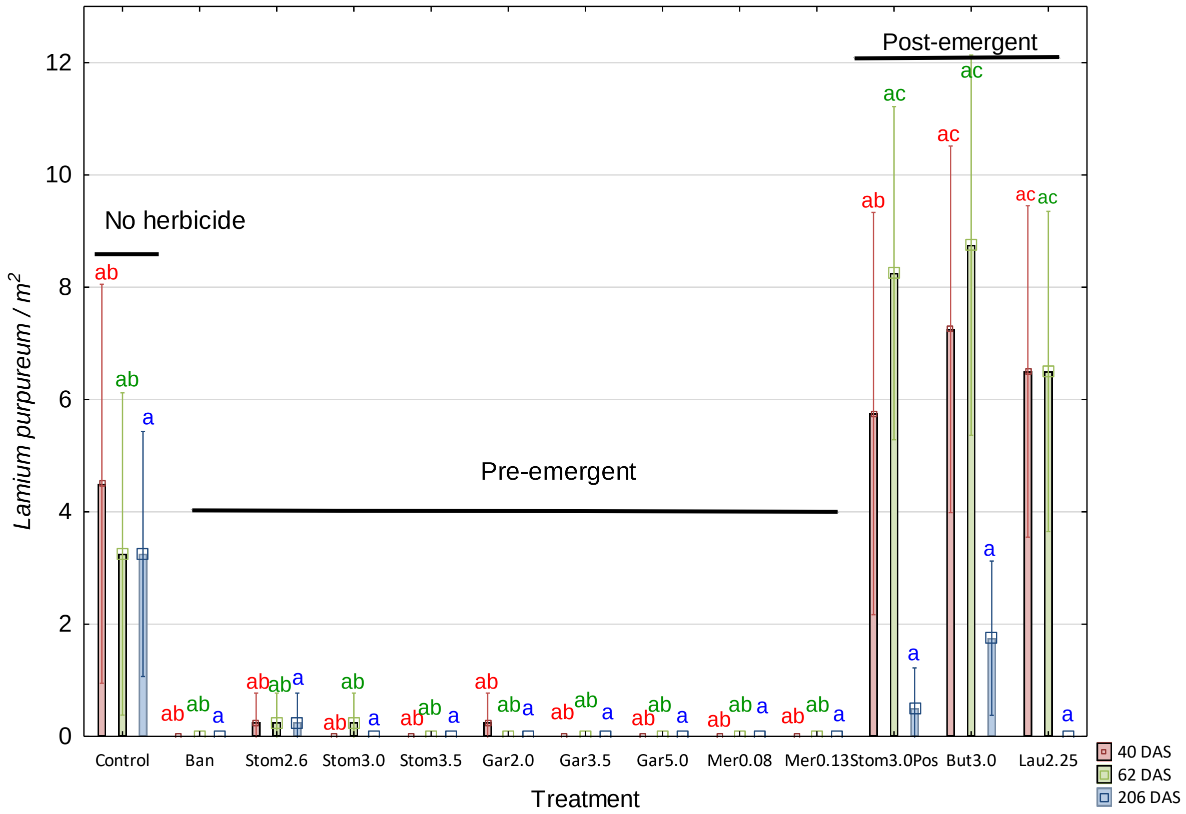

Figure 16.Number of individuals of Lamium purpureum in each treatment/m2. Mean ± standard deviation of the mean.. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. Same letter in the same color indicates no difference (p<0.05) between the treatments on the corresponding date. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

Veronica persica: 40 DAS control presented higher number of individuals than and all the treatments with pre-emergent application ($p<0.05$) except Stom2.6. The post- emergent application treatments were the same as control. Additionally, Stom2.6 did not differ with any of the other treatments. Stom3.0 had no significative difference with But3.0. (Figure 17)

For the second assessment 62 DAS, the results were similar, lower number of individuals in control compared with pre-emergent herbicides($p<0.05$) except Stom2.6. The number of individuals of *Veronica persica* did not have any difference between the control and the herbicide treatments on the last assessment after winter (Figure 17).

