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Evaluation of the new cropping practices in sugar beet (*Beta vulgaris* L.) cultivation in the central black soil region of Russian Federation

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Contents

For Anna and Zoe

1. General Introduction

Sugar beet (*Beta vulgaris* L.) and the sugar cane (*Saccharum officinarum* L.) are two main crops, used for the industrial production of sucrose (Erdal et al., 2007; Zimdahl, 2004). The total volume of white sugar produced globally during the production campaign of 2017/18 was equal to 191,81 million tons and about 20 % of this amount comes from sugar beet (Erdal et al., 2007; NASS, 2018).

Nowadays, Russian Federation (RF) is the biggest producer of the beet sugar (Fairtrade, 2013; FAO, 2018). The area under sugar beet equals 1,1 million hectares in RF, it equals to nearly 24% of the global acreage sown with the crop (FAO, 2018). On the global scale Russian Federation belongs to the main sugar producing nations too. By the end of the production campaign of 2017/18 RF contributed to the global sugar output with 4 % by producing about 6,47 million tons of refined sugar (Soyuzrossahar, 2018). Furthermore, the amount of sugar produced during the processing campaign 2018/19 covers the total demand of RF in sugar with the surplus of approximately 500.000 t (Soyuzrossahar, 2018).

Full stocks caused by the overproduction will force the Russian producers of sugar to search for the new markets outside RF (Kuzminov et al., 2018). However, the internal price for one ton of sugar on the Russian market in November 2018 was about 35 % higher than in United Kingdom (UK) or Ukraine, and 50 % higher than in the United States of America (USA) which makes trading a difficult task (Soyuzrossahar, 2018). The high internal price of sugar is driven by few factors. First – the amount of sugar produced in RF has reached values that cover national needs only in the past two years, earlier the country has been dependant on the imported sugar, that came with the added maintenance costs (Soyuzrossahar, 2018). Second – utilization of low-efficient technologies, which leads to high production costs. Average Russian grower is harvesting about half as much sugar beets per hectare as do the growers in many Western countries like the USA, Germany or France (FAO, 2018). The national average of the sugar beet yield in RF equals 39,6 t ha^{-1}, while on the global scale growers harvest about 60,1 tons of roots out of one hectare. Furthermore, yield in one of the leading beet growing countries – France harvest the root yield of 88 t ha^{-1} (Heno et al., 2017). This demonstrates how tremendous is the potential for the increase of productivity that the Russian sugar industry has. This thesis focuses on the agronomic aspects of sugar beet growing which may help the Russian growers to improve the productivity of sugar beet cultivation and to cut the costs of production to make Russian sugar more competitive on the other markets.

There are several factors which define optimality of the sugar beet production technology. The scope of this work covers the area of chemical weed control and sugar beet seed priming.

Since the beginning of the sugar beet cultivation weeds have been reported as the major yield limiting factor (May and Wilson, 2006). Sugar beet is a low growing crop with wide spaces between the rows. Together with the slow development on the early stages it makes the sugar beets to react sensitively on the weed infestation (Cioni and Maines, 2010; Kenter et al., 2006; Petersen, 2008). Bräutigam (1998) derived that the sugar beet fields must be completely free of the weeds until BBCH 18 stage of crop development to avoid the yield reduction. Schweizer and Dexter (1987) report about yield loss caused by the weed competition in range between 26 and 100 % depending on the duration of crop and weed interference and the composition of weed population. Even if the yield reduction may not be very high, there are other ways how weeds reduce the crop productivity. Plants that escaped the weed management operations may act as hosts for the sugar beet pathogens and their vectors spreading the disease to the crop (Wisler and Norris, 2005). Additionally, mature weed plants produce seeds and will cause problems to succeeding crops of the crop rotation or contribute to the soil seed bank (May et al., 2005) as well as impurifying of sugar beet roots with weed biomass causes losses during sugar beet harvesting and storage (Campbell and Klotz, 2006). That is why, the supply of the homogenous and dense canopy in the shortest possible time as well as highly-efficient weed control are playing decisive role for receiving high yields of sugar beet.

Mechanical and chemical weed management remain two most reliable and common methods to control weed population. Chemical weed control has proven to be highly reliable, flexible and labour-efficient method of weed management (Kunz et al., 2016b). That is why nowadays it is prevailing over the other weed management practices used in conventional agriculture. In most of the sugar beet growing areas, the mixtures of herbicides selective to sugar beets are applied. Herbicides are usually applied as the tank-mixture of the substances with multiple active ingredients having several different modes of action to get the best control of the broad spectrum of weeds (Buhre et al., 2011; Nichterlein et al., 2013; Vasel et al., 2012).

