A DISSERTATION FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Establishment of Weed Management System Based on Soybean-Weed Competition Model for Soybean Production

BY

JONG-SEOK SONG

FEBRUARY, 2016

MAJOR IN CROP SCIENCE AND BIOTECHNOLOGY

DEPARTMENT OF PLANT SCIENCE

THE GRADUATE SCHOOL OF SEOUL NATIONAL UNIVERSITY

Establishment of Weed Management System Based on Soybean-Weed Competition Model for Soybean Production

UNDER THE DIRECTION OF PROF. DO-SOON KIM
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF SEOUL NATIONAL UNIVERSITY

BY
JONG-SEOK SONG

MAJOR IN CROP SCIENCE AND BIOTECHNOLOGY
DEPARTMENT OF PLANT SCIENCE
NOVEMBER, 2015

APPROVED AS A QUALIFIED DISSERTATION OF JONG-SEOK SONG
FOR THE DEGREE OF DOCTOR OF PHILOSOPY
BY THE COMMITTEE MEMBERS
DECEMBER, 2015

CHAIRMAN ______________________
Byun-Woo Lee, Ph. D.

VICE-CHAIRMAN ______________________
Do-Soon Kim, Ph. D.

MEMBER ______________________
Kwang-Soo Kim, Ph. D.

MEMBER ______________________
DoKyoung Lee, Ph. D.

MEMBER ______________________
Byeong-Chul Moon, Ph. D.

Establishment of Weed Management System Based on Soybean-Weed Competition Model for Soybean Production

Jong-Seok Song
Crop Science and Biotechnology
Department of Plant Science
The Graduate School
Seoul National University

GENERAL ABSTRACT

Primorsky-krai, located in far-eastern regions of Russia, is a core agricultural area for Korea's overseas farming operations to secure food crop supply. In the region, about 10 Korean farming firms have been operated for soybean production in a large scale farming system. Average soybean yield in this region was as low as 1.05 ton ha^{-1}, much lower than 1.46 ton ha^{-1} of average soybean yield in Russia (Russian Statistical Yearbook, 2011). The main reason of such low soybean yield may be due to lack of adequate weed management system. Therefore, this study was conducted to investigate soybean-weed competition to determine economic thresholds for weed control under different nitrogen fertilizer levels, and to establish weed management system based on soybean-weed competition model and sequential application of PRE and POST herbicides. The competition effects of single weeds, *Ambrosia artemisiifolia*, *Sonchus oleraceus*, *Chenopodium album*, *Echinochloa crus-galli*, and *Beckmannia syzigachne*, on soybean yields were modeled using the rectangular hyperbolic model, resulting in weed compeititivities of 0.134, 0.083, 0.064, 0.151 and 0.076, respectively. The competition effects of multiple weed interferences on soybean yield were modeled using the multivariate rectangular hyperbolic model with density equivalents estimated from soybean and single weed competition experiments. Under different levels of nitrogen fertilizer, the rectangular hyperbolic and the multivariate rectangular hyperbolic models showed good description of soybean yields as influenced by single weed and multiple weed interferences, respectively. In the rectangular hyperbolic model, two parameters Y_0 and β responded to nitrogen fertilizer level in the inverse quadratic function, suggesting that inverse quadratic functions for the two parameter can be incorporated to the rectangular hyperbolic model. As a result, the combined model well described both nitrogen fertilizer and weed competition effects on soybean yield under single and multiple weed interferences. Pre-emergence (PRE) and post-emergence (POST) herbicides tested alone or in a sequential combination showed that the sequential application of acetochlor followed by bentazon+acifluorfen or bentazon+imazamox controlled weeds most effectively and minimized soybean yield losses from weed competition. The acetochlor-based sequential application with bentazon mixtures showed greater soybean yield, resulting in better gross profit than the common practice of herbicide use in the region. Economic thresholds for weed management in soybean with acetochlor-based sequential herbicide application range from 0.39 to 0.75 density equivalents m^{-2} in soybean cultivation under multiple weed interference. In conclusion, the models developed for soybean-weed competition under different nitrogen fertilizer levels in either single or multiple weed interference are useful for predicting soybean yield as influenced by weed competition and nitrogen fertilizer and decision-making for weed management in this region. The herbicide-based weed management system based on sequential application of PRE and POST herbicides can provide effective and economic weed management for soybean cultivation in Primorsky-krai, Russia.

Keywords: competition, weed management, nitrogen, sequential application, soybean, Primorsky-krai

Student number: 2010-21152

Establishment of Weed Management System Based on Soybean-Weed Competition Model for Soybean Production

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

The values in parenthesis are standard errors.

APPENDIX 2-4. Observed and regressed soybean yield as a function of weed density of *Echinochloa crus-galli* in 2013 and 2014. The predicted soybean yield (continuous line) was calculated using rectangular hyperbola.

APPENDIX 2-5. Parameter estimates for the functions tested to describe the relationship between parameter β and nitrogen in *Echinochloa crus-galli*. The values in parenthesis are standard errors.

APPENDIX 2-6. Observed and predicted soybean yield as a function of weed density of *Beckmannia syzigachne* in 2013 and 2014. The predicted soybean yield (continuous line) was calculated using rectangular hyperbola.

APPENDIX 2-7. Parameter estimates for the functions tested to describe the relationship between parameter β and nitrogen in *Beckmannia syzigachne*. The values in parenthesis are standard errors.

APPENDIX 2-8. Parameter estimates for the functions tested to describe the relationship between parameter β and nitrogen in multiple weed species. The values in parenthesis are standard errors.

ABBREVIATIONS

ABUTH: *Abutilon theophrasti*

AMAHY: *Amaranthus hybridus*

AMARE: *Amaranthus retroflexus*

AMATU: *Amaranthus tuberculatus*

AMBAR: *Ambrosia artemisiifolia*

AMBTR: *Ambrosia trifida*

CHEAL: *Chenopodium album*

DIGSA: *Digitaria sanguinalis*

ECHCR: *Echinochloa crus-galli*

ERIVI: *Eriochloa villosa*

GR: Glyphosate-resistant

IPOHE: *Ipomoea hederacea*

PANMI: *Panicum miliaceum*

PANDI: *panicum dichotomiflorum*

PRE: Pre-emergenc

POST: Post-emergence

POLPE: *Polygonum persicaria*

SETVI: *Setaria viridis*

SETGL: *Setaria glauca*

SOLPT: *Solanum ptycanthum*

SORHA: *Sorghum halepense*

XANST: *Xanthium strumarium*

GENERAL INTRODUCTON

Soybean self-sufficiency in Korea has been reduced dramatically over the last 44 years from 86.1% in 1970 to 9.7% in 2013 (Statistics Korea, 2014). This indicates that Korea mainly depends on imported soybean from overseas. The major countries of soybean production and export are limited to a few countries such as USA, Brazil, and Argentina, producing 87% of the world production in 2013 (FAO stat, 2014). In this monopolistic market situation, Korea is now facing food security as it has solely relied on these countries for soybean supply and has no alternative supply chain. Therefore, Korean government has encouraged private companies and agricultural firms to invest to overseas farming with financial supports.

Primorsky-krai located in the far eastern part of Russia is about 164,673 km^2 in size, about 1.65 times greater than South Korea, with about 2 M people living and has currently about 0.7M ha of crop land with much greater potential land, which has never been used but can be converted to crop land estimated to be up to 2 Mha. Due to lack of farmers and farming system including machinery, currently only a half of the crop land is cultivated for crop production. Due to geographical proximity and potential crop land, several Korean farming firms started crop cultivation in this region from early 2000, and now almost 10 Korean farming firms own about 170,000 ha of crop land and cultivate 50,000 ha mainly for soybean production annually in a massive machinery farming system. However, most of them are still suffering from poor soybean productivity as low as 1.05 ton ha^{-1}, which is much low than Russian average soybean yield of 1.46 ton ha^{-1} (Russian Statistical Yearbook, 2011). A weed survey revealed that the dominant weed species interfered in soybean field across Primorsky-krai included *Ambrosia artemisiifolia*, *Acalypha australis*, *Sonchus oleraceus*, *Echinochloa crus-galli*, *Beckmannia syzigachne*, and *Chenopodium album* (Song et al., 2013a), and weeds were poorly managed due to inappropriate herbicide use, improper spray of herbicide, and improper timing of herbicide application, resulting in significant yield losses. In particular, *A. artemisiifolia* and *E. crus-galli* were not well controlled by the sole application of pre-emergence or post-emergence herbicide, and thus caused severe losses of soybean yield (Vail & Oliver, 1993; Cowbrough et al., 2003).

As soybean is vulnerable to weed competition, many efforts have been made to model the competition between soybean and weed by empirical models, and thus to support decision-making of herbicide use. Cousens' (1985) rectangular hyperbolic model has most commonly been used to predict soybean yield as a function of plant density of single weed species. Previous studies indicated that this model well predicted soybean yield losses caused by *E. crus-galli* (Cowan et al., 1998), *C. album* (Weaver, 2001), and *A. artemisiifolia* (Cowbrough et al., 2003). Additionally, several modified versions of Cousens (1985)' model were developed to predict crop yield as influenced by multiple weed interferences (Berti & Zanin, 1994; Swinton et al., 1994; Kim et al., 2006a). They can assess the effects of multiple weed interference on soybean yield under weed-infested field conditions. In far-eastern regions of Russia, the effects of dominant weed species on soybean yield should be evaluated and modelled to estimate soybean yield loss from weed competition, and to support decision-making for weed control, but so far no study has been made in this regard.

In far-eastern regions of Russia, nitrogen fertilizer has intensively been used for soybean production within the short growing season from May until late September. However, under weed-infested field conditions, the nitrogen effect on soybean yield may be offset by the weeds outcompeting for the nitrogen. Previous studies reported that crop yields were reduced more by nitrophilous weeds at high level of nitrogen fertilizer (Buchanan and Mclaughlin, 1975; Wells, 1979; Ampong-Nyarko and Datta, 1992; Dhima and Eleftherohorinos, 2001; Naderi and Ghadiri, 2011). Only a few study has investigated the effects of both nitrogen and weed interference on soybean yield (Shafagh-Kolvanagh et al., 2008), and particularly information for predicting soybean yield loss from weed competition at a given nitrogen level is limited. Under weedy field conditions at high levels of nitrogen fertilizer, the nitrogen effect on soybean-weed competition should be evaluated to establish a decision-support for nitrogen fertilizer application and weed management.