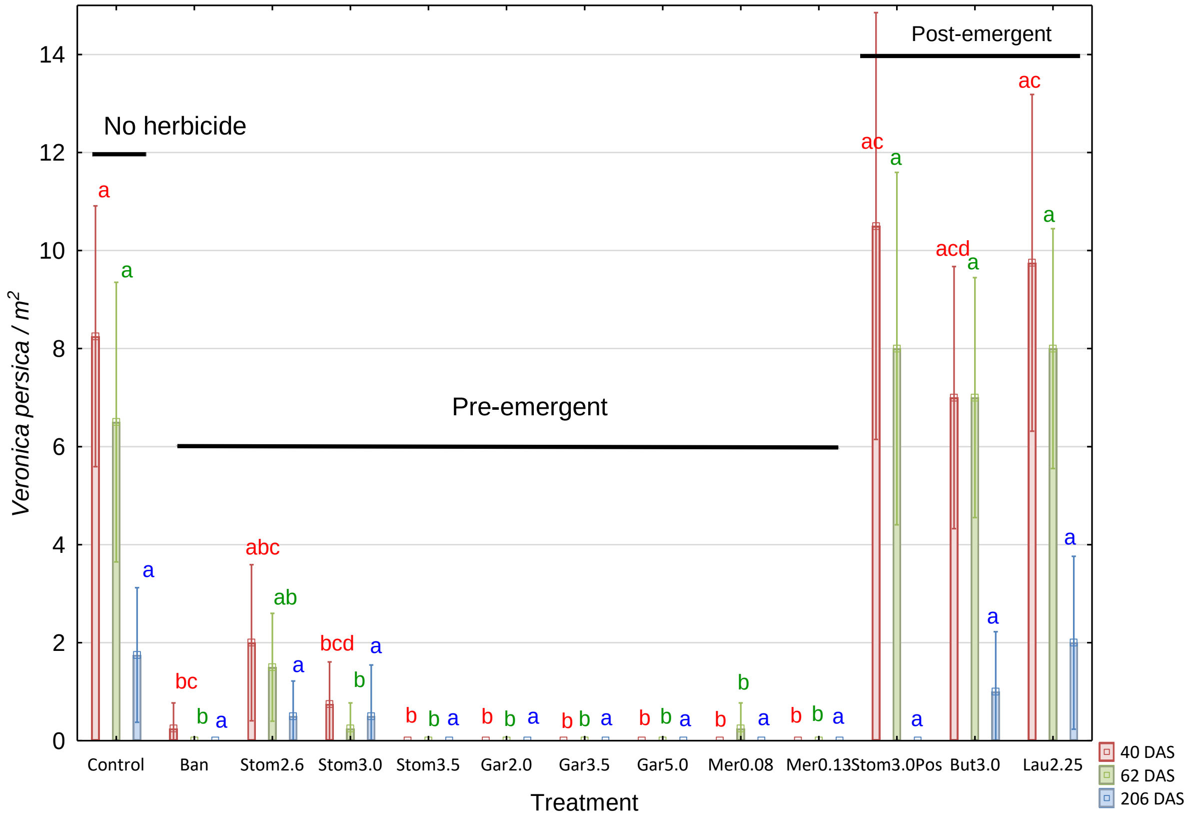

Figure 17. Number of individuals of Veronica persica in each treatment/m2. Mean ± standard deviation of the mean. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. Same letter in the same color indicates no difference (p<0.05) between the treatments on the corresponding date. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

Viola arvensis: higher number of individuals of *Viola arvensis* 40 DAS were present in control in comparison with pre-emergent treatments ($p<0.05$). There was no difference ($p>0.05$) between the control and all the other treatments 62 DAS but there were lower number of individuals in the plots treated with pre-emergent herbicides than the post-emergent (Figure 18). After winter, the abundance of *Viola arvensis* was the same ($p>0.05$) for all treatments and control (Figure 18)

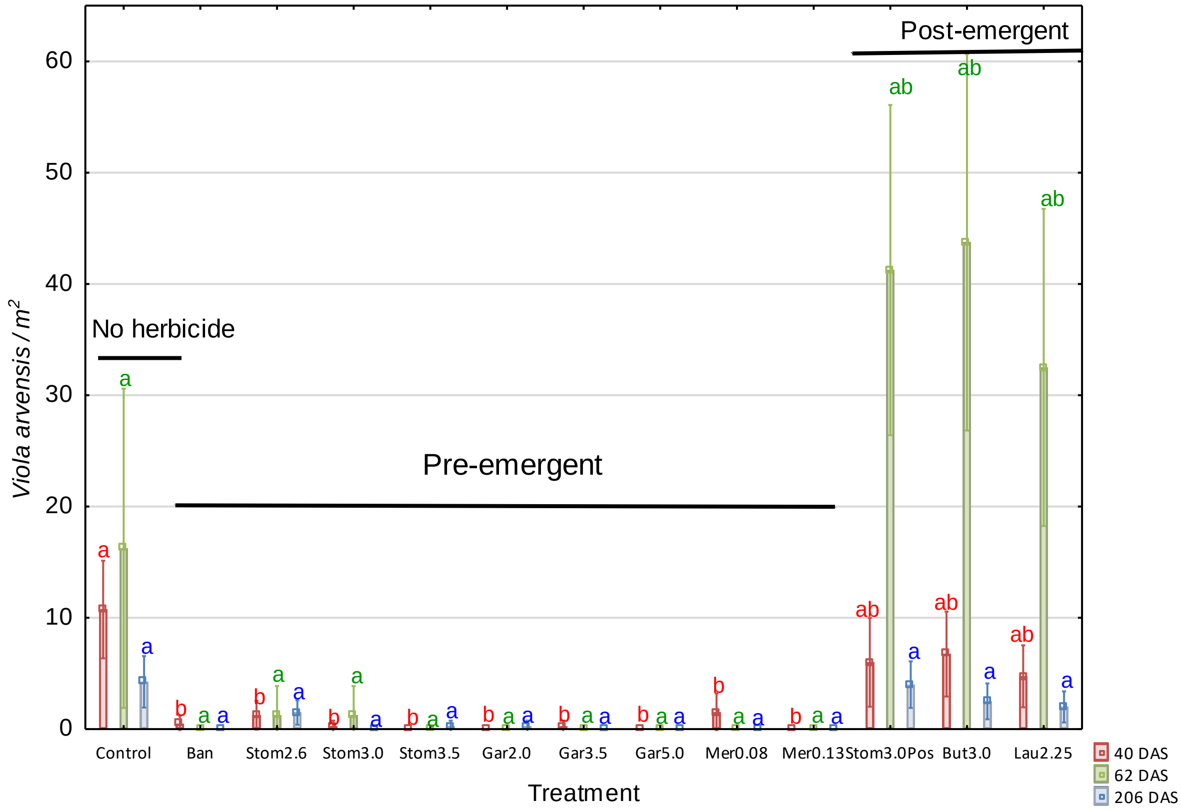

Figure 18. Number of individuals of Viola arvensis in each treatment/m2. Mean ± standard deviation of the mean. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. Same letter in the same color indicates no difference (p<0.05) between the treatments on the corresponding date. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

6.1.3 *Herbicide effectiveness*

The effectiveness of the herbicides was calculated for every treatment, 206 DAS according to Equation 1 (*indicates statistically significant difference from the control with no herbicides at p<0.05 level; n.s. not significant. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. *Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.*

). The effectiveness of applied herbicides on the most common species (*Lamium purpureum*, *Veronica persica* and *Viola arvensis*) was also calculated.