In North America another technology of weed control in sugar beets was introduced and became most common weed management practice within just a few years after the market launch. In 2008 the Roundup Ready® Event H7-1 has been approved in the USA. It gives the sugar beet tolerance to the herbicide *glyphosate* which provided an excellent control of the broad spectrum of weeds (Khan, 2010). Before the launch of the GT sugar beets on the USA market in 2008, the growers of the biggest sugar beet growing region in the USA - the Red River Valley (states of Minnesota and North Dakota) used to spend on weed control in average \$220 ha^{-1} (Dillen and Demont, 2014; Khan, 2010). After the market introduction of GT sugar beets in 2008, the cost of weed control discounted by about 70 % consisted of the price of *glyphosate*-based product - \$92 ha^{-1} for two spraying and the technology fee of \$38 ha^{-1} (Khan, 2010).

The first paper of this dissertation is describing a study conducted by means of a series of field experiments testing the weed control method, based on the *glyphosate*-tolerant (GT) sugar beet. The purpose of the experiment is to research the weed control efficacy and crop productivity, delivered by the GT sugar beet technology and compare it with the conventionally used weed control technologies in RF and Germany. The location in Germany was selected as the benchmark to test the performance of *glyphosate* in different environments.

The *Glyphosate* provide good efficacy of control of the weeds in more advanced development stages compared to conventionally used selective herbicides and consequently it may offer a possibility to reduce the number of herbicide applications (Nichterlein et al., 2013). However, lower number of treatments implies the longer time of interference of the crop and the weed, forcing the crop to compete with the weeds for resources.

Second paper is focused on the study of the yield loss caused by the competition between the sugar beet and weed population, composed out of typically occurring weeds in the respecting growing areas. Purpose of the study is to define the most competitive species of the weed population, the dimension of the yield loss in Germany and the Russian Federation and compare weed density, weed biomass and relative weed cover as the predictors of crop yield loss.

Apart of the weed control operations the supply of optimal number of plants per hectare and quick development of the crop foliage are crucial for optimal light interception and play decisive role in yield formation (Deen et al., 2003; Michalska-Klimczak et al., 2018). Before crop reaches a dicotyledonous stage of development, it is relying exclusively on the resources of the seed. Furthermore, rapid emergence and development reduces the probability of seedling damage or destruction by severe weather, pests or diseases (Gureev, 2011). On many markets sugar beet seed suppliers offer priming as a cheap and proven way of homogenisation of seed maturity and acceleration of the seedling development (Boubriak et al., 2012).

The third paper is researching the effect of seed priming on the speed of sugar beet seed germination in controlled and open environments and studying the effect of seed priming on the crop-weed interaction. The purpose of this study was to define if primed seeds germinate faster than non-primed seeds in controlled environment and in the field conditions, whether seed priming influence the weed suppressive ability of the crop and supply higher yield.

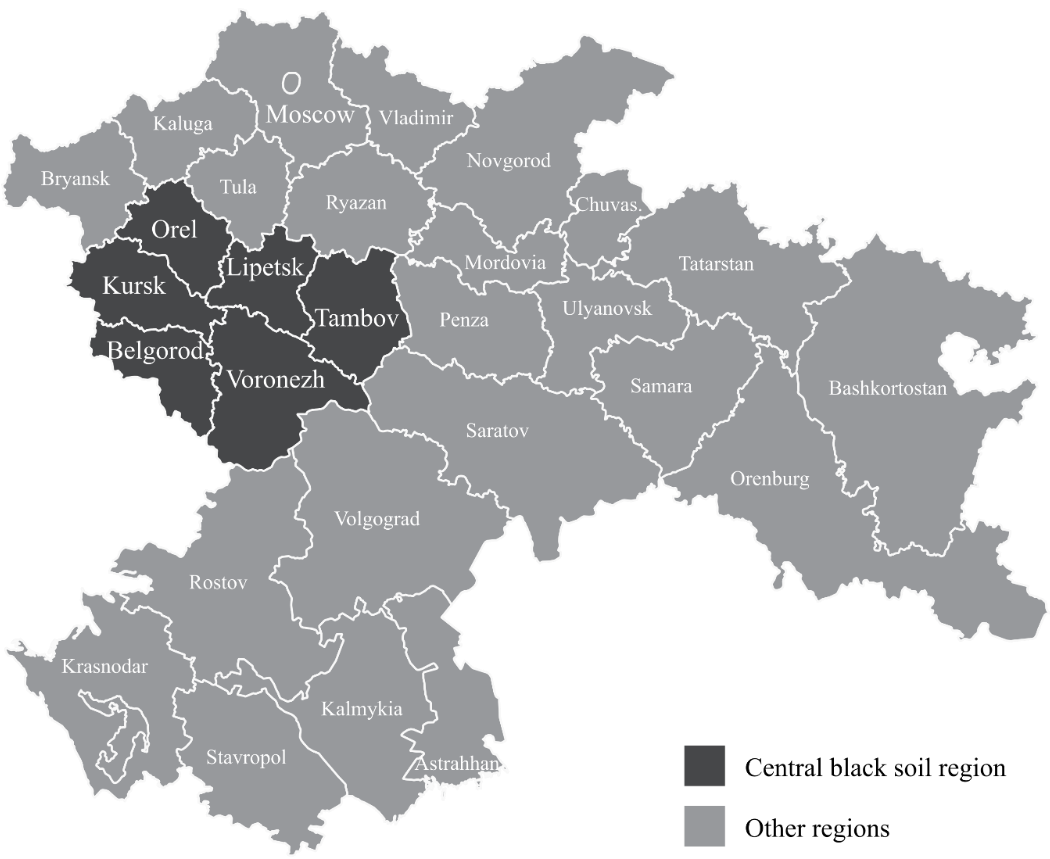

Figure 1: Location of the Central black soil region of the RF and other regions (Gossort, 2018).