For effective and economic weed management in a large scale farming system, herbicide has been a core element in many crops. In far-eastern regions of Russia, conventional weed management practices have focused on post-emergence weed control by a single application of POST herbicide. Due to lack of knowledge on herbicide and weed, and consequential inappropriate herbicide use in application timing and method, herbicide use was not always successful in weed management and beneficial for crop cultivation. To achieve greater soybean yield and better economic returns from herbicide use for weed control, systematic investigation of herbicide use should be made to establish a herbicide-based weed management system for soybean in far-eastern regions of Russia. Previous studies indicated that sequential applications of pre-emergence and post emergence herbicides provided greater soybean yield than sole herbicide applications (Johnson BJ, 1971; Anderson & McWhorter, 1976; Watts et al., 1997; Soltani et al., 2009). However, no study has been made to establish a herbicide-based weed management system which can be effective and economic for soybean production in far-eastern regions of Russia.

Therefore, this study was conducted with the following objectives,

Chapter I

To investigate the effect of weed interference on soybean yield and yield component, and thus to model soybean-weed competition using the empirical models (Cousens, 1985; Kim et al., 2006a)

Chapter II

To investigate and model the effect of nitrogen fertilizer on soybean-weed competition using a new model, which can support decision-making for weed control under different nitrogen schemes in soybean

Chapter III

To establish effective and economic weed management and to determine economic thresholds for weed control based on soybean-weed competition model

LITERATURE REVIEW

1. Weed management in soybean

The terms of 'weed management' should be used differently from 'weed control'. Weed management implies preventing weed reproduction, reducing weed emergence after crop planting, and minimizing weed competition with the crop, more than control of an existing weed population (Buhler, 2002). Weeds have been regard as simply can-be-removed for a long time, still many farmers experience crop yield loss caused by weed infestations. Although many soybean producers have introduced effective weed control practices, weeds cannot be looked down as simple problem in crop production. Especially, in massive farming, it may be difficult to prevent crop yield loss using the weed control practices due to the unpredictable agriculture situations. Recently, climate change accelerates the situations. C4 weeds are grown faster and adapted well in elevated temperature and CO_2 than C3 crops, so crop yield loss would be more increased than ever before. In such situations, weed management become more important for reducing long-term weed risk.

Soybean is vulnerable to weed competition over growing seasons. Among major crops, soybean was the most heavily weed-infested crop, followed by corn, wheat, rice, and other crops (Figure 1). As a broadleaf crop, soybean is drilled at wide spacing to develop branches and expand its canopy fully at the late growth stage. The late canopy closure allows weeds to be easier naturally established in soybean than other crops. The early established weeds in soybean caused more severe yield loss than weeds emerging at the later growth stage (Hock et al., 2006). So, the early weed management is of the critical for soybean production. In North and South America, glyphosate-resistant (GR) soybean has been widely cultivated to manage weed infestations in soybean field. In other countries, sequential application of herbicides, tillage practices, and crop rotation are commonly used for conventional weed management practices in non-GR soybean field.

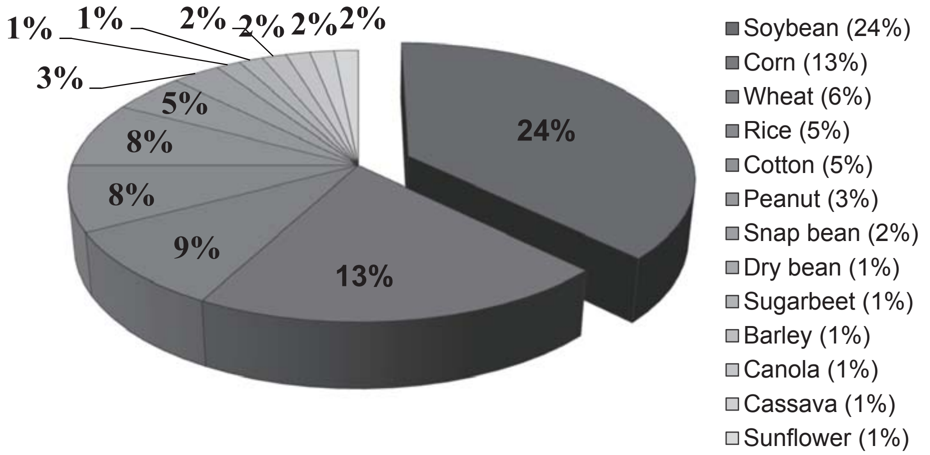


Figure 1. The major crops infested with weeds reported in the 64 papers published between 1990 and 2014 in Weed Science.

Genetic modification technology has changed the conventional weed management in soybean. Glyphosate-resistant (GR) soybean has been widely cultivated in US, Brazil, and Argentina since the first introduction of GR technology (GR soybean + glyphosate) in soybean in the 1990s. Currently, the GR soybean accounts for almost 93%, 80%, and 99% of total soybean grown in US, Brazil, and Argentina, respectively (El-shemy, 2013). The reason for such an extension is that the weed management practices based on GR technology is very effective on a broad spectrum of weed species, but is safe on GR soybean at a single application of glyphosate. Thus, the simple and effective weed management practices become the most attractive for many soybean producers. However, several glyphosate resistant weeds have begun to emerge in GR soybean field since the 1990s. In total, 32 weed species have been reported to be resistant to glyphosate (Heap, 2015). The occurrence of glyphosate resistance weeds raised a concern about weed management practices depending on glyphosate. To be more specific, the practices have characteristics of repeated use of glyphosate, continuous cropping, no tillage and the lack of weed survey (El-shemy, 2013). The characteristics may be attributed to the evolution of glyphosate resistant weeds. Accordingly, a modified weed management practice should include more varieties of herbicides, crop rotations, tillage practices, and monitoring practices (El-shemy, 2013). To support farmers who experienced glyphosate resistant weeds, GR crop providers have included a herbicide with different mode of action in marketing programs to control glyphosate resistant weeds in the US (Dill et al., 2008). Many studies have suggested that tillage is effective in managing herbicide resistant weeds (El-shemy, 2013).

In many countries including Russia, non-GR soybean has been widely cultivated to produce food and feedstock as GR soybean has not been approved by their governments. Weed infestations are the most constraint to produce stable and sustainable soybean yield. To reduce yield loss caused by weeds, many efforts should be taken from soil preparation to harvest in non-

GR soybean. As a procedure of weed management, the primary herbicide application and tillage are used to prevent the weed emergence at planting of soybean, and the secondary herbicide application and tillage are used to suppress weed growth at the early growth stage of soybean. The time-consuming and laborious works for weed management allow many farmers to depend on simple and easy method to manage weeds. Recently, the weed management in non-GR soybean is dependent on over-use of same herbicide and minimum tillage to achieve the high weed control necessary (Moss and Rubin, 1993). The practices has evolved herbicide-resistant weeds worldwide in 167 weed species (Heap, 2015). To reduce the occurrence of herbicide resistant weeds in non-GR soybean, more complex weed management practices should be done for a long-term approach. Actually, the proposed practices integrate all of traditional controls, including cultural (crop rotation), physical (tillage), and chemical (herbicide rotation) (El-shemy, 2013).

2. Impacts of weeds on soybean production

Soybean yield losses have been reported in many literatures. Although recent weed management in soybean has been improved even more than previous one, weeds always survive from it and compete soybean over growing season. Weed species found in soybean have caused significant yield losses with losses of 51%, 78%, 27%, and 55% by *Avena fatua*, *Echinochloa crus-galli*, *Setaria faberi*, and *Agropyron repens*, respectively, and losses of 38-79%, 61-98%, 25%, 47%, 57%, 20-66%, 43%, 68%, 59%, and 67% by *Amaranthus* spp., *Ambrosia* spp., *Chenopodium album*, *Datura stramonium*, *Hibiscus trionum*, *Ipomoea* spp., *Sesbania exaltata*, *Sonchus arvensis*, *Xanthium strumarium*, and *Apocynum cannabinum*, respectively (Table 1). Annual broadleaf weed species are troublesome in soybean. Once they infest into soybean, soybean yield can be reduced by over 50%. *Ambrosia* spp. and *Amaranthus* spp. are frequently reported in literatures, and regarded as the most noxious broadleaf weeds in soybean.

In a practical field situation, crop fields are infested with multiple weed species. Therefore, investigation of the effects of multiple weed interference on crop yield is practically important. However, only a few papers reported soybean and multiple weed competition. Actually, weeds in mixture are more harmful than those alone. The maximum yield losses reported are 98%, 70%, 68%, 55%, 46%, and 28% in Berti and Zanin (1994), Mosier and Oliver (1995), Cowan et al (1998), Jechke et al (2011), Toler et al (1996), and Harris and Ritter (1987), respectively, under multiple weed interferences. Although field studies for crop and multiple weed competition are difficult to conduct, it is necessary to investigate the competition effects of multiple weeds on crop, particularly for soybean, which is very vulnerable to weed interference and infested with many different weeds in a field condtion.

Table 1. Weed-free soybean yield and soybean yield loss as heavily infested with single weed species.

Weed spp.	Life form	Weed-free yield (t ha^{-1})	Max. weed density (plant m^{-2})	Max. yield loss (%)	Reference
Grass					
Avena fatua	Annual	2.0	-	51	Rathmann et al. 1981
Echinochloa crus-galli	Annual	2.1		78	Vail and Oliver, 1993
Setaria faberi	Annual	2.6	-	27	Harrison et al. 1985
Agropyron repens	Perennial	3.0	910	55	Young et al. 1982
Broad-leaves					
Amaranthus rudis	Annual	3.4	199	43	Hager et al. 2002
Amaranthus rudis	Annual	3.3	-	56	Bensch et al. 2003
Amaranthus palmeri	Annual	3.2	-	79	Bensch et al. 2003
Amaranthus retroflexus	Annual	3.3	-	38	Bensch et al. 2003
Ambrosia artemisiifolia	Annual	1.7	-	62	Coble et al. 1981
Ambrosia artemisiifolia	Annual	3.6	-	81	Cowbrough et al. 2003
Ambrosia trifida	Annual	3.6	1	61	Webster et al. 1994
Ambrosia trifida	Annual	1.4	29	98	Baysinger and Sims 1991
Chenopodium album	Annual	3.5	-	25	Harrison, 1990
Datura stramonium	Annual	3.4	16	47	Hagood et al. 1981
Hibiscus trionum	Annual	2.0	275	57	Eaton et al. 1973
Ipomoea hederacea	Annual	2.2	-	20	Mosier and Oliver, 1995
Ipomoea purpurea	Annual	-	7	66	Oliver et al. 1976
Sesbania exaltata	Annual	-	16	43	King and Purcell, 1997
Sonchus arvensis	Annual	2.7	87	68	Zollinger and Kells, 1993
Xanthium strumarium	Annual	2.2	-	59	Mosier and Oliver, 1995
Apocynum cannabinum	Perennial	-		67	Webster et al. 2000

Table 2. Weed-free soybean yield and soybean yield loss as infesting with multiple weed species at maximum density.