*Table 3.Herbicide's effectiveness using Abbott's equation 206 DAS. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. *p<0.05 n.s. not significant*

	%Effectiveness				
	Treatment	Total weeds	*Viola arvensis*	*Lamium purpureum*	*Veronica persica*
Pre-emergent	**Ban**	90.2 (±0) *	100(±0) *	100(±0) *	100(±0) *
	Stom2.6	75.6(±5.7) *	64.7(±10.2) n. s	92.3(±6.25) n. s	71.4(±28.9) n. s
	Stom3.0	95.1(±3.8) *	100(±16.6) *	100(±0) *	71.4(±0) *
	Stom3.5	90.2(±5.3) *	94.1(±6.25) *	100(±0) *	100(±0) *
	Gar2.0	97.5(±1.9) *	94.1(±5) *	100(±0) *	100(±0) *
	Gar3.5	100(±0) *	100(±0) *	100(±0) *	100(±0) *
	Gar5.0	100(±0) *	100(±0) *	100(±0) *	100(±0) *
	Mer0.08	92.7(±9.4) *	100(±0) *	100(±0) *	100(±0) *
	Mer0.13	100(±0) *	100(±0) *	100(±0) *	100(±0) *
Post-emergent	**Stom3.0Pos**	51.2(±10.3) *	5.9(±45.3) n. s	84.6(±7.2) n. s	100(±0) n. s
	But3.0	48.7(±10.6) *	41.2(±21.6) n. s	46.2(±70.) n. s	42.9(±20.8) n. s
	Lau2.25	58.5(±12.1) *	52.9(±12.1) n. s	100(±0) *	-14.2(±88.6) n. s

**indicates statistically significant difference from the control with no herbicides at p<0.05 level; n.s. not significant. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.*

6.2 Caraway performance

6.2.1 Biomass

In autumn (63 DAS), the biomass of the caraway did not differ among the treatments, including control (p>0.05) (Figure 19). After winter, the biomass of the caraway was lower in Gar5.0 compared with control and lower compared with Stom3.5, Gar2.0, Mer0.08 and the post-emergent treatments. (Figure 19)

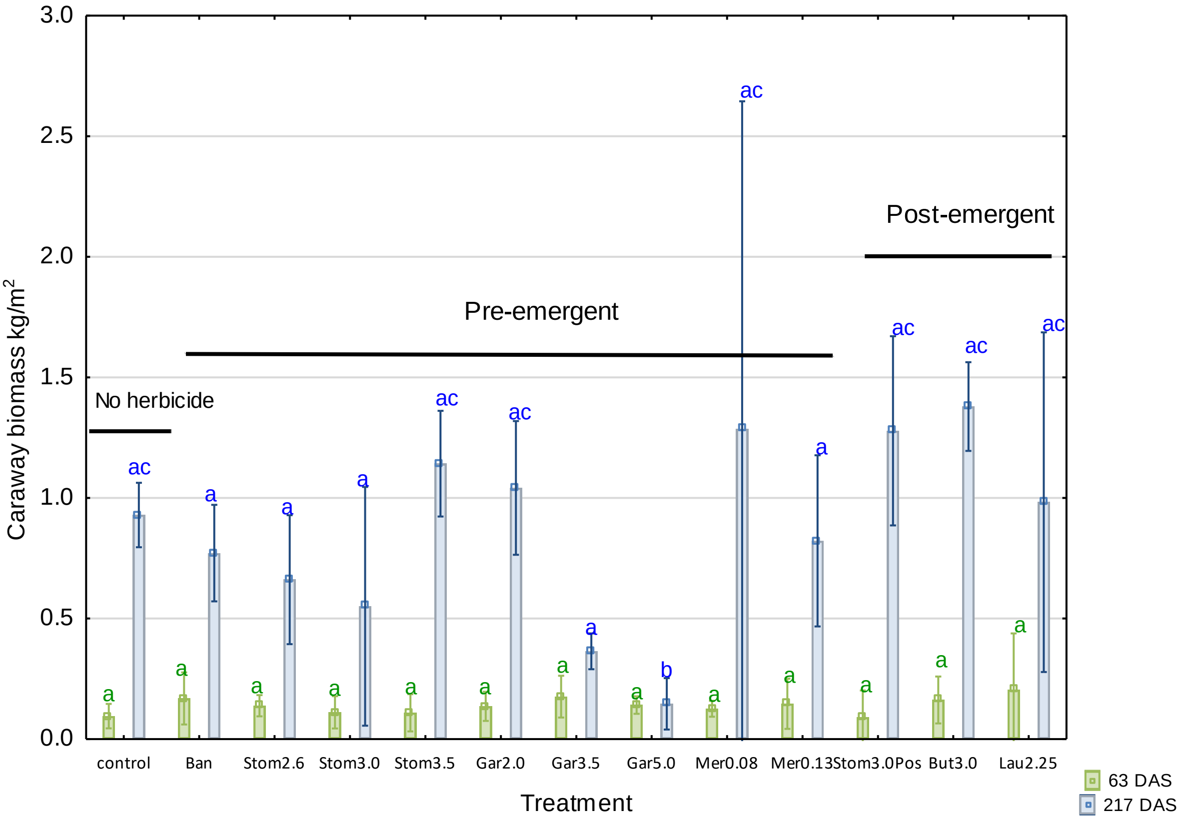

Figure 19.Caraway Biomass expressed in kg/m2. Mean ± standard deviation of the mean. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25 Same letter in the same color indicates no difference (p<0.05) between the treatments on the corresponding date. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

6.2.2 Plant growth parameters

A significant and positive correlation was found between the RSD and the stage of development of the flower primordia (r =0.431), the same as for the number of leaves and the stage of flower primordia (r =0.502) in the spring caraway assessment (after winter). There was no significant correlation between the number of leaves and the RSD.

This evaluation presented some significant differences among the treatments on the number of leaves, rootstock diameter and stage of flower primordia. The RSD was lower ($p<0.05$) in the pre-emergent treatments with Stomp Aqua and Gardoprim Plus Gold at all rates, when compared with control.The highest values were found in Ban, Mer0.13 and the pos-emergent Stom3.0Pos,But3.0 and Lau2.25 (Figure 20). The stage of the flower primordia was also affected by the different treatments, the stage was lower on the Stom3.5, Gar2.0 and Gar5.0 treatments($p<0.05$). The post-emergent treatments presented plants with higher flower development stage in general (Figure 21). For the case of the number of leaves per plant the results were variables as seen on Figure 22, ranking from 3.8 leaves/plant (Ban) to 7.25 leaves/plant (Mer0.08) also having lower values on pre-emergent treatments.