In the RF, during the cropping season 2012 field trial was located in the Tambov region (Figure 1) and during the cropping seasons in 2013 and 2014 – in the Lipetsk. Tambov and Lipetsk regions belong to the central black soil region according to the classification of the State commission of the Russian Federation for testing and approval of Plant Breeding Material (Figure 1) (Gossort, 2018). The central black soil region plays a very important role for national sugar industry, supplying more than 75 % of the national sugar production.

Aside from the Russian locations, the same field experiments were duplicated in Germany (Ihinger Hof experimental station, Baden-Württemberg) in order conduct the tests in various conditions: different cropping practices, soil, and weather conditions. Both sites are characterised as typical for sugar beet cultivation.

1.1 Objectives

Present study was focused on the evaluation of improvement of crop productivity and the optimisation of weed control in sugar beet by means of the weed control technology, based of GT sugar beet varieties and priming of sugar beet seeds. The objectives of the research:

- Estimate possibility to reduce the number of herbicide applications in Russian Federation by introducing *glyphosate*-tolerant (GT) sugar beet varieties;
- Define number of *glyphosate* applications needed to control the weed population;
- Study the efficacy of weed control with glyphosate and conventional herbicides;
- Estimate potential to increase the white sugar yield in the *glyphosate* sprayed sugar beets;
- Estimate crop yield reduction caused by interference with weed population due to delay of herbicide application to four true leaf stage;
- Study crop yield response to weed competition in German and Russian environments;
- Research the influence of seed priming on the speed of seed germination and emergence as well as the crop yield response to seed priming;
- Study the influence of the seed priming on crop-weed interaction.

1.2 Structure of the dissertation

This thesis consists out of three parts. The first part – general introduction is giving the background by explaining the current situation within the focused area of sugar beet production and explains the objectives of this study. Second part is presenting the manuscripts of the scientific papers that were published in the international peer-reviewed scientific journals. A discussion of the outcomes of these three scientific publications is presented in the third part – the general discussion.

Scientific papers which contribute to the present study are listed as follows:

- Bezhin, K., Santel, H.-J., Gerhards, R. (2015). Evaluation of two chemical weed control systems in sugar beet in Germany and the Russian Federation. *Plant, Soil and Environment,* 61: 489–495.

- Gerhards, R., Bezhin, K., Santel, H.J., 2017. Sugar beet yield loss predicted by relative weed cover, weed biomass and weed density. *Plant Protection Science,* 53: 118–125.

- Bezhin, K., Santel, H., Gerhards, R., 2018. The Effect of Sugar Beet Seed Priming on Sugar Beet Yield and Weed Suppressive Ability. *Journal of Plant Science,* 6: 149–156.

2. Publications

2.1 Evaluation of two chemical weed control systems in sugar beet in Germany and the Russian Federation

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Czech Academy of Agricultural Sciences, Prague, Czech Republic

Abstract

Roundup Ready® sugar beets are widely grown in the USA since their market introduction in 2005. The system has proven to be cost-efficient and reliable. However, the negative social image among consumers and politicians has prohibited the adoption of this technology in Europe. Seven field experiments were conducted over three years in Germany and the Russian Federation to compare weed control efficacy and sugar beet yields of post-emergent glyphosate applications with conventional selective herbicides. Although weed infestations at the Russian sites were higher than in Germany, weed control efficacies were similar at both locations ranging between 78% and 100%. Applications of glyphosate resulted in significantly higher weed control efficacies than the conventional herbicides in four out of 7 experiments. In five experiments, a single glyphosate application gave equal weed control efficacy as two and three glyphosate applications. White sugar yield was always higher in the weed control treatments than in the untreated plots. There was no yield difference between treatments based on glyphosate and conventional herbicide applications in 6 out of 7 experiments. The results demonstrate a slight benefit of the glyphosate-based weed control program compared to the conventional herbicide system in terms of weed control efficacy.

Keywords: Weed management; Competition; Beta vulgaris; Pesticide; Yield loss

2.2 Sugar Beet Yield Loss Predicted by Relative Weed Cover, Weed Biomass and Weed Density

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Czech Academy of Agricultural Sciences, Prague, Czech Republic

Abstract

Sugar beet yield loss was predicted from early observations of weed density, relative weed cover, and weed biomass using non-linear regression models. Six field experiments were conducted in Germany and in the Russian Federation in 2012, 2013 and 2014. Average weed densities varied from 20 to 131 with typical weed species compositions for sugar beet fields at both locations. Sugar beet yielded higher in Germany. Relative yield losses were lower than in Russia. Data of weed density, relative weed cover, weed biomass and relative yield loss fitted well to the non-linear regression models. Competitive weed species such as Chenopodium album and Amaranthus retroflexus caused more than 80% yield loss. Relative weed cover regression models provided more accurate predictions of sugar beet yield losses than weed biomass and weed density.