Weed spp. (no. of species)	Weed-free yield (t ha^{-1})	Max. weed ensity (plant m^{-2})	Max. yield loss (%)	Reference
SETVI, PANDI (2)	2.2	75	28	Harris and Ritter, 1987
XANST, POLPE, PANMI (3)	3.4	32	98	Berti and Zanin. 1994
SETVI, SETGL, ECHCR, AMARE, ABUTH, AMBAR, SOLPT (7)	2.2	-	-	Swinton et al. 1994
XANST, IPOHE (2)	2.2	-	70	Mosier and Oliver 1995
ECHCR, AMARE (2)	3.3	-	68	Cowan et al. 1998
SORHA, AMAHY (2)	2.4	16	46	Toler et al. 1996
ERIVI, SETVI, SETGL, ECHCR, DIGSA, CHEAL, AMBTR, ABUTH, AMARE AMATU (10)	3.3	-	55	Jechke et al. 2011

ABUTH: *Abutilon theophrasti*, AMAHY: *Amaranthus hybridus*, AMARE: *Amaranthus retroflexus*, AMATU: *Amaranthus tuberculatus*, AMBAR: *Ambrosia artemisiifolia*, AMBTR: *Ambrosia trifida*, CHEAL: *Chenopodium album*, DIGSA: *Digitaria sanguinalis*, ECHCR: *Echinochloa crus-galli*, ERIVI: *Eriochloa villosa*, IPOHE: *Ipomoea hederacea*, PANMI: *Panicum miliaceum*, PANDI: *panicum dichotomiflorum*, POLPE: *Polygonum persicaria*, SETVI: *Setaria viridis*, SETGL: *Setaria glauca*, SOLPT: *Solanum ptycanthum*, SORHA: *Sorghum halepense*, XANST: *Xanthium strumarium*

3. Factors affecting soybean-weed competition

Agricultural factors including nitrogen fertilizer, row spacing, tillage, herbicide application, and crop rotation have a direct or indirect effect on soybean-weed competition. Weeds emerge from the soil and compete a crop between rows for resources (e.g. nitrogen) during the whole growing period. At the end of the growing season, weeds reproduce seeds and in turn the weed seeds bury in the soil. Weed seed burials turn up at the top of the soil by tillage practices for soil preparation. In other words, the tillage practices change weed populations at the top of the soil. Also, weed populations are changed by the application of herbicides for weed control. Moreover, crop rotation with other crops change the weed seedbank and weed population, combining with the tillage practices and the application of herbicides.

Soybean has been traditionally sowed in rows. The distance of row varies from 0.25 to 1.00 m according to cropping system (Nelson and Renner, 1998; Shibles and Weber, 1966). Early cropping system of soybean needed wide space for implements to pass between rows for mechanical weeding prior to the introduction of herbicides. Row spacing may be widened in soybean where tillage became widely adopted for weed control. However, advances in herbicides changed the conventional system in which farmers had sowed soybean (Harder et al, 2007). A trend toward reducing row spacing appeared as herbicides became available for selective control of weeds and a fewer tillage was required after herbicide application in soybean (Wax and Pendleton, 1968). Reducing row spacing can provide higher yield of soybean due to increase in seeding rate. In a recent system of weed management, most farmers sow soybean in optimal rows where weed control can be obtained by using combination of timely tillage and herbicides than by using either tillage or herbicide alone (Wax and Pendleton, 1968). Row spacing is the place on which soybean and weeds compete for natural resources such as light, soil nutrient and water. Change in row spacing may have influence on canopy closure of soybean. Soybean grown in narrow rows can close canopy between the rows early in the growth stage than those in wide rows. In Nebraska, the time of canopy closure between the rows was 36, 47, 58, and 67 days after planting for soybean grown in 25-, 50-, 75-, and 100-cm rows, respectively (Burnside and Colville, 1964). In Illinois, soybean formed a complete canopy over the ground between the rows at 35, 50, 65, 80 days after planting for soybean grown in 25-, 50-, 75-, and 100-cm rows, respectively (Wax and Pendleton, 1968). Similarly, many studies reported that canopy closure in soybean was delayed by increasing the row spacing (Carey and Defelice, 1991; Nelson and Renner, 1999; Harder et al, 2007). As soybean canopy was closed earlier between the rows, emergence and early growth of weed can be suppressed due to the depletion of light throughout the growing season. Weed population and weed growth were reduced by 50% and 75% when row spacing decreased from 91- to 23-cm rows in soybean (Yelverton and Coble, 1991).

Table 3.Characteristics of two row spacing in soybean.

Characteristic	Narrow (<50)	Wide (>75)
seedling rate	High	Low
Crop light interception	High	Low
Ground-shading rate	High	Low
Crop competitiveness	High	Low
Weed emergence rate	Low	High
Weed growth suppression	High	Low
Feasibility of mechanical weed control	Low	High
Selection pressure of herbicide	High	Low
Risk for herbicide resistant weeds	High	Low
Risk of crop lodging	High	Low

Inorganic fertilizer is recognized as a determinant for improving crop productivity. Many studies have focused on the increase in crop yield following the application of fertilizer to soil, particularly nitrogen. In contrast, relatively fewer has studied crop yield loss caused by weed species in the field where fertilizers were applied. That yield loss cannot be underestimated because the fertilization benefited weeds more than crops (Tomaso, 1995). Although nitrogen fertilizer increased crop yield, the increased crop yield could be offset from weeds that is outcompete for resources. In many crops, the addition of nitrogen fertilizer increased weed biomass and thus provided little advantage on crop yield. Crop yield loss was higher at maximum nitrogen fertilizer in wheat which is infested with weed species of *Lamium amplexicaule* (Wells, 1979), *Fumaria parviflora* (Wells, 1979), *Avena fatua* (Pourreza et al, 2010; Carlson and Hill, 1986), *Brassica napus* (Kim et al., 2006b), and *Chenopodium album* (Dodamani and Das, 2013). In triticale, crop yield loss was also higher at maximum nitrogen fertilizer as infested with *Avena fatua* (Dhima and Eleftherohorinos, 2001). Also, rapeseed yield loss was higher at maximum nitrogen fertilizer as infested with *Sinapis arvense* (Naderi and Ghadiri, 2011). In case of multiple weed interferences in crops, crop yields for cotton, rice, and soybean were severely reduced when applied with high nitrogen (Buchana and Mclaughlin, 1975; Ampong-Nyarko and Datta, 1992; Shafagh-Kolvanagh et al., 2008).

Tillage was an essential component of crop cultivation practices. The history of tillage date back to first period of crop cultivation. Tillage destroys the soil crust to sow the seed. The practice leads to give an effect on weeds in crop cultivation. Tillage can be used in different timing of crop cultivation. The primary tillage is used to prepare seedbed before sowing seeds. At that time, burial weed seed can turn up on top of the soil. Clements et al (1996) reported that moldboard or chisel tillage reduced weed size in upper soil considerably compared with no tillage. The other is the secondary tillage. The secondary tillage is used to remove weeds in rows at the early or middle growing season. The effect is valid only for post-emergence weeds, but not for pre-emergence weeds. Ball (1992) reported that the secondary tillage is limited for row crops. On the other hand, the use of tillage has been decreased more and more to prevent the soil erosion and to maintain sustainable soil fertility. The intensity of tillage also affected weed seedbank. Tebrügge and Düring (1999) reported that the conventional tillage, reduced tillage, and no-till differently changed weed seed bank size. Rather, conventional tillage provides new weed seed compared to reduced tillage and no-till. That is because burial weed seeds emerge immediately after tillage. Nowadays, reduced tillage is recommended for soil fertility and weed management.

Herbicide is simple and easy method to use for controlling weeds in crop field. The application of herbicide can considerably reduce weed effects on crops. However, repeated and over-dose use of herbicide has changed weed populations in crop field and evolves its resistant weeds around the countries. The herbicide resistant weeds become again competitive over crops. The bigger problem is that they may be dispersed temporally and spatially into other field. Maxwell et al (1990) reported that the dispersion of herbicide resistant weeds was completely reached to 95% after 5 continuous years of herbicide use. However, no studies have investigated crop yield loss as interfered with herbicide resistant weeds. The occurrence of herbicide resistant weeds provided poor weed control when the same herbicide was applied. Several weed managements were suggested to control herbicide resistant weeds. Herbicide tactics including herbicide rotation and mixtures, sequential application can delay the selection for herbicide resistance (Beckie, 2006). Agronomic practices such as the double knockdown (pre-seeding sequential application of nonselective herbicides), increased seeding rate, and targeting of weed seed production were used to reduce the herbicide resistant weed population in Australian dryland (Walsh et al, 2007). More seriously, single herbicides no longer control non-target site herbicide resistant weeds. To manage those weeds, the conventional weed management including mechanical and cultural weed control was regard as alternative method.

Crop rotation is reported to reduce the weed population. But it is difficult to demonstrate that the reduction in weed population was resulted from only crop rotation, not from other related factors. Many studies reported that weed seedbanks were reduced as crop rotation was associated with other factors. Crop rotation provides weed species with unfavorable environments. In the procedure of crop rotation, cultivation method (herbicide, fertilizer, and sowing date) varied with crops. Soybean has been traditionally rotated with maize. Rotating soybean with maize changed cultivation method differently from continuous soybean. Cultivation on soil and sowing seeds are earlier in maize than in soybean. After sowing seeds, pre-emergence herbicide safe for maize is used, reducing broadleaf weeds considerably in maize. Moreover, post-emergence herbicides provide completely excellent weed control for broadleaf weed. Furthermore, fertilizer for maize is not favorable to weed species in soybean. That reason is why crop rotation is a good weed management in soybean.

CO_2 emission has globally increased air mean temperature by 0.85 ^oC during the period from 1850 to 2012 (IPCC, 2013). The elevated CO_2 and air temperature may change the agricultural environment, which have been adapted in a region over the long time. Generally, under the elevated CO_2 and temperature, both crop and weeds grow faster and produce higher biomass than otherwise. More importantly, the competition relationship between crop and weed in field may be changed according to the environment, which is unfavorable for crops. Among edible crops, the major crops are included in C3 photosynthesis, which is less effective to fit CO_2 than C4 photosynthesis. The most troublesome weed species are known as C4 photosynthesis in the field of major crops. Crop growth and yield would be expected to be reduced by higher growth of weed species although the elevated temperature and CO_2 had a positive effect on both crop and weed. The conventional weed management system may be changed as needed to establish effective weed management for the elevated CO_2 and temperature. However, no research for crop-weed competition was conducted.