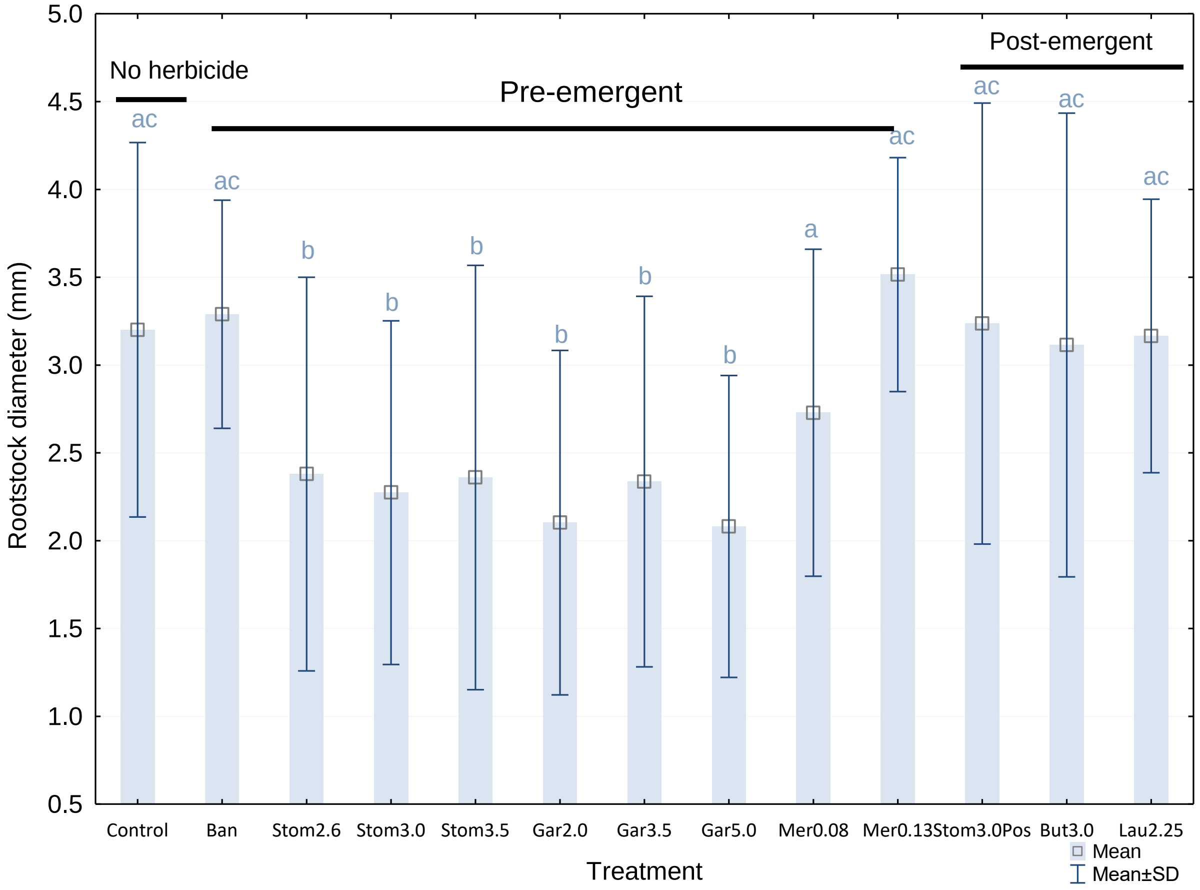

Figure 20. Rootstock diameter (181 DAS). Mean ± standard deviation of the mean. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. Same letter indicates no significative difference ($p<0.05$). Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