Keywords: Crop–weed interaction, Weed competition, Yield loss function

2.3 The Effect of Sugar Beet Seed Priming on Sugar Beet Yield and Weed Suppressive Ability

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Abstract

For optimal development in the field, sugar beets require fast emergence and rapid establishment of a homogenous stand. Environmental influences such as low soil temperatures or crusting of the soil surface usually slow down crop emergence and early development. Priming of the sugar beet seeds has proven to be a cost-effective method facilitating the rapid formation of a dense crop stand. Market penetration of the seed priming technology is variable. It ranges from very high in Western Europe and the USA to minimal in Eastern Europe. In this study, one commercial activated sugar beet variety was analysed under controlled climatic conditions in the growth chamber, in the greenhouse and in a field environment. Under controlled conditions in petri-dishes and in the greenhouse, seed priming significantly accelerated seed germination and reduced the time until the maximum number of sugar beet plants had emerged from 12 days to 6 days after seeding. In the field, no significant effect of seed priming on sugar beet emergence was observed. Weed density, weed biomass and relative weed cover were similar in the activated and non-activated seed treatments indication that seed priming did not increase competitive ability of sugar beets. Yields of both treatments were equal. Seed priming seems to be only beneficial under controlled and optimal growing conditions.

Keywords: Seed Treatment, Seed Activation, Germination Test, Weed Competition

3. General Discussion

The purpose of the present thesis is to study the potential of the use of *glyphosate* and *glyphosate*-tolerant sugar beets as well as seed priming to increase the productivity of sugar beet cultivation in RF. Previous part of this dissertation has presented the results of the growth chamber, greenhouse and field experiments evaluating these two technologies. This chapter presents the discussion of results from the perspective of the implementation of the GT sugar beet and seed priming in the RF.

Out of the findings of the project the following statements can be made:

i) one, two and three applications of *glyphosate* at concentrations of 900 g a.e. ha^{-1} and 1350 g a.e. ha^{-1} showed benefits in terms of the weed control efficacy comparing with conventional system, the effect of the treatments on the white sugar yield was observed only in two experiments out of seven;

ii) it is possible to reduce the number of the herbicide applications to two by using *glyphosate*;

iii) delay of *glyphosate* application to 4-6 true leaves of the weeds caused the reduction of crop yield;

iv) in the Russian locations the crop yield was strongly reduced through competing weed flora;

v) priming of the sugar beet seeds has accelerated seed germination and plant emergence in controlled environment;

vi) in the field conditions, the speed of emergence, crop-weed interaction and white sugar yield were not influenced by priming.

The studies presented in this dissertation have proven that the application of *glyphosate* for controlling of weeds in sugar beet fields can offer certain benefits for the Russian growers, however the requirement of this technology to use the genetically-modified

(GM), *glyphosate*-tolerant sugar beets, require special approach for weed management.

The occurrence of weed resistance to the *glyphosate* is an issue which must be considered for successful application of the GT sugar beet technology which is discussed in this thesis in the RF. After the market launch of *glyphosate*-tolerant crops in the USA growers have started using only *glyphosate* for weed control (Waltz, 2010). This has increased selective pressure on weed population in favour of the weed biotypes with natural resistance to *glyphosate* (Duke and Powles, 2008). Currently, *glyphosate* resistance has been documented in 43 weeds species from 27 countries and four continents (Heap, 2014; Heap and Duke, 2018; WSSA, 2018). Kumar et al. (2018) have reported that the ratio of resistant to susceptible plants of kochia (*Kochia scoparia* L.) that were collected in the commercial sugar beet fields in Oregon and Idaho had the value between 2,0 and 9,6. The dose of *glyphosate,* needed to control the GR kochia was exceeding doses, applied in present study with approximately 5 to 15 times (Kumar et al., 2018). This makes chemical weed control unprofitable and exceeds maximum level of the approved *glyphosate* dosage, that can be applied on sugar beets (Khan, 2018). On the longer perspective, such trends as discovered in the USA agriculture support the opposite statement as assumed in this thesis, that introduction of GT technology reduces the number of treatments and provides better weed control (Schütte et al., 2017).