4. Modeling crop-weed competition

4.1 Single weed interference

The rectangular hyperbola model was developed by Cousens (1985) to describe crop yield loss based on weed density. Since then, the model has been commonly used to interpret crop-weed competition in additive experiments. The model equation is based on two parameters (Y_0 and β). The value of two parameters can be changed according to weed species as well as a variety of crop.

$$Y = \frac{Y_0}{1+\beta x} \quad (1)$$

Where Y_0 is weed-free crop yield (%) and β is the competitivity of weed species ($1/\beta$ is a density for 50% of crop yield loss).

4.2 Multiple weed interference

The Cousens (1985)' model was only available for predicting crop yield loss caused by single weed. It can be limited to interpret practical field situation because crop yield loss normally happened by multiple weed. So, the model should be modified by combining the competition effect of multiple weed species on crop yield. Several threshold concepts for multiple weed species were developed to improve the Cousens (1985)' model. For example, standard weed unit (Aarts and Visser, 1985), unit production ratio (Hakansson, 1986), crop equivalent ratios (Wilson, 1986), competitive index (Swinton et al., 1994), and density equivalent (Berti and Zanin, 1994) were known for its use in multivariate rectangular hyperbola model. Among the four threshold concepts, density equivalent is widely used to evaluate the competition effect of multiple weed species on crop yield. The term of density equivalent is defined as the relative density of the weed to a reference weed species, which causes a yield loss equivalent to that caused by a reference weed species (Berti and Zanin, 1994). The simple multivariate rectangular hyperbola model was developed by Kim et al (2006a) to describe crop yield loss based on multiple weed density using density equivalent. The model equation is based on two parameters (Y_0 and β). The model equation is based on two parameters (Y_0 and $\frac{\beta_i}{\beta_1}$).

$$Y = \frac{Y_0}{1+\beta_1(X_1+\sum_{i=1}\frac{\beta_i}{\beta_1}X_i)} \quad (2)$$

Where Y_0 is weed-free crop yield (%) and β_i is the competitivity of the ith

weed species (β_1 is a reference weed species).

4.3 Nitrogen effect

The Cousens (1985)' model can be combined with other model as influenced by many factors affecting crop-weed competition. The use of nitrogen fertilizer has a direct effect on crop-weed competition. Kim et al. (2006b) firstly tried to incorporate nitrogen fertilizer response into the Cousens (1985)' model to evaluate the effect of nitrogen fertilizer on crop yield and weed competitivity.

$$Y = \frac{\frac{a+bN}{1+cN+dN^2}}{1+lm^N x} \quad (3)$$

Where a, b, c, d, and l are unknown parameters. Kim (1999) suggested a new combined model to describe the complex effects of nitrogen and multiple weed on crop-weed competition.

5. Soybean production in Primorsky-krai, Russia

5.1 Crop production

Primorsky-krai is the south-easternmost region of Russia located between the 42° and 48° north latitude. The climate is temperate, monsoon, and humid at a monthly temperature range of −12.5 to 20.2 °C and monthly precipitation range of 15 to 153 mm (Figure 2). Crop growing season in Primorsky-krai is the period of time between the middle of May and late September. The length of the growing season is around four months only when early-maturing cultivar of crops can be fully matured by the end of September. During that cropping season, monthly temperature and monthly precipitation are a range of 10.5 ~ 20.2°C and 61 ~ 153mm, respectively.

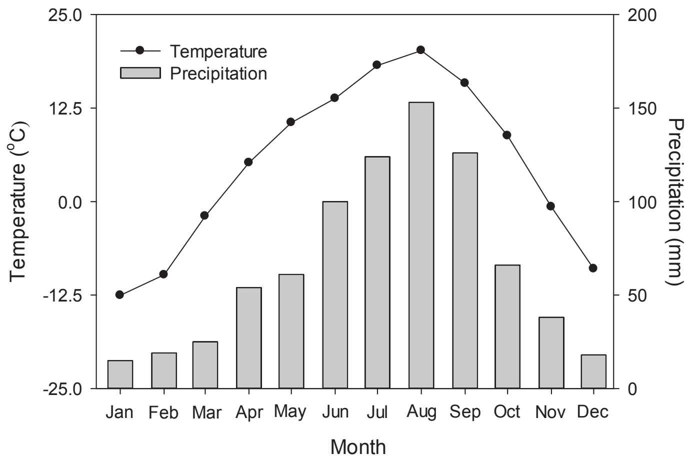


Figure 2. Monthly average temperature and precipitation in Primorsky-krai over the last 30 years (Source: www. worldweather.wmo.int).

The major crops production in Primorsky-krai, Russia are presented in Table 4. Soybean was the largest cultivated crop in Primorsky-krai, followed by Rice, Wheat, and Corn. The area cultivated for soybean in Primorsky-krai was reached to 12.4% of that in Russia. In that region, soybean production quantity was relatively lower as 8.9% compared with the cultivated area. Its soybean productivity was consequentially lower than 1.46 t ha^{-1} in comparison with other provinces in Russia. For reference, soybean productivity should be over 1.5 t ha^{-1} to reach economic thresholds in Primorsky-krai. In rice, the cultivated area and production quantity were about 11.9% and 5.8% of total value in Russia, respectively, and thus rice productivity was reduced by 46.8% compared to the total one of Russia. In wheat, the cultivated area and production quantity were about 0.6% and 0.06% of total value in Russia, respectively, and thus wheat productivity was reduced by 21.1% compared to the total one of Russia. Conversely, corn productivity in Primorsky-krai was higher than the average value of Russia, but the cultivated corn area was much smaller compared to the total corn area of Russia.

Table 4. Major crops production in 2011 in Primorsky-krai, Russia.

Crop	Area cultivated (1,000ha)		Production quantity (1,000t)		Crop productivity (t ha^{-1})	
	Russia (total)	Primorsky-krai	Russia (total)	Primorsky-krai	Russia (total)	Primorsky-krai
Soybean	1,096	136.3	1,600	143.5	1.46	1.05
Rice	208	22.7	1,200	70.0	5.79	3.08
Wheat	2,506	16.7	59,400	34.7	2.37	1.77
Corn	1,025	8.4	2,700	32.2	2.83	3.81
Total	4,835	184.1	-	-	-	-

Source: Federal State Statistics Service (www.gks.ru)

5.2 Soybean production practices in Primorsky-krai

A process of cultivating soybean began with conventional tillage (disk + cultivation) of the soil (Figure 3 and Table 5). A tractor drawn disk plough was ploughed at 20 cm depth on a working rate of 6 ha $hour^{-1}$ followed by rotary harrow at 10 ha $hour^{-1}$ on May just prior to sowing seeds of soybean. An N-P-K basal fertilizer was also applied at a rate of 12-31-31 kg ha^{-1} with a spreader (30m width) on a working rate of 12 ha $hour^{-1}$ before sowing them. The seeds of soybean were sowing at 80 kg ha^{-1} on a working rate of 5.5 ha hour^{-1} with a variety of row width range of 15 ~ 75 cm by the early June. After sowing seeds of soybean, crop management including chemical weed control, mechanical weed control, and pest control was used around the late May through August. As chemical weed control, the application of pre-emergence herbicide was often omitted on the late May or the early June, while that of post-emergence herbicide was required for weed control on the late June or the early July. The herbicide was applied with boom sprayer (26m or 36m boom with) on a working rate of 12 ~ 15 ha hour^{-1}. Sometimes, mechanical weed control was used in heavily weed-infested region. For other pest control, an insecticide or germicide were applied with boom sprayer (26m or 36m boom with) on a working rate of 12 ~ 15 ha hour^{-1} from July to August. On the late September, soybean was firstly harvested with harvester on a working rate of 2~4 ha hour^{-1}.

Figure 3. Soybean cultivation system in Primorsky-krai, Russia.

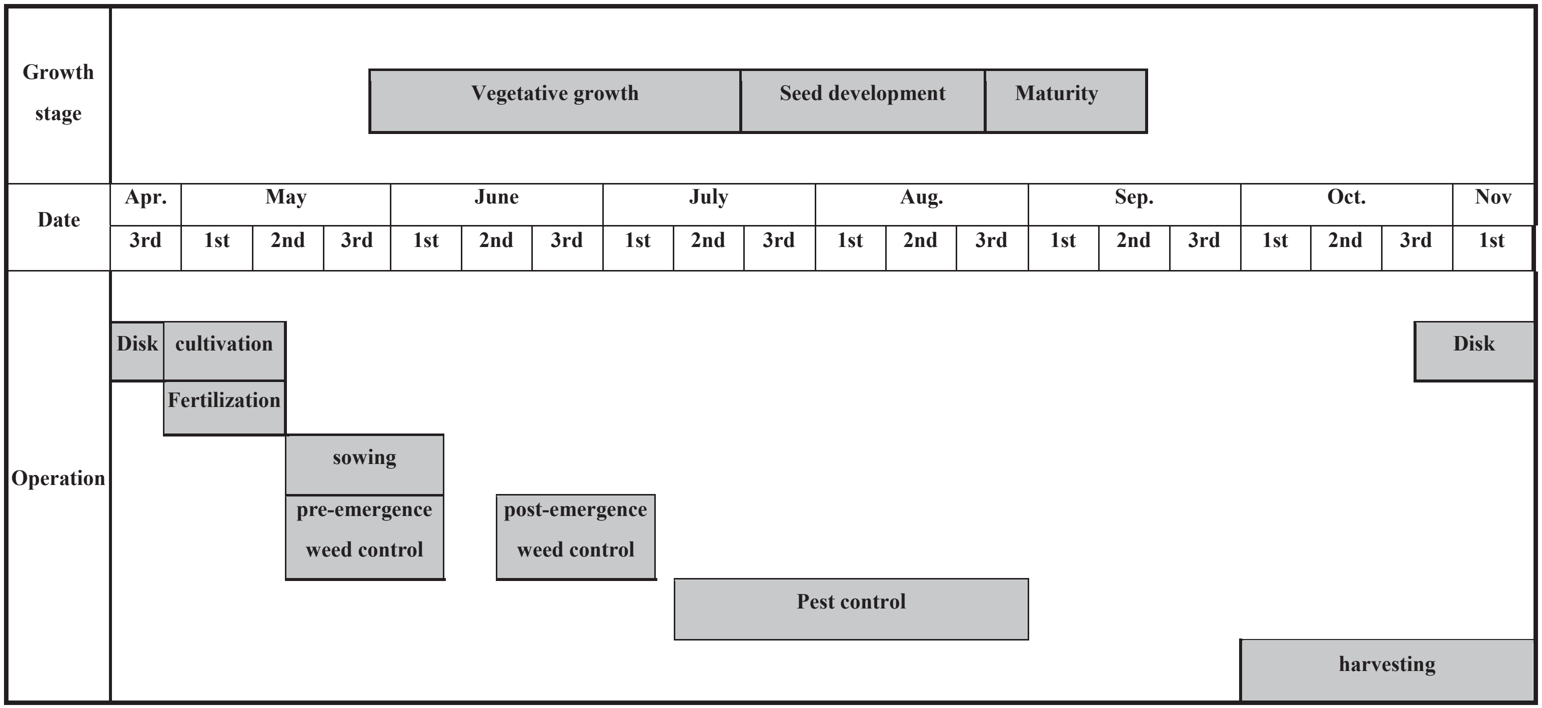


Table 5. Detailed descriptions of soybean cultivation system in Primorsky-krai, Russia.