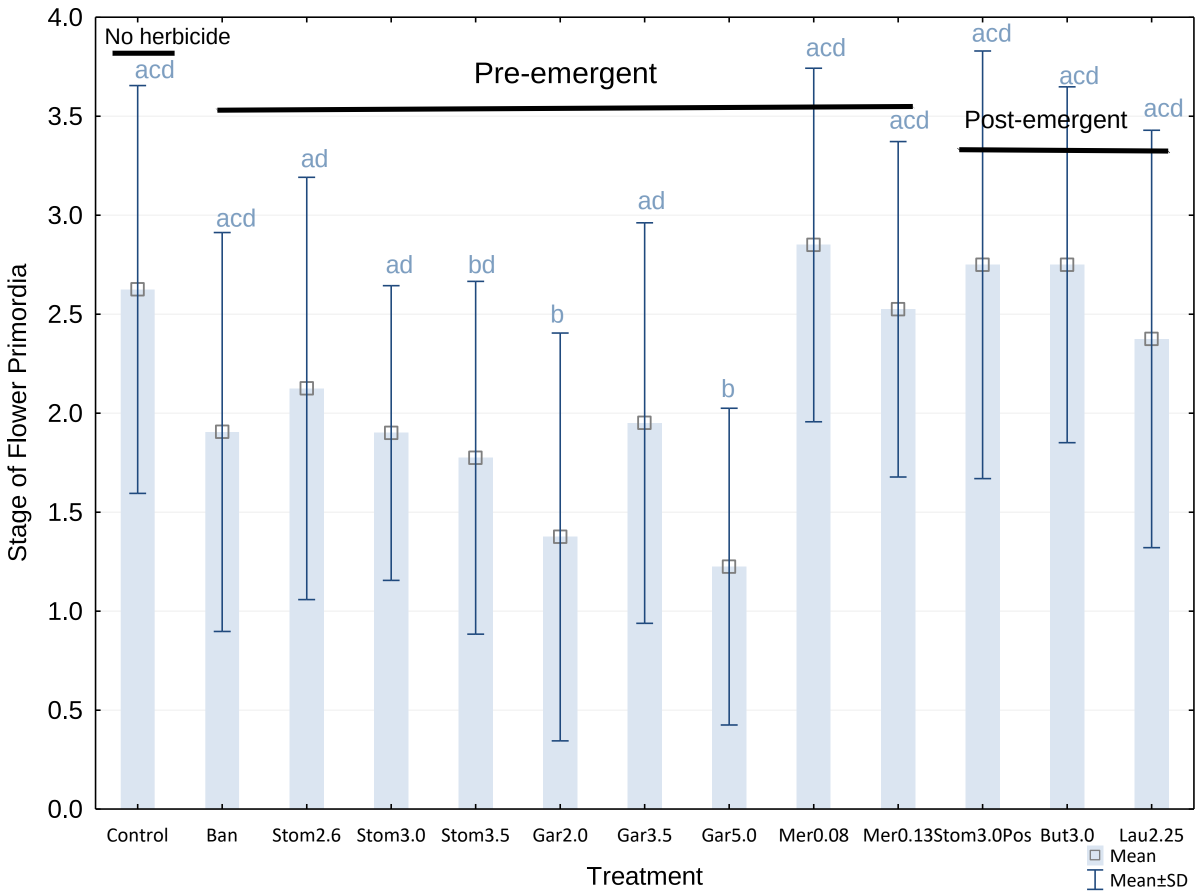

Figure 21. Stage of development of Flower Primordia (181 DAS). Mean ± standard deviation of the mean. Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. Same letter indicates no significative difference (p<0.05). Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

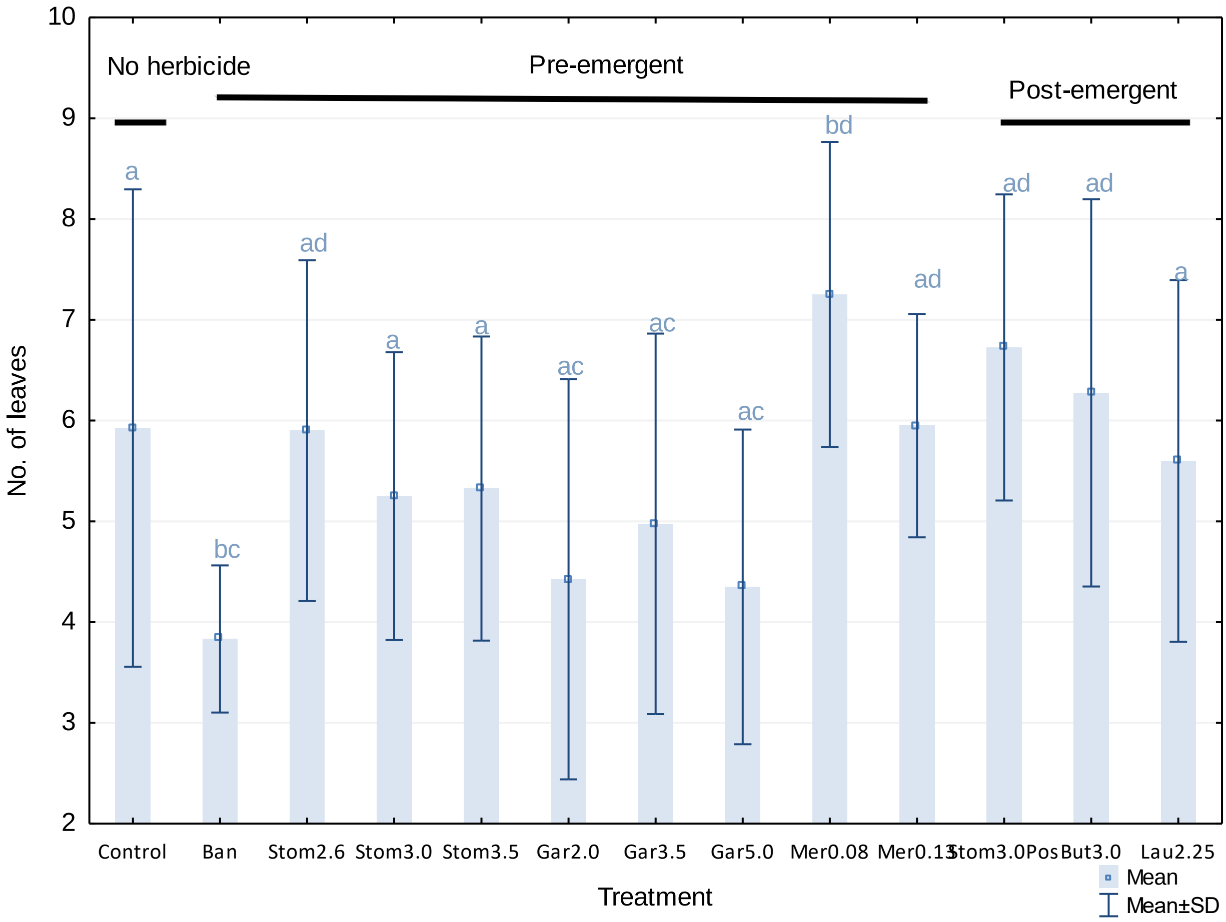

Figure 22. Number of leaves per caraway plant (181 DAS). Ban: Bandur, Stom2.6: Stomp Aqua 2.6, Stom3.0: Stomp Aqua 3.0, Stom3.5: Stomp Aqua 3.5, Gar2.0: Gardoprim 2.0, Gar3.5: Gardoprim 3.5, Gar5.0: Gardoprim 5.0, Mer0.08: Merlin 750 WG 0.08, Mer0.13: Merlin 750 WG 0.13, Stom3.0Pos: Stomp Aqua 3.0, But3.0: Butoxone 3.0, Lau2.25: Laudis 2.25. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

6.2.3 Field observations

During the first assessment (40 DAS) it was observed that some of the plants in the plots treated with Gardoprim Plus Gold 500 SC at 3.5 and 5 l/ha showed some symptoms of curling of the leaves.