By now, the most common response of the growers to herbicide resistant weeds was the application of chemicals (Price et al., 2011). To reduce the population of the *glyphosate*-resistant weeds in sugar beet the extension service of the North Dakota State University (NDSU) and the University of Minnesota recommend their growers incorporate herbicides with multiple modes of action into their treatment programs together with the *glyphosate* to minimize the risk of evolving resistance to *glyphosate*. In the fields, where presence of the resistant weed population is already evident, or there is a problem with *glyphosate* tolerant volunteer crops, preemergence application of *s-metolachlor* or tank-mixture of *glyphosate* with *ethofumesate* or *clopyralid* or *triflusulfuron-methyl* or other is recommended (Khan, 2018; Peters and Carlson, 2015). However, some species have already evolved the resistance to these herbicides as well. For example, it is evident about multiple resistant kochia to ALS-inhibitors and *glyphosate*, as well as the other single resistances to two important broad spectrum herbicides: *dicamba* (auxin mimic) and *atrazine* (photosynthesis system II inhibitor) (Kumar et al., 2018; Varanasi et al., 2015).

Cioni and Maines (2010) stated that preserving from the weed resistance may be achieved by the diversification of weed control techniques, including other methods of weed control apart from the pesticides. The use of a living mulch received from cover crops may help to control weed population without intensifying soil tillage. Thus, due to the increase of *glyphosate*-resistant weed population Southern Minnesota Beet Sugar Cooperative encourage the use of cover crops by refund $4 a^{-1} for the utilization of cover crops (SMBSC, 2011).

The suppressive ability of the cover crops can reach high values and be an option for herbicides, thus Brust et al. (2014) stated that the reduction up to 95 % of the weed population by using a cover crop mixture in sugar beet can be achieved. The authors indicate that different species, used for the cover crop demonstrate different efficacy of weed control. It can be assumed that efficacy of weed control depend on the weather conditions and weed composition as well. Results of this study were obtained in the well moistened, maritime climate of South Germany. To estimate the applicability of this technology for the continental climate with hot and severely dry summer of central black soil region of RF further research in this region is needed. Possible areas to study are: rate and speed of the cover crop germination, weed suppressive ability of cover crops, consequences of the interference of the main and the cover crops and its influence on the crop yield. Several studies have demonstrated that the living and dead mulch from cover crops suppress weed germination by competition for resources and through allelopathy (Kunz et al., 2016a; Sturm et al., 2016). Allelopathic interaction must be further studied in the conditions of Central black soil region – arid climate, Chernozem soil with low water holding capacity and high organic matter content.

Other beneficial effects from incorporating of the complementary crop into the cultivation system is evident in the RF by using catch crops. Catch crop may be sown in autumn or included into crop rotation being sown upon the fallow field. It improves the content soil minerals, prevents the flushing of nutrients, protects the soil from wind and water erosion (Sinchenko et al., 2014). Cover crops can secure sugar beet stand by preventing of the wind erosion and can contribute to the weed management practice during crop vegetation. Furthermore, sown as a mixture cover crops better adopt to various environmental conditions and can produce more biomass and show good results than single specie cover crop (Brust, 2014).

Besides the use of cover crops, mechanical weeding is an important part of the integrated weed management (Schütte et al., 2017; Vencill et al., 2012). Unfortunately, the use of the cover crops and mechanical weed control is not possible on the same area because it will cause the cover crop plant displacement, damage or burial under the soil. Mechanical weeding poses one of the most effective ways to destroy unwanted vegetation and can be used as a possibility to reduce the herbicide input and solve the issues of weed resistance (Heap, 2014). Controlling the weeds by cultivating space between the rows with the hoe blade is a simple operation. However, non-selectiveness of most mechanical weeding tool makes it difficult to control the weeds within the row (Van der Weide et al., 2008). Study of Melander and Rasmussen (2001) show that the hoeing close to the row may help to destroy up to 90 % of the weed population. The use of camera-guided hoe allows to place the hoe closer to the sugar beet row than manually-steered hoe without damaging the plants (Kunz et al., 2015). However, the remaining weeds within the row are located nearest to the crop and are the strongest competitors (Kunz, 2017). A combination of mechanical weed control in the inter-row area and the band spraying of the herbicide within the row is a good solution (Nordmeyer, 2006). Vasileiadis et al. (2016) points on the economic viability of such weed control method achieved through herbicide use reduction. However, this study shows that mechanical weeding resulted in less effective weed control than conventionally treated variant, or than the band-sprayed area, nevertheless the reduction of yield of the corn (*Zea mays* L.) in mechanically treated variants was not observed. Kunz et al. (2016b, 2015) concluded that combination of band spraying of the herbicide within the intra-row area and the repeated hoeing of the inter-row offers a possibility to successfully manage weed population and reduce herbicide input by up to 80 %. However, no significant differences of the weed control efficacy and the yield were observed between conventional herbicide treated variants and the combination of mechanical weed management and band spraying or using exclusively mechanical weed management. Such method of weed control can give a high efficacy of weed control and let the growers to reduce the amount of herbicide applied. However, due to the low speed of the mechanical weeding and the need to cover significant number of passes through the field for band spraying and inter-row hoeing (Kunz et al., 2015), the applicability of this method for the Russian large-scaled field need to be studied. However, the dependency of the weed control efficacy of mechanical weeding on the weather condition narrows the time for the application of this weed control method in comparison with *glyphosate* applications (Kunz et al., 2015; Kurstjens and Kropff, 2001).