	Operation	Machinery	Working rate (ha/hour)	notes
Soil preparation	Pre-planting fertilization	Fertilizer spreader	12	Spreader width: 30 (m)
	Primary soil cultivation	Disk plough	6	Ploughing at 20 cm depth
	Secondary soil cultivation	Rotary harrow	10	-
sowing	sowing	Drill seeder	5.5	Row width: 15, 45, 70, 75 (cm)
Crop management	Chemical weed control	Boom sprayer	12~15	Boom width: 26, 36 (m)
	Mechanical weed control	plough	-	-
	Pest control	Boom sprayer	12~15	Boom width: 26, 36 (m)
	Cover fertilization	Fertilizer spreader	-	Spreader width: 30 (m)
Harvest	Harvest	Harvester	2~4	

5.3 Weed management

Soybean yield in Primorsky-krai was much low as 1.05 ton ha^{-1} in comparison of 1.46 ton ha^{-1} in averaged soybean yield of Russia (Table 4). Such low soybean yield was attributed to weed interference resulted from a lack of effective weed management system in the region. In a massive farming system, adequate herbicide-based weed management should be established to prevent soybean yield loss from weeds. Many studies including weed survey, soybean-weed competition, and herbicide screening should be conducted to provide a basic information for effective weed management strategies. A weed survey of soybean fields from 5 locations in Primorsky-krai was conducted in 2011 and 2012 to determine the most common and prevalent weeds associated with soybean production (Figure 4; Song et al., 2013). The weed survey was made in the farm stations of Seoul Feed Co., Ltd. in 2011 and 2012; Komissarovo, Pervomayskoye, and Bogatyrka in 2011, and Il'inka, Grigoryevka, and Bogatyrka in 2012. *Ambrosia artemisiifolia* was the most dominant weed species, spreading throughout Primorsky-krai. The weed species was followed by *Acalypha australis*, *Sonchus oleraceus*, *Echinochloa crus-galli*, *Beckmannia syzigachne*, and *Chenopodium album* for their relative weed dominance. The weed dominance was resulted from inappropriate herbicide use, improper spray of herbicide, and improper timing of herbicide application, so caused severe soybean yield loss. However, no study has been conducted to evaluate the effect of weed interference on soybean yield, and particularly the information for establishing effective herbicide-based weed management are limited.

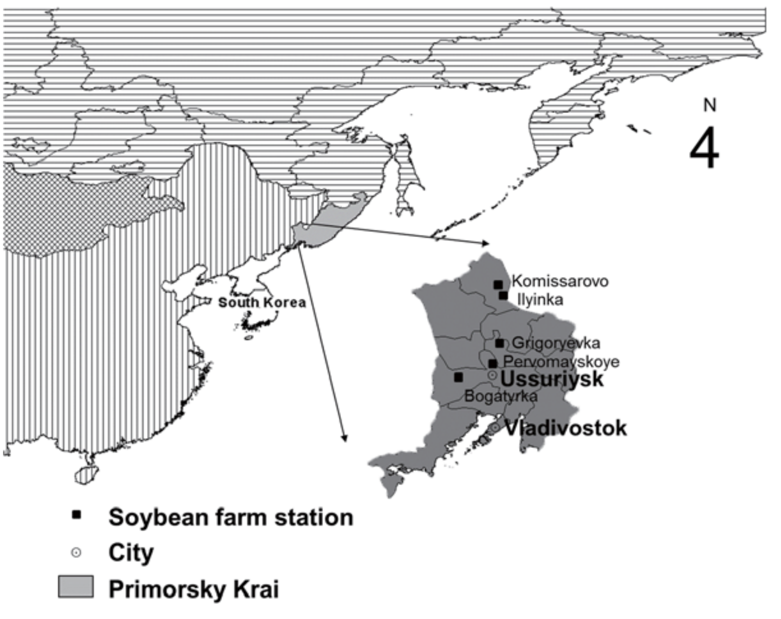


Figure 4. Soybean farm station monitored during weed survey in 2011 and 2012.

REFERENCES

Aarts HFM and De Visser CLM. 1985. A management information system for weed control in winter wheat. In: Proceeding 1985 Brighton Crop Protection Conference-Weeds, Brighton, UK, 679-686.

Ampong-Nyarko K and Datta SKD. 1993. Effects of nitrogen application on growth, nitrogen use efficiency and rice-weed interaction. Weed Research 33: 269-276.

Anderson JM and McWhorter CG. 1976. The economics of common cocklebur control in soybean production. Weed Science 24: 397-400.

Ball DA. 1992. Weed seedbank response to tillage, herbicides, and crop rotation sequence. Weed Science 40(4): 654-659.

Baysinger JA and Sims BD. 1991. Giant ragweed (*Ambrosia trifida*) interference in soybeans (Glycine max). Weed Science 39(3): 358-362.

Beckie HJ. 2006. Herbicide-resistant weeds: management tactics and practices. Weed Technology 20(3) 793-814.

Berti A and Zanin G. 1994. Density equivalent: a method for forcasting yield loss caused by mixed weed populations. Weed Research 34: 327-332.

Bensch CN, Horak MJ, and Peterson D. 2003. Inteference of redroot pigweed (*Amaranthus retroflexus*), palmer amaranth (*A. palmeri*) and common waterhemp (*A. rudis*) in soybean. Weed Science 51(1): 37-43.

Buchanan GA and McLaughlin RD. 1975. Influence of nitrogen on weed competition in cotton. Weed Science 23(4):324-328.

Buhler DD. 2002. 50th anniversary-invited article: challenges and opportunities for integrated weed management. Weed Science 50(3): 273-280.

Burnside OC and Colville WL. 1964. Soybean and weed yields as affected by irrigation, row spacing, tillage, and amiben. Weeds 12(2): 109-112.

Carlson HL and Hill JE. 1986. Wild oat (*Avena fatua*) competition with spring what: Effects of nitrogen fertilization. Weed Science 34(1): 29-33.

Carey JB and Defelice MS. 1991. Timing of chlorimuron and imazaquin application for weed control control in no-till soybeans (*Glycine max*). Weed Science 39(2): 232-237.

Clements DR, Benott DL, Murphy SD, and Swanton CJ. 1996. Tillage effects on weed seed return and seedbank composition. Weed Science 44(2): 314-322.

Coble HD, Williams FM, and Ritter RL. 1981. Common ragweed (*Ambrosia artemisiifolia*) interference in soybean (*Glycine max*). Weed Science 29(3): 339-342.

Cowan P, Weaver SE, and Swanton CJ. 1998. Interference between pigweed (*Amaranthus* spp.), barnyardgrass (*Echinochloa cru-galli*), and soybean (*Glycine max*). 46(5): 533-539.

Cowbrough MJ, Brown RB, and Tardif FJ. 2003. Impact of common ragweed (*Ambrosia artemisiifolia*) aggregation on economic thresholds in soybean. Weed Science 51(6): 947-954.

Cousens R. 1985. A simple model relating yield loss to weed density. Annals of Applied Biology 107(2): 239-252.

Dhima KV and Eleftherohorinos IG. 2001. Influence of nitrogen on competition between winter cereals and sterile oat. Weed Science 49(1): 77-82.

Dill GM, CaJacob CA, and Padgette SR. 2008. Glyphosate-resistant crops: adoption, use and future considerations. Pest Management Science 64: 326-331

Dodamani BM and Das TK. 2013. Density and nitrogen effects on interference and economic threshold of common lambsquarters in wheat. Journal of Pest Science 86(3): 611-619.

Eaton BJ, Feltner KC, and Russ OG. 1973. Venice mallow competition in soybeans. Weed Science 21(2): 89-94.

El-Shemy HA. 2013. Soybean-pest resistance. In: Vivian R, Reis A, Kálnay PA, Vargas L, Ferreira ACC, and Mariani F (ed) Weed management in soybean-issue and practices. InTech, Croatia, pp 47-84.

FAOSTAT. 2014. [Accessed 29 Jan 2016]. Available from URL: http://faostat3.fao.org/browse/Q/QC/E.

Federal State Statistics. 2012. [Accessed 10 Nov 2015]. Available from URL: http:// www.gks.ru.

Hakansson S. 1986. Competition between crops and weeds – influencing factors, experimental methods and research needs. In: Proceedings EWRS Symposium, Economic Weed Control, Stuttgart, Germany, 49-60.

Harder DB, Spaque CL, Renner KA. 2007. Effect of row width and population on weeds, crop yield, and economic return. Weed Technology 21(3):744-752.

Hager AG, Wax LM, Stoller EW, and Bollero GA. 2002. Common waterhemp (*Amaranthus rudis*) interference in soybean. Weed Science 50(5): 607-610.

Hagood ES, Bauman TT, Williams JL, and Schreiber MM. 1981. Growth analysis of soybeans (*Glycine max*) in competition with jimsonweed (*Datura stramonium*). Weed Science 29(4): 500-504.

Harris TC and Ritter RL. 1987. Giant green foxtail (*Setaria viridis* var. major) and fall panicum (*Panicum dichotomiflorum*) competition in soybeans (*Glycine max*). Weed Science 35(5): 663-668.

Harrison SK. 1990. Interference and seed production by common lambsquaters (*Chenopodium album*) in soybeans (*Glycine max*). Weed Science 38(2): 113-118.

Harrison SK, Williams CS, and Wax LM. 1985. Interference and control of giant foxtail (*Setaria faberi*) in soybean (*Glycine max*). Weed Science 33(2): 203-208.

Heap I. 2015. International survey of herbicide resistant weeds. Available from URL:http://weedscience.org/.

Hock MS, Knezevic SZ, Martin AR, and Lindquist JL. 2006. Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. Weed Science 54(1): 38-46.

IPCC. 2013. Summary for policymakers. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker TF,Qin D, Plattner GK, Tignor MSK, Allen J, Boschung

A, Nauels Y, Xia Y, Bex V, Midgley PM (eds). Cambridge University Press: Cambridge, UK and New York, NY.