In the second assessment (62 DAS), it was recorded that the plants were relatively smaller in some plots treated with Gardoprim Plus Gold 500 SC at 3.5 and 5 l/ha and in plots treated with Stomp AQUA at 3.0 l/ha

A third observation was made 105 DAS to detect phytotoxicity of the applied herbicides and it was recorded that the plants treated with Gardoprim Plus Gold 500 SC at 3.5 and 5 l/ha presented some degree of yellowing, leaf curling and were stunted compared to the plants of the other treatments. The plots treated with Stomp AQUA at 3.0 l/ha were slightly stunted compared to the control. Some of these observations can be seen on Figure 23.

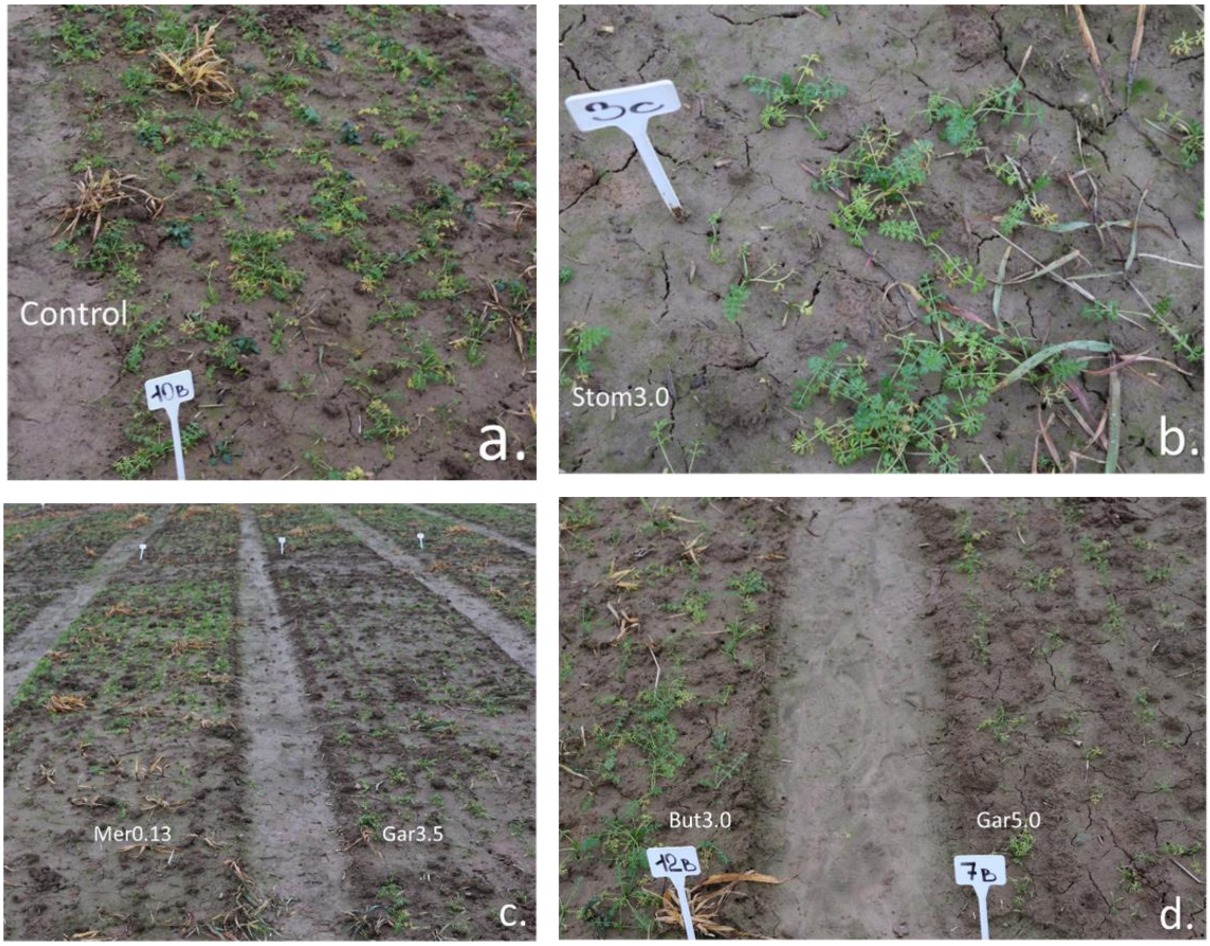

Figure 23. Observations on the plots 105 DAS. a. Control, b. Stom3.0, c. Mer0.13 vs Gar 3.5, d. But3.0 vs Gar5.0. Bandur, Butaxone and Laudis are the only herbicides, which are registered for the use in caraway in the Czech Republic.

6.3 Correlation among studied variables

The abundance of weeds and the caraway biomass 62 DAS were not correlated ($p>0.05$). Positive correlation was found between caraway biomass 217 DAS and the abundance of weeds at 62 ($r=0.407$) and 206 ($r=0.30$) days after sowing. The stage of flower primordia and the number of leaves of the caraway plants also presented a positive correlation ($p<0.05$) with the abundance of weeds at 62 and 206 DAS (Table 4)

Table 4. Pearson's correlations coefficients of the relationship between caraway and weed variables

Variable	Rootstock Diameter(mm)	Stage of flower primordia	No. of leaves	Caraway Biomass 62 DAS	Caraway Biomass 217 DAS
Weeds 206 DAS	0.492	0.377 *	0.197 *	0.235	0.301 *
Weeds 62 DAS	0.521	0.351 *	0.239 *	0.0442	0.407 *

DAS: Days after sowing. *significant at p<0.05

7 Discussion

This thesis revealed considerable effect of used herbicides on caraway performance, reflected in caraway biomass production, stage of development of the flower primordia, number of leaves, and rootstock diameter. The results of this study can be used as a preamble of herbicides registration for the control of weeds on caraway. Excluding Gardoprim Plus Gold 500 SC, the applied herbicides were efficient in weed control without affecting the crop according to the EPPO (2017), and can thus be accepted as appropriate weed control in caraway.