Additionally, the application of *glyphosate* to reduce weed density prior to crop emergence in combination with discussed above mechanical or combined methods of weed control can be researched for the applicability in Russia. Masmirov (2008) reports that the application of glyphosate two weeks prior to the sowing of sugar beet reduced the weed density to 3 plants m^{-2} by the time of the first application of conventional herbicide. At the same time, in the untreated control plot weed density was 99,7 plants m^{-2}. Author documented perfect control of all the weeds that were abundant within the trial site and considered as typical sugar beet weeds in the central black soil region of the RF:

i) annual weeds dicotyledonous: *Amaranthus retroflexus* L., *Chenopodium album* L., *Galium aparine* L., *Thlaspi arvense* L.;

ii) annual grass weeds: *Echinochloa crus-galli* L., *Avena fatua* L. and *Setaria glauca* L.;

iii) perennials weeds: *Convolvulus arvensis* L. and *Cirsium arvense* L.

The ban of use of genetically-modified crops in the European Union and the RF is causing a lack of agronomic experience and applied practices of the weed management methods, relying on *glyphosate* applications. However, these results show the potential of this technology.

Another approach which may help to reduce the number of herbicide applications and improve weed control efficacy compared to the conventional technology has been recently launched on a few European markets under the commercial name Conviso®. This technology offers two options:

i) single application of the 1 l ha^{-1} of herbicide mixture, including 50 g l^{-1} of *foramsulfuron* (FSM) and 30 g l^{-1} *thiencarbazone-methyl* (TCM);

ii) “split-application” of two times with the 50 % of mentioned above dosage (Wegener et al., 2016).

This herbicide offers excellent control of a wide range of broadleaf and grass weeds and more flexible application timings compared with conventional technology (Wendt et al., 2016b, 2016a). Due to the long duration of residual soil activity of TCM weed suppression from the herbicide application may last for several weeks (Santel, 2012). Therefore, the treatment programs with one or two applications may cover even the late emerging weeds (Wendt, 2017). This technology offers a good control of major sugar beet weeds which are difficult to control with conventional herbicides, like the *Mercurialis spec*. L. or *Aethusa cynapium* L. However, for many species, efficacy of control declines after BBCH 14-16 development stage (Balgheim et al., 2016). For the control of *C. album* and *P. convolvulus* careful scouting of the development stage is critical, since the control efficacy of both species goes down to 90 and 95 % for each specie respectively if herbicide is applied after development stage BBCH 14 (Balgheim et al., 2016; Wendt et al., 2016b). Other limitation of this technology is the low control efficacy of *Veronica persica* L., or *Matricaria inodora* L. Use of herbicide tank-mixpartners is recommended on the fields with prognosed development of these species (Wendt et al., 2016a). Wendt et al. (2016b) has observed a decrease of control efficacy of FSM + TCM if applied under high temperatures and low humidity. This might be caused by the decrease of activity of the TCM in the dry soil. The application time for FSM + TCM was similar to *glyphosate*-treated variants in this study (BBCH 14-16 of the weeds). In the Russian locations the second application of *glyphosate* was conducted in June, when the probability of severe drought in the central black soil region of RF is very high. The technology of ALS-tolerant sugar beets needs to be further studied in such conditions to define the consequences of hot and dry weather on the weed control efficacy.

In RF the herbicide is currently passing through the registration procedure that is why, currently this system is not available. Both active substances (FSM and TCM) belong to the class of aceto-lactate-synthase (ALS)-inhibiting herbicides, and are classified as “highly-risky” towards evolving weed resistance (Heap, 2014). For successful and sustainable use of this technology in RF, integrated weed management practices must be considered in this technology as well as bolter management to prevent gene flow (Wendt et al., 2016a).

Bolter management practices are not widely applicable nowadays in RF. The only independent body controlling the growers for the presence of bolting beets are sugar factories. According to the state standard of RF, the amount of bolter beets in the sample taken at sugar factory must be below 1%. (Ivanov, 2007). If the number of bolters is below this threshold, control is not mandatory and bolter management turns into a personal decision of each grower, depending on the severity of the problems caused by weed-beets. Experience of the US American growers can be adopted – in this area growers who wanted to plant Roundup Ready® sugar beets were obliged to remove bolting plants within their fields on the contract basis. Obviously, such measures were needed because relying exclusively on *glyphosate*-tolerant crops in the rotation makes it impossible to control the weed-beets with herbicides, since the typical beet crop rotation in two major sugar beet growing states (MN, ND) includes GT soybean (*Glycine max* L.) and GT maize (*Zea mays* L.) with 30 to 40 % of the state arable land for each crop and location (NASS, 2018).