Jeschke MR, Stoltenberg DE, Kegode GO, Sprague CL, Knezevic SZ, Hock SM, and Johnson GA. 2011. Predicted soybean yield loss as affected by emergence time of mixed-species weed communities. 59:416-423.

Johnson BJ. 1971. Effects of sequential herbicide treatments on weeds and soybeans. Weed Science 19(6): 695-700.

Kim DS. 1999. Modeling herbicide and nitrogen effects on crop-wee competition. PH.D Thesis, University of Bristol, Bristol, UK.

Kim DS, Marshall EJP, Brain P, and Caseley JC. 2006a. Modeling interactions between herbicide dose and multiple weed species interference in crop-weed competition. Weed Research 46: 175-184.

Kim DS, Marshall EJP, Caseley JC, and Brain P. 2006b. Modeling the effects of sub-lethal doses of herbicide and nitrogen fertilizer on crop-weed competition. Weed Research 46: 492-502.

King CA and Purcell LC. 1997. Interference between hemp sesbania (*Sesbania exaltata*) and soybean (*Glycine max*) in response to irrigation and nitrogen. Weed Science 45(1): 91-97.

Maxwell BD, Roush ML, and Radosevich SR. 1990. Predicing the evolution and dynamics of herbicide resistance in weed populations. Weed Technology 4(1): 2-13.

Moss SR and Rubin B. 1993. Herbicide-resistant weeds: a worldwide perspective. Journal of Agricultural Science, Cambridge 120: 141-148.

Mosier DG and Oliver LR. 1995. Common cocklebur (*Xanthium strumarium*) and entireleaf morningglory (*Ipomoea hederacea* var. integriuscula) interference on soybeans (*Glycine max*). Weed Science 43(2): 239-246.

Naderi R and Ghadiri H. 2011. Competition of wild mustard (*Sinapis arvense* L.) densities with rapeseed (*Brassica napus* L.) under different levels of nitrogen fertilizer. J. Agr. Sci. Tech. 13: 45-51.

Nelson KA and Renner KA. 1998. Weed control I wide- and narrow-row soybean (*Glycine max*) with imazamox, imazethapyr, and CGA-277476 plus quizalofop. Weed Technology 12(1): 137-144.

Oliver LR, Frans RE, and Talbert RE. 1976. Field competition between tall morningglory and soybean. I. growth analysis. Weed Science 24(5): 482-488.

Pourreza J, Bahrani A, and Karami S. 2010. Effect of nitrogen fertilization application on simulating wheat (*Triticum aestivum*) yield loss caused by wild oat (*Avena fatua*) interference. American-Eurasian J. Agric. & Environ. Sci., 9(1): 55-61.

Rathmann DP and Miller SD. 1981. Wild oat (*Avena fatua*) competition in soybean (*Glycine max*). Weed Science 29(4): 410-414.

Russian Statistical Yearbook. 2011. Annual statistics. Russian statistical yearbook. Rosstat.

Shafagh-Kolvanagh J, Zehtab-Salmasi S, Javanshir A, Moghaddam M, and Nasab. 2008. Effect of nitrogen and duration of weed interference on grain yield and SPAD (chlorophyll) value of soybean (*Glycine max* (L.)

Merrill.). Journal of Food Agriculture and the Environment 6(3-4): 368-373.

Shibles RM and Weber CR. 1966. Interception of solar radidation and dry matter production by various soybean planting pattern. Crop Science 6(1): 55-59.

Soltani N, Vyn JD, and Sikkema PH. 2009. Control of common waterhemp (*Amaranthus tuberculatus* var. *rudis*) in corn and soybean with sequential herbicide applications. Canadian Journal of Plant Science 89(1): 127-132.

Song JS, Jung JH, Kwon JH, Lim SH, and Kim DS. 2013. Weed survey in soybean fields of Seoul Feed Farm in Primorsky-Krai, Russia. Proceedings of the Korean Society of Weed Science 33(1): 147-148 (In Korean).

Statistics Korea (KOSTAT). 2014. [Accessed 29 Jan 2016]. Available from URL:http://www.index.go.kr/potal/stts/idxMain/selectPoSttsIdxSearch.do?idx_cd=2747&stts_cd=274706&clas_div=&idx_sys_cd=518&idx_clas_cd=1.

Swinton SM, Buhler DD, Forcella F, Gunsolus JL, and King RP. 1994 Estimation of crop yield loss due to interference by multiple weed species. Weed Science 42(1): 103-109.

Tebrügge and Düring. 1999. Reducing tillage intensity – a review of results from a long-term study in Germany. Soil and Tillage Research 53:15-28.

Toler JE, Guice JB, and Murdock EC. 1996. Interference between johnsongrass (*Sorghum halepense*), smooth pigweed (*Amaranthus hybridus*), and soybean (*Glycine max*). Weed Science 44(2): 331-338.

Tomaso JMD. 1995. Approaches for improving crop competitiveness through the manipulation of fertilization strategies. Weed Science 43(3): 491-497.

Vail GD and Oliver LR. 1993. Barnyardgrass (*Echinochloa crus-galli*) interference in soybeans (*Glycine max*). Weed Technology 7(1): 220-225.

Watts JR, Murdock EC, Stapleton GS, and Toler JE. 1997. Sicklepod (*Senna obtusifolia*) control in soybean (*Glycine max*) with single and sequential herbicide application. Weed Technology 11: 157-163.

Wax LM and Pendleton JW. 1968. Effect of row spacing on weed control in soybeans. Weed Science 16(4): 462-465.

Walsh MJ and Powles SB. 2007. Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technology 21(2): 332-338.

Weaver SE. 2001. Impact of lamb's-quarters, common ragweed and green foxtail on yield of corn and soybean in Ontario. Canadian Journal of Plant Science 81(4): 821-828.

Webster TM, Loux MM, Regnier EE, and Harrison SK. 1994. Giant ragweed (*Ambrosia trifida*) canopy architecture and interference studies in soybean (*Glycine max*). Weed Technology 8(3): 559-564.

Webster TM, Cardina J, and Woods SJ. 2000. *Apocynum cannabinum* interference in no-till Glycine max. Weed Science 48(6): 716-719.

Wells GJ. 1979. Annual weed competition in wheat crops: the effect of weed density and applied nitrogen. Weed Research 19: 185-191.

Wilson BJ. 1986. Yield response of winter cereals to the control of broad-leaved weeds. In: Proceedings of 1986 EWRS symposium, Economic weed control, Stuttgart, Germany, 75-82.

Yelverton FH and Coble HD. 1991. Narrow row spacing and canopy formation reduces weed resurgence in soybeans (*Glycine max*). Weed Technology 5(1): 169-174.

Young FL, Wyse DL, and Jones RJ. 1982. Influence of quackgrass (*Agropyron repens*) density and duration of interference on soybean (*Glycine max*). Weed Science 30(6): 614-619.

Zollinger RK and Kells JJ. 1993. Perennial sowthistle (*Sonchus arvensis*) interference in soybean (*Glycine max*) and dry edible bean (*Phaseolus vulgaris*). Weed Technology 7(1): 52-57.

CHAPTER I. Modelling the effect of weed interference on soybean yield

ABSTRACT

The effect of multiple weed interference on soybean yield was investigated to predict soybean yield as influenced by multiple weed interference based on Kim et al. (2006)'s model, which can be useful to estimate weed thresholds of multiple weed interference in a soybean field of Bogatyrka (N43º49', E131º36'), Primorsky-krai, Russia. Among the yield components of soybean, dry weight was most negatively affected by weed interference, followed by number of pods and number of seeds. Soybean yield hyperbolically decreased with increasing total equivalent density of multiple weed species including *Ambrosia artemisiifolia*, *Sonchus oleraceus*, *Chenopodium album*, *Echinochloa crus-galli*, and *Beckmannia syzigachne*. The multivariate rectangular hyperbolic model (Kim et al., 2006) well described the shape of soybean yield along the total equivalent density of five weed species which were naturally established in soybean field in 2013 and 2014. Parameter estimates indicated that weed-free soybean yields were similarly estimated 1.71 t and 175 t ha^{-1} in 2013 and 2014, respectively, while weed competitivities were differently estimated 0.1349 and 0.1709 as weed species randomly occurred in natural field conditions. The results including model can be

applied to soybean under natural weed interference condition for decision support to weed management for soybean cultivation in Primorsky-krai.

Keywords: crop-weed competition, modeling, rectangular hyperbolic model, soybean, *Ambrosia artemisiifolia*, *Echinochloa crus-galli*

Introduction

Soybean in far-eastern regions of Russia has been produced by a number of local firms which have secured 170,000 hectares of large farmlands. The soybean production has not reached higher productivity, more than 1.7 t ha^{-1} since weed interference was a major problem to cause soybean yield to decrease more than expected. However, any attention has not been given to study the effect of weed interference on soybean yield in the region. Considering the potential to increase soybean yield without weed damage, the study is required to suggest effective weed management system in the region.

Many studies for modelling crop-weed competition have provided a tool to predict crop yield as influenced by weed interference under field conditions. Cousens (1985)' model is commonly used to estimate crop yield as a function of weed density for individual weed species. However, the model is only available for crop yield loss caused by single weed species. In practical field situations, crop yield loss happened by multiple weed species. Kim et al. (2006) suggested multivariate rectangular hyperbolic model that can predict crop yield as influenced by multiple weed interference using density equivalent of individual weed species. Recently, Kim et al. (2006)'s model has attracted attention to study the effects of multiple weed interference on crop yield. Yousefi et al. (2012) and Oveisi et al. (2013) reported that the multivariate form of rectangular hyperbolic model can be useful to describe the crop yield loss as affected by multiple weed interference. The multivariate rectangular hyperbolic model would be useful to evaluate the level of weed interference which causes crop yield loss, to evaluate the effect of sub-lethal doses of herbicide on crop-weed competition, and finally to support decision-making for weed control.

As soybean is vulnerable to weed competition, many efforts have made to apply the competition models to predict the competition effects on soybean yield. Previous studies indicated that Cousens (1985)' model well predicted soybean yield caused by individual weed species such as *Sorghum bicolor* (Fellow & Roeth, 1992), *Echinochloa crus-galli* (Cowan et al., 1998), *Amaranthus* spp. (Bensch et al., 2003), *Chenopodium album* (Weaver, 2001), and *Ambrosia artemisiifolia* (Cowbrough et al., 2003). Berti & Zanin (1994) and Swinton et al. (1994) developed modified versions of Cousens (1985)' model to predict soybean yield loss as a function of combined density of all weed species. The models well predicted soybean yield caused by multiple weed interference although the parameters of the models were too many to test experimentally. Since then, any further study has not progressed to model the effect of multiple weed interference on soybean yield.