7.1 Effects of herbicides application on weeds

Herbicides reduced weed abundance and thus, one of the main tested hypotheses was confirmed. As also hypothesized, lower number of weeds was encountered in plots treated with pre-emergence herbicides. On the contrary, post-emergence herbicides allowed for weed development during the early stages of caraway growth. This was particularly the case in the autumn. Nevertheless, it should be noted that the total number of weeds in the whole trial was significatively reduced during the winter, even in the untreated control, possibly as a result of cold stress during the winter season (Yadav 2010), rather than due to the action of applied herbicides.

Herbicide effectiveness for the weed control of the most frequent weed species encountered on the field trial (*Lamium purpureum, Veronica persica* and *Viola arvensis)* was significant in all the pre-emergent treatments except Stom2.6. On the other hand, post-emergent herbicides did not have effect against specific weeds (except for Lau2.25 in *Lamium purpureum*). According to the labels, all the pre-emergent herbicides used in the present study (except Merlin 750 WG) include *Lamium purpureum*, *Veronica persica* and *Viola arvensis* in the spectrum of their efficiency, listing them as a "sensitive weed" (Agromanual 2020g). Stomp AQUA as post emergent was not effective against the specific weed even though it is labelled against it, which could possibly be explained by the inadequate time of application in this case. These species are not labelled as target in Butoxone, Laudis only has *Lamium purpureum* as sensitive weed, thus the result concords with the labels.

Nevertheless, according to the growers in the area, the most problematic weeds in the cultivation of the caraway are dicotyledons plants, especially the *Chamomille* group and *Cirsium arvense*, although they were not identified in this study, which warrant future studies from areas an extended to more growing seasons to optimize herbicide utilization in caraway under more scenarios.

Currently only Bandur (Pre-emergent), Butoxone 400 and Laudis (Post-emergent) are registered in the Czech Republic for the use on caraway crops, and their effectiveness against weeds was confirmed in the present study. From the unregistered products, Gardorprim Plus Gold SC was effective but also showed symptoms of phytotoxicity, reflected on biomass and likely also low yield. Stomp AQUA was effective as pre-emergent and post-emergent and the caraway biomass was affected by neither types of application. Merlin 750 WG at a rate of 0.13 kg/ha was also effective against weeds and caraway plants in these plots produced the highest biomass and stage of flower primordia of all treatments.

7.2 Effects on caraway performance

In autumn, caraway biomass was not affected by the presence of weeds or herbicide application. After the winter, some treatments had the lowest biomass values, Gar5.0 and Gar3.5 presented the lowest mean value overall. This can result in the reduction of the number of branches and lateral shoots, the number of umbels per plant or the seed size, influencing the final yield of the crop (Seidler & Bocianowski, 2011). In a similar trial in caraway, the untreated control, resulted in a yield only about one third compared to the plants treated with pre-emergent herbicides (Vaculik 2008). In the present trial, the post emergent treatments only differed with Gar3.5 and Gar3.0, what indicates that the caraway biomass is not affected by the post emergent herbicides or the weeds present at the moment of assessment.

The plots treated with Gardoprim Plus Gold 500 SC at 3.5 and 5 l/ha showed some degree of phytotoxicity on the caraway plants and lower biomass compared with the other treatments. These results concur partially with other trials on caraway where the herbicides Gardoprim Plus Gold 500 SC and Merlin 750 WG showed problems with selectiveness with caraway plants in the retardation of emergency and partial absence of emerging plants and after emergency. Despite that, in this trial Merlin 750 WG (Isoxaflutole) did not affect the caraway plants, on the opposite, the plots treated with Mer0.08 were the ones with highest biomass and high effectiveness

According to Nemeth (1999) in the caraway ,the plant size plays an important role in the development of flowers and the capacity of plants to create more and larger flowers, that are the target parts for the crop cultivation. Apparently, for the biennial form of caraway, a minimum rootstock diameter of 5mm after wintering is a precondition for generative differentiation in the second year (Németh et al. 1997), however for the winter form of caraway used in this study, the rootstock diameter on the control was 3.2 mm after winter and it presented generative differentiation. Although, the number of leaves and the rootstock diameter did not present a significant correlation, it is confirmed by other studies that the flowering stage is characterized by the diameter of the rootstock and number of leaves (Nemeth *et al* 1997). The rootstock diameter and its positive correlation with the stage of flower primordia could mean that the plants with more advanced stage of development, would have more success on the flowering phase and thus the crop development, what translates on a higher probability of better yield. This result can be used in next studies of this form of caraway to also understand the plant development and the role of temperatures on flowering initiation.

7.3 Agricultural and ecological aspects

Although generally considered a nuisance in agricultural production, the weed community can play a substantial role in the agroecosystems supporting the biodiversity, attracting natural enemies and being alternative host for phytophagous insect species (Marshall et al. 2003). Thus, the weeds should not be completely eliminated from the crop fields as they maintain certain diversity that can bring ecological, agriculture and economic benefits. On the present trial, the diversity was not affected, and even the control plot had lower diversity than other treatments, so it is not discussed further. The results of the present study concur with previous studies made by (Kieloch & Domaradzki 2011) that concluded that the highest susceptibility of the weeds in general is at early growth stages and it decrease along with plant development, this can explain why the post emergent herbicides did not have any effectiveness on the specific weed species

Although the use of herbicides can be effective on controlling the weeds in the crops, the management practices also play an important role on the weed development and the possibility of reducing yield loss in general. Colbach & Cordeau (2018) compared simulated effects of weeds and herbicide use intensity with other cultural practices on crop production and concluded that, at any stage of the crop, yield loss was always more correlated to weed biomass than to weed plant density, and that the yield loss increases when herbicides are eliminated without any other change in management practices. And this agrees with the results of the positive correlations found between the weed abundance and caraway growth parameters thus, it can be inferred that the abundance of weeds for this specific trial did not directly affect the development of the caraway, rejecting the hypothesis of inverse correlation. This can be also explained with the effects of the herbicides on reducing the abundance of weeds in general as discussed above.