Conducted study has shown that under certain environmental conditions priming gives obvious advantage in terms speed of seed emergence and development of the crop leaf area and the biomass. On practice, assuming the average yield in Russia and the lowest price for sugar during the last three years in Russia, the increase in white sugar yield of more than 1 % would make the use of primed seeds economically viable covering the added cost of the primed seeds compared with not primed (Soyuzrossahar, 2018). Furthermore, in RF the common percentage of seed emergence in the field is ranges between 65 and 85 %, depending on climate conditions and the quality of seedbed preparation, and if seeds are sown under the drought conditions it may go down to 50 % (Nananenko and Zabugin, 2007). For the justified use of primed seeds by the Russian growers, further research is needed to define the environmental conditions which let the seed priming improve crop performance. Additionally, the performance of the alternative priming methods must be studied.

This thesis has shown that following topics could be interesting for future research:

i) test of the weed control efficacy of the cover crops, and cover crop mixtures in the central black soil region of RF;

ii) efficacy of the inter-row hoeing in combination with the band spraying or mechanical weeding within the row in the central black soil region of RF;

iii) efficacy of a combination of the pre-emergence or pre-sowing application of the *glyphosate* with mechanical weeding;

iv) weed control efficacy and duration of the soil residual activity in the soil and weather conditions of the central black soil region of RF;

v) further field experiments to discover the climate conditions when seed priming is improving the crop performance.

4. Summary

In recent years Russian sugar production has exceeded the country needs with a surplus of 500.000 tons. Sugar producers and traders are forced to start trading on the global markets. However, ineffective production, caused by low yields of sugar puts the price of Russian sugar 35 to 50 % higher than the leading sugar exporters.

Weeds belong to one of the main factors reducing sugar beet yield. Weeds that survive control operations may cause significant crop yield reductions. Rapid emergence and homogeneous crop stand are very important for competition with weeds. At the same time, the crop may be suppressed by selective herbicide application, if herbicides are applied during suboptimal weather conditions. This study evaluated *glyphosate*-tolerant sugar beet technology and seed priming for the possibility to increase the productivity of sugar beet cultivation.

A series of studies were carried out in different environments in Germany and in Russian Federation. The scope of the studies was dealing with:

i) comparison of the conventional weed control technology with technology, based on *glyphosate* applications;

ii) a study of the crop weed interaction in German environment and in the environment of the Central black soil region of the Russian Federation;

iii) tests of sugar beet seed priming for the speed of germination by means of growth chamber test, and for the speed of emergence in the soil seedbed, by means of greenhouse and field experiments.

The results of the conducted experiments are concentrated in three scientific articles that have been published in the international peer-reviewed journals:

The purpose of the **first article** was to analyse the weed control efficacy of weed control schemes with one, two and three applications of *glyphosate* and compare it with the conventional weed control technology. The results show that the application of *glyphosate* supplied significantly higher efficacy of weed control than conventional herbicides. In five out of 7 experiments single application of *glyphosate* gave the same weed control efficacy as two or three applications. No significant differences in weed control efficacy were observed between two different dosages of *glyphosate* – 900 and 1350 g a.e. ha^{-1}. The variants treated with conventional herbicides and with two and three *glyphosate* applications showed no significant differences in white sugar yield. In one location, the variant with one application of *glyphosate* resulted in lower white sugar yield due to delayed application of herbicide, and longer time of crop and weed interference.

The aim of the **second article** was to study the yield loss caused by the competition with weeds in different environments. In the Russian locations *Chenopodium album* L. and *Amaranthus retroflexus* L. caused serious yield reduction already at low plant densities. White sugar yields harvested at Russian locations were approximately 45 % lower than in German locations. At Russian locations 50 % of the maximum weed population has caused more than 80 % yield reduction. Relative weed cover was the best predictor of the sugar beet yield loss. Weed biomass and weed density gave less accurate predictions.

The **third article** was focused on testing of priming technology on the seed performance and crop establishment. In the controlled environment, primed seeds needed 10 days to reach full germination percentage of the seeds, for not primed seeds it took between 12 and 14 days. Primed seeds produced significantly larger area of plant foliage area and amount of dry biomass than non-rimed seeds. In uncontrolled environments, findings of previous experiments could not be confirmed. Priming did not influence the weed suppressive ability of the crop and the white sugar yield.

The general conclusion of this dissertation is that GT technology may help to improve the profitability of sugar beet cultivation for Russian growers by reducing the number of herbicide applications and increase weed control efficacy. Seed priming can give benefits for crop establishment, however only under specific environmental conditions.

5. Zusammenfassung

In den letzten Jahren übertraf die russische Zuckerproduktion den Bedarf des Landes mit einem Überschuss von 500.000 Tonnen. Zuckerproduzenten und -händler sind gezwungen, auf den Weltmärkten zu handeln. Ineffektive Produktion, verursacht durch niedrige Zuckererträge, führt jedoch dazu, dass der russische Zuckerpreis um 35 bis 50% höher liegt als die führenden Zuckerexporteure.