Ambrosia artemisiifolia, *Sonchus oleraceus*, *Chenopodium album*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* were dominant weed species found in soybean in far-eastern regions of Russia (Song et al., 2013). *A. artemisiifolia* has high competitivity than soybean, intercepting most of photosynthetically active radiation with high canopy architecture (Coble et al., 1981). *E. crus-galli* has better growth characteristics with a broad adaptability and high nutrient efficiency, resulting in soybean yield loss by 50% (Vail & Oliver, 1993). *C. album* is troublesome weed species in soybean because of large seed production (Crook & Renner, 1990). *B. syzigachne* and *S. oleraceus* have not been reported for their competition effects on soybean yield. To establish effective weed management in the region, the effect of the major weed species on soybean yield should be evaluated and modelled for farmers and field managers to decide for weed control. Therefore, this study was conducted to predict soybean yield as influenced by multiple weed interference in soybean field using the multivariate rectangular hyperbolic model (Kim et al., 2006).

Materials and Methods

Field experiments

Field experiments were conducted in 2013 and 2014 to evaluate competition effects of multiple weed interferences on soybean yield in Bogatyrka, Russia. Temperature and rainfall during the growing season were recorded each year at a weather station adjacent to the site (Figure 1-1). The field had a soil texture of silty loam with CEC of 22.62 cmol kg^{-1}, organic matter of 29.59 g kg^{-1}, total N of 1.58 g kg^{-1}, inorganic NH^{4+}-N of 0.85 mg kg^{-1}, inorganic NO^{3-}-N of 14.01 mg kg^{-1}, available P of 18.19 mg kg^{-1}, and pH of 6.61. An N-P-K basal fertilizer was applied at a rate of 12-31-31 kg ha^{-1} on 27 May, 2013 and May 22, 2014, respectively.

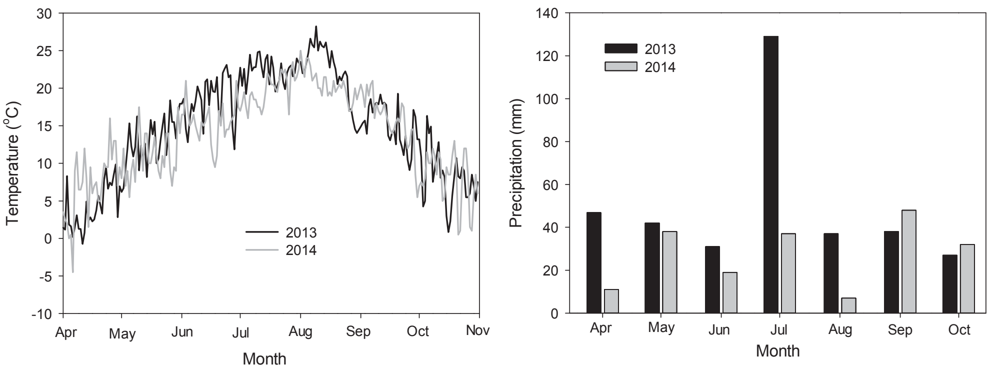


Figure 1-1. Monthly average temperature and precipitation in Bogatyrka, Primorsky-krai in 2013 and 2014.

Soybean (cv. Heinong 48) was drilled at 80 kg ha^{-1} with a row width of 70 cm on May 27, 2013 and May 22, 2014. After drilling soybean, weed species were naturally established within 35 cm on either side of each row. Weed species tested are *Ambrosia artemisiifolia*, *Sonchus oleraceus*, *Chenopodium album*, *Echinochloa crus-galli*, and *Beckmannia syzigachne*. The other weed species was removed by hand-weeding. Weed seedlings which had be established naturally in the field were thinned to target weed density of individual weed species and their different weed density combinations by late June in 2013 and 2014 (Table 1-1). The maximum weed densities for individual weed species were 45, 94, 304, 166, and 135 (plants plot^{-1}) with 13, 13, 14, 13, and 12 (plot) for *A. artemisiifolia*, *S. oleraceus*, *C. album*, *E. crus-galli*, *B. syzigachne*, respectively, in 2013. In 2014, they were 174, 60, 160, 252, and 151 (plants plot^{-1}) with 17, 13, 13, 17, and 16 (plot), respectively. The density combinations of five weed species consisted of 45 and 35 (plot) in 2013 and 2014, respectively. The plots were laid-out in completely randomized design. The plot size was 2.1 m × 1 m in which three soybean rows were included. Soybean was harvested by hand at maturity in October of each year. Soybean seed weight and moisture content were measured and yield was adjusted to 14% moisture for soybean.

Table 1-1. Weed species and densities for soybean-weed competition studies in 2013 and 2014.

Year	Weed species	A range of densities (plants $plot^{-1}$)	Number of plots
2013	<u>Single weed</u>		
	Ambrosia artemisiifolia	0 ~ 45	13
	Sonchus oleraceus	0 ~ 94	13
	Chenopodium album	0 ~ 304	14
	Echinochloa crus-galli	0 ~ 166	13
	Beckmannia syzigachne	0 ~ 135	12
	<u>Multiple weed</u>		
	A. artemisiifolia, *S. oleraceus*, *C. album*, *E. crus-galli*, *B. syzigachne*		45
2014	<u>Single weed</u>		
	Ambrosia artemisiifolia	0 ~ 174	17
	Sonchus oleraceus	0 ~ 60	13
	Chenopodium album	0 ~ 160	13
	Echinochloa crus-galli	0 ~ 252	17
	Beckmannia syzigachne	0 ~ 151	16
	<u>Multiple weed</u>		
	A. artemisiifolia, *S. oleraceus*, *C. album*, *E. crus-galli*, *B. syzigachne*		35

Prediction model

The rectangular hyperbola model (Cousens, 1985) was basically used to predict soybean yield based on weed density.

$$Y = \frac{Y_0}{1+\beta x} \quad (1)$$

Where Y_0 is weed-free soybean yield (%) and β is the competitivity of weed species (1/ β is a density for 50% of soybean yield loss). The Cousens (1985)' model was only valid for describing soybean yield loss caused by single weed. It can be advanced through modification of the Cousens (1985)' model with combining the competition effect of multiple weed species on soybean yield as Kim et al. (2006)' model. In Cousens (1985)' model, model equation was rewritten to describe the relationship between soybean yield (Y_0) and initial weed densities of two weed species denoted as 1 and 2 as follow,

$$Y = \frac{Y_0}{1+\beta_1 X_1+\beta_2 X_2+\lambda X_1 X_2} \quad (2)$$

Where, Y_0 is the weed-free soybean yield, β_1 and β_2 are the competitivities of the two weed species, λ is interaction effect of the two weed species, and X_1 and X_2 are the initial weed densities of the two weed species. The interaction parameter λ could be omitted to make the model simpler (Kim et al., 2006). Then, equation 2 can be rewritten as follows,

$$Y = \frac{Y_0}{1+\beta_1 X_1+\beta_2 X_2} \quad (3)$$

This model (equation 3) can be rewritten as equation 4 to compare relative weed competitivity ($\frac{\beta_2}{\beta_1}$) and convert original weed density to relative one, based on the relative competitivity of each species

$$Y = \frac{Y_0}{1+\beta_1(X_1+\frac{\beta_2}{\beta_1}X_2)} \quad (4)$$

In equation 4, $X_1 + \frac{\beta_2}{\beta_1}X_2$ is total equivalent density, which causes soybean yield loss equivalent to that caused by a reference weed species 1. The total equivalent density is the sum of the relative densities of the weeds that are calculated by multiplying actual density of each weed with its density equivalent, the relative competitivity of the weed to a reference weed species (Berti and Zanin, 1994). If the weed community consists of n weed species, the total equivalent density is $X_1 + \frac{\beta_2}{\beta_1}X_2 + \frac{\beta_3}{\beta_1}X_3 + \cdots + \frac{\beta_n}{\beta_1}X_n$, so that soybean yield can be predicted by using equation 5 below which is a generalization of equation 4.

$$Y = \frac{Y_0}{1+\beta_1(X_1+\sum_{i=1}\frac{\beta_i}{\beta_1}X_i)} \quad (5)$$

Where Y_0 is weed-free soybean yield (%) and β_i is the competitivity of the i^{th} weed species (β_1 is a reference weed species).

Statistical analyses

All measurements were initially subjected to analysis of variance (ANOVA) with the third-order interaction as an estimate of variability as the experiment was not replicated. Correlation analyses were conducted among yield components, soybean yield, and weed density to evaluate the negative effects of weed density on soybean yield and yield components. Non-linear regression analyses were then conducted to fit yield data caused by weed density of single weed and multiple weed using Cousens (1985)' model (equation 1) and Kim et al. (2006)' model (model equation 5), respectively. The performance of models was evaluated by coefficients of determination of models (R^2) and the root mean square error in prediction (RMS). All the statistical analyses were conducted using Genstat (Genstat Committee, 2002).

Results

Competition effects of single weed species on soybean

Correlation analysis was used to evaluate correlation between weed density and soybean yield components in 2013 and 2014 (Figure 1-2). Regardless of weed species, number of pods, number of seeds, and dry weight were negatively correlated with weed density, and positively correlated with soybean yield. However, the number of plants and hundred seed weight were not always significantly correlated with weed density.

Non-linear regression analysis indicated that dry weight was the most negatively affected by weed density, followed by the number of pods and the number of seeds. To reduce dry weight of soybean by 50%, weed densities were 14, 20, 28, 18, and 48 plants m^{-2} in of *A. artemisiifolia, S. oleraceus*, *C. album*, and *E. crus-galli*, and *B. syzigachne* in 2013, respectively. In 2014, they were 12, 18, 24, 17, and 23 plants m^{-2}. To reduce the number of pods for soybean by 50%, weed densities were 19, 20, 20, 17, and 36 plants m^{-2} in of *A. artemisiifolia, S. oleraceus*, *C. album*, and *E. crus-galli*, and *B. syzigachne* in 2013, respectively. In 2014, they were 21, 22, 40, 18, and 24 plants m^{-2}. To reduce the number of seeds for soybean by 50%, weed densities were 58, 294, 141, 323, and 232 plants m^{-2} in of *A. artemisiifolia, S. oleraceus*, *C. album*, and *E. crus-galli*, and *B. syzigachne* in 2013, respectively. In 2014, they were 98, 87, 123, 169, and 400 plants m^{-2}.

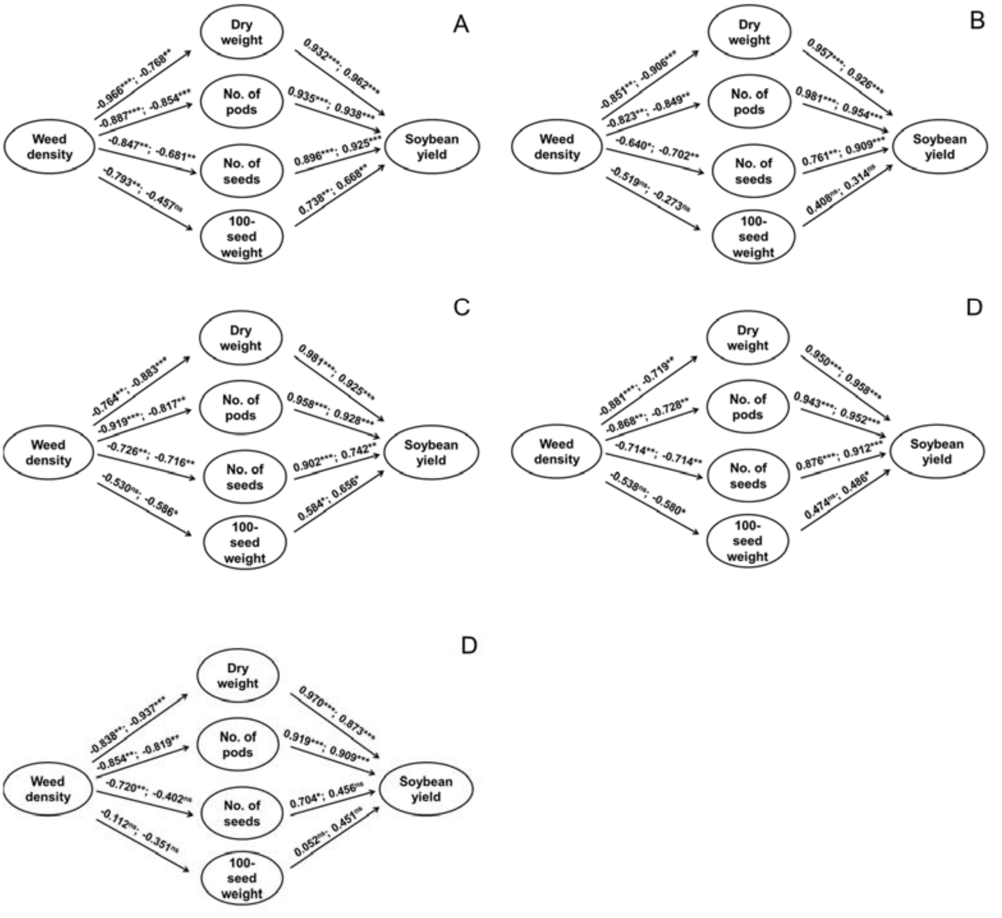


Figure 1-2. Schematic representations of the correlations among plant densities of *Ambrosia artemisiifolia* (A), *Sonchus oleraceus* (B), *Chenopodium album* (C), *Echinochloa crus-galli* (D), and *Beckmannia syzigachne* (E) and yield components (no. of pods, no. of seeds, 100-seed weight, and dry weight), and soybean yield in 2013 and 2014. Significance is indicated as follows, * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$.

Modelling the effect of single weed interference on soybean yield

Soybean yield affected by single weed interferences was fitted to the rectangular hyperbolic model (Figure 1-3 and Table 1-2). Weed-free soybean yield was estimated between 1.71 t and 1.76 t ha^{-1} regardless of weed species. Weed competitivity differed among weed species. Weed competitivities were 0.1116, 0.0739, 0.0497, 0.1770, and 0.0653 in *A. artemisiifolia*, *S. oleraceus*, *C. album*, and *E. crus-galli*, and *B. syzigachne* in 2013, respectively. In 2014, they were 0.1571, 0.0897, 0.0773, 0.1371, and 0.0855. To reduce soybean yield by 50%, weed densities were 9, 15, 14, 20, and 6 plants m^{-2} in *A. artemisiifolia*, *B. syzigachne*, *S. oleraceus*, *C. album*, and *E. crus-galli* in 2013, respectively. In 2014, they were 6, 10, 11, 13, and 7 plants m^{-2}.

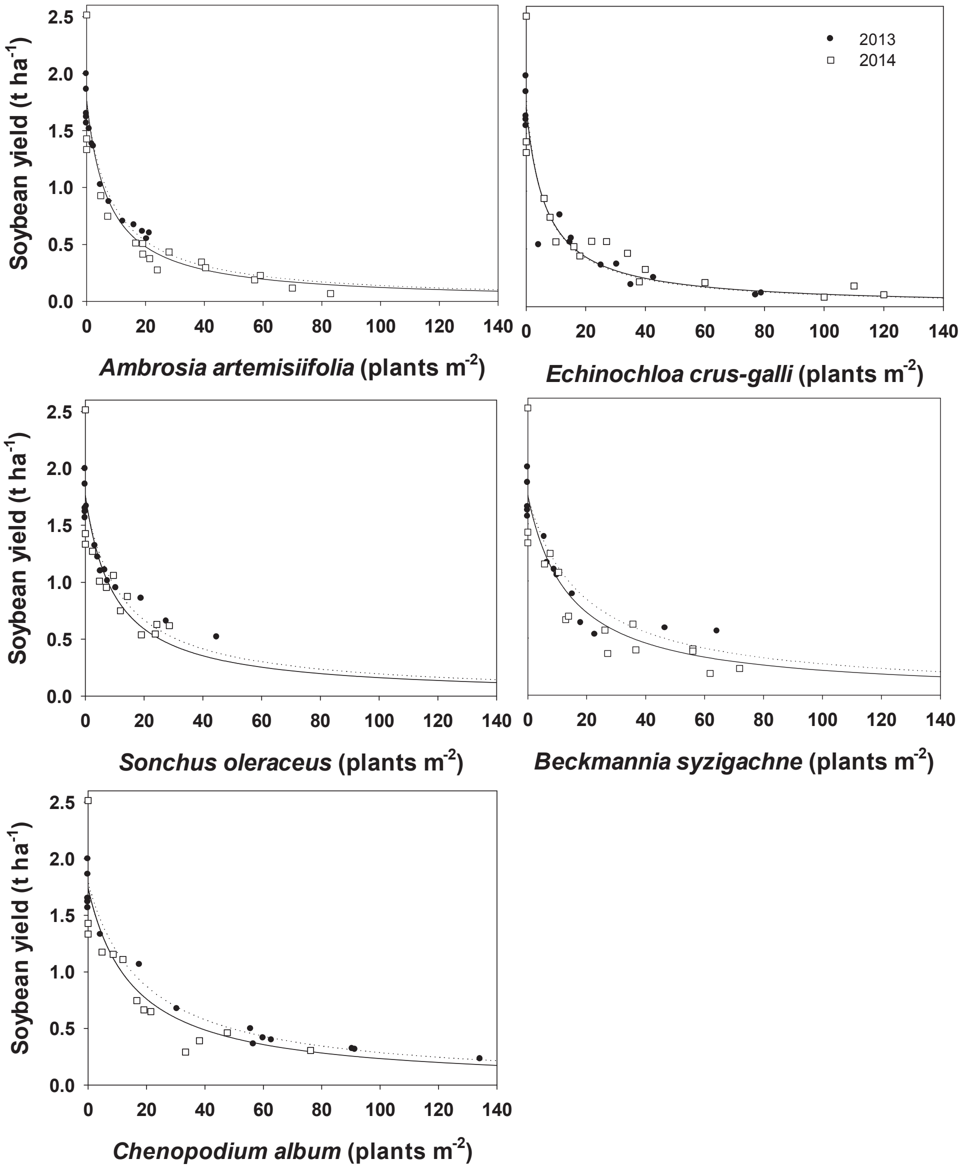


Figure 1-3. Observed and regressed soybean yield as a function of weed density of *Ambrosia artemisiifolia, Beckmannia syzigachne, Chenopodium album, Sonchus oleraceus,* and *Echinochloa crus-galli* in 2013 and 2014. The continuous lines are fitted values calculated using the equation 1.

Table 1-2. Parameter estimates for the regression of soybean seed yield as a result of competition between soybean and single weed including *Ambrosia artemisiifolia, Chenopodium album, Sonchus oleraceus, Echinochloa crus-galli*, and *Beckmannia syzigachne,* in 2013 and 2014.

Weed species	Year	Parameter		d.f.	RMS	R^2
		Y_0	β			
Ambrosia	2013	1.719 (0.0467)	0.1116 (0.0136)	13	0.1148	0.95
artemisiifolia	2014	1.747 (0.141)	0.1571 (0.0415)	15	0.2469	0.85
Sonchus	2013	1.709 (0.0527)	0.0739 (0.0109)	13	0.1312	0.92
oleraceus	2014	1.706 (0.1630)	0.0897 (0.0290)	11	0.3017	0.71
Chenopodium	2013	1.731 (0.0485)	0.0497 (0.0059)	14	0.1123	0.97
album	2014	1.757 (0.166)	0.0773 (0.0240)	11	0.2973	0.79
Echinochloa	2013	1.718 (0.0806)	0.1770 (0.0387)	13	0.1810	0.94
crus-galli	2014	1.744 (0.1470)	0.1371 (0.0364)	15	0.2564	0.84
Beckmannia	2013	1.738 (0.0676)	0.0653 (0.0105)	12	0.1546	0.91
syzigachne	2014	1.764 (0.1540)	0.0855 (0.0229)	14	0.2734	0.81

Modelling multiple weed interference on soybean yield

Rectangular hyperbolic model was used to fit pooled data of soybean yield influenced by single weed interferences in order to remove yearly variation of the parameter estimates for weed-free soybean yield and weed competitivity. The resultes indicated that the weed-free soybean yield was estimated similarly, while the weed competitivity varied among weed species. Weed-free soybean yield was between 1.71 t and 1.75 t ha^{-1}, and weed competitvity was 0.1335, 0.0828, 0.0642, 0.1505, and 0.0760 in *A. artemisiifolia*, *S. oleraceus*, *C. album*, *E. crus-galli*, and *B. syzigachne*, respectively (Figure 1-4 and Table 1-3). *E. cru-galli* was the most competitive of five weed species, and followed by *A. artemisiifolia*, *S. oleraceus*, *B. syzigachne*, and *C. album*.

Multivariate rectangular hyperbolic model was used to model the competitive effects of multiple weed interferences on soybean yield. By using *A. artemisiifolia* as a reference weed species, weed competitivity of individual weed species was converted into density equivalent (Table 1-4). Based on pooled data, the density equivalent of *A. artemisiifolia*, *S. oleraceus*, *C. album*, *E. crus-galli*, and *B. syzigachne* were 1.00, 0.62, 0.48, 1.13, and 0.57, respectively. Under the field conditions where soybean was interfered with multiple weed interferences, soybean yield was regressed with