Increasing the yield of the crop is the main objective for the growers, so the weed management should focus on caraway performance as affected directly (phytotoxicity) and indirectly (changes of caraway growth and production via reduced competition with weeds) by weed management. The selection of the correct herbicide treatment will depend on the objectives and the status of the weed infestation on the crop, it is necessary to know the history of the land and according to this, choose the most suitable herbicide. For the present study, related with weed control, all treatments were effective. However, effects on the crop were also present with the use of herbicides, specially Gardorprim Plus Gold 500 SC (S-metolachlor + terbuthylazine), it would be recommended to avoid the use of this herbicide on the caraway crop.

Currently, the agricultural trend is to reduce the use of synthetic inputs to the arable land for the plant protection (Kieloch & Domaradzki 2011). Following this, when there is no difference between the treated plants with the same herbicide, the recommendation would be to use the herbicide with the lowest rate. In the case of this trial, for the general treatment of the weeds in the caraway crop, both types of herbicides were effective but also phytotoxic in some cases and should be excluded of the possible future weed management

8 Conclusions

- The use of both pre-emergent and post-emergent herbicides is effective against the control of weeds in the caraway crop, however the use of Gardorprim Plus Gold 500 SC (S-metolachlor + terbuthylazine) cannot be recommended based on the results of the present study due to its phytotoxic effects on caraway
- Rates of the selected herbicides should depend on the abundance of weeds on the crop
- No relationship was found between weed biomass and caraway biomass, suggesting other mechanisms of improved crop growth
- Future studies should focus on interactions of caraway with specific weeds under wider range of climatic and conditions and management practices

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10 Appendices

List of the appendices

Appendix 1. Commercial herbicides used on the trial, registered crops and the corresponding weed species declared susceptible

Commercial Name	Active Ingredient	Registered for these crops in the Czech Republic	Declared group of susceptible weed species
Bandur	aclonifen (600 g/L)	Potatoes, maize, sunflower, faba bean, pea, *Carthamus tinctorius* , **spice and vegetable plants from family *Apiacae* - and caraway**	monocotyledons: *Apera spica-venti* , *Alopecurus agrestis* = syn. *A. myosuroides* , *Poa annua;* dicotyledons: *Thlaspi arvense* , *Sinapis arvense* , *Spergula arvensis* , *Viola arvensis* , *Amaranthus* spp. especially *A . retroflexus* , winter oilseed rape as a weed, *Veronica* spp., *Fumaria officinalis* , *Galinsoga parviflora* , *Chaenopodium album* , *Lapsana communis* , *Capsella bursa-pastoris* , Chamomile group, *Urtica urens* , *Galium aparine* , *Polygonum* spp., *Senecio vulgaris* , *Lamium* spp., *Stelaria media* , *Euphorbia* spp., *Atriplex* patula and its relatives
Stomp AQUA	pendimethalin (455 g/L)	Soya, sunflower, pea, bean, lupine, garlic, many grass species, winter wheat, winter barley, triticale - winter form, **some APIACAE: celery, Coriandrum sativum, Foeniculum vulgare**	monocotyledons: *Apera spica-venti, Alopecurus agrestis = syn. A. myosuroides, Digitaria sanguinalis, Echinochloa crus-galli, Setaria pumila and S. viridis, Poa trivialis;* dicotyledons*: Sinapis arvense, Viola arvensis, Amaranthus spp. especially A. retroflexus, Veronica spp., Fumaria officinalis, Chaenopodium album, Capsella bursa-pastoris, Chamomile group, Urtica urens, Galium aparine, Polygonum spp., Lamium spp., Stelaria media, Atriplex patula and its relatives, Anagalis arvensis, Solanum nigrum, Sonchus oleraceus and S. arvensis, Papaver rhoea*
Gardoprym Plus Gold 500 SC	S-metolachlor (312.5 g/L) + terbuthylazine (187.5 g/L)	Maize, sorghum	ONLY 1-YEAR WEEDS; monocotyledons: *Digitaria sanguinalis, Echinochloa crus-galli, Setaria pumila and S. viridis, Alopecurus agrestis = syn. A. myosuroides;* dicotyledons*: Sinapis arvense, Viola arvensis, Amaranthus spp. especially A. retroflexus, Veronica spp., Fumaria officinalis, Chaenopodium album, Galinsoga parviflora, Capsella bursa-pastoris, Thlaspi arvense, Chamomile group, Polygonum spp., Lamium spp., Senecio vulgaris, Stelaria media, Anagalis arvensis, Datura stramonium, Solanum nigrum, Vicia spp.,*
Merlin 750 WG	isoxaflutole (750 g/L)	Maize, poppy	monocotyledons:*Echinochloa crus galli ;* dicotyledons: *Chaenopodium album, Amaranthus retroflexus, Capsella bursa-pasteris, chamomile and chamomile relatives,Thlaspi arvense, Persicaria maculosa syn. Polygonum persicaria, Solanum nigrum, Stellaria media, Lamium purpureum*
Butoxone 400	MCPB (400 g/L)	Peas, **caraway**	*Capsella bursa-pastoris, Chenopodium album, Thlaspi arvense, Cirsium arvense, Rape*
Laudis	tembotrione(44 g/L)+ isoxadifen-ethyl (22 g/L)	Maize, poppy	*monocotyledons: Echinochloa crus-galli, dicotyledons: Chenopodium album, Amaranthus retroflexus, Galium aparine, Stellaria media, Thlaspi arvense, Lamium purpureum, Capsella bursa-pastoris*

Appendix 2. Simpson diversity index for 40,62 and 206 DAS in all treatments