Unkräuter, welche Bekämpfungsmaßnahmen überleben, gehören zu den wichtigsten Faktoren, die den Zuckerrüben erheblich reduzieren. Ein schneller Feldaufgang und ein homogener Rübenpflanzenbestand sind für die Konkurrenz mit Unkräutern sehr wichtig. Allerdings kann die Kulturpflanze durch Herbizide negativ beeinflusst werden, wenn das Herbizid nicht unter optimalen Wetterbedingungen angewendet wird. In der vorliegenden Studie wurden die *Glyphosat*-tolerante Zuckerrübentechnologie und die Saatgutaktivierung auf mögliche Produktivitätssteigerungen im Zuckerrübenanbau untersucht.

Eine Reihe von Untersuchungen wurde in verschiedenen Umgebungen in Deutschland und in der Russischen Föderation durchgeführt. Der Umfang der Studien befasste sich mit:

i) Vergleich der konventionellen Unkrautbekämpfungstechnologie mit der auf Glyphosat-Anwendungen basierenden Technologie;

ii) eine Untersuchung der Interaktion zwischen Kulturpflanzen und Unkräuter in der deutschen Umwelt und in der Umgebung der zentralen Schwarzbodenregion der Russischen Föderation;

iii) Tests der Aktivierung von Zuckerrübensamen auf die Keimungsgeschwindigkeit mittels Klimakammerversuch und auf die Geschwindigkeit des Aufgangs im Bodensaatbett durch Gewächshaus- und Feldversuche.

Die Ergebnisse der durchgeführten Experimente sind in drei wissenschaftlichen Veröffentlichungen zusammengefasst, die in internationalen, Peer-Reviewed Zeitschriften veröffentlicht wurden:

Ziel der **ersten Veröffentlichung** ist es, den Erfolg der Unkrautkontrolle mit einer, zwei und drei Anwendungen von *Glyphosat* mit der konventionellen Technologie der Unkrautkontrolle zu vergleichen. In fünf von sieben Versuchen ergab die einmalige Anwendung von *Glyphosat* die gleiche Effizienz der Unkrautkontrolle wie bei zwei oder drei *Glyphosatanwendungen*. Es wurden keine signifikanten Unterschiede in der Effizienz der Unkrautkontrolle zwischen zwei verschiedenen Dosierungen von *Glyphosat* (900 und 1350 g a.e. ha^{-1}) beobachtet. Die mit konventionellen Herbiziden und mit zwei und drei *Glyphosat*-Anwendungen behandelten Varianten zeigten keine signifikanten Unterschiede im Zuckerertrag. An einem Standort führte die Variante mit einer einmaligen *Glyphosatanwendung* zu einem niedrigeren Zuckerertrag aufgrund einer verzögerten Herbizidbehandlung und einer längeren Konkurrenzdauer zwischen Kulturpflanzen und Unkräutern.

Ziel der **zweiten Veröffentlichung** war es, den Ertragsverlust zu untersuchen, der durch die Konkurrenz mit Unkraut in verschiedenen Umgebungen verursacht wurde. An den Standorten in Russland führten *Chenopodium album* L. und *Amaranthus retroflexus* L. bereits bei niedrigen Pflanzendichten zu einer erheblichen Ertragsreduzierung. Die an russischen Standorten geernteten Zuckererträge waren etwa 45 % niedriger als an deutschen Standorten. An russischen Standorten haben 50 % der maximalen Unkrautpopulation eine Ertragsminderung von mehr als 80 % verursacht. Die relative Unkrautbedeckung war der beste Prädiktor für den Ertragsverlust der Zuckerrüben. Mit Hilfe der Unkrautbiomasse und der Unkrautdichte waren die Verlustprognosen weniger Präzis.

Die **dritte Veröffentlichung** konzentrierte sich auf die Bewertung des Effekts der Priming-Technologie auf die Leistung des Saatguts, sowie Etablierung und der Produktivität von Zuckerrüben. In der kontrollierten Umgebung benötigte aktiviertes Saatgut 10 Tage, um den vollen Keimungsprozentsatz zu erreichen. Für nicht aktiviertes Saatgut dauerte es zwischen 12 und 14 Tagen. Aktiviertes Saatgut erzeugte eine wesentlich größere Blattfläche und Menge an trockener Biomasse als Saatgut ohne Aktivierung. In Feldversuchen, in unkontrollierten Umgebungen konnten frühere Entdeckungen nicht bestätigt werden. Die Unkrautunterdrückungsfähigkeit der Kulturpflanzen und der Zuckerertrag wurden durch die Aktivierung nicht beeinflusst.

Die allgemeine Schlussfolgerung dieser Dissertation lautet, dass die GT-Technologie russischen Zuckerrübenanbauern dabei helfen kann, die Rentabilität des Zuckerrübenanbaus zu verbessern, indem die Anzahl der Herbizidbehandlungen reduziert und die Wirksamkeit der Unkrautkontrolle erhöht wird. Saatgutaktivierung kann Vorteile für die Etablierung von Kulturpflanzen bieten, jedoch nur unter bestimmten Umweltbedingungen.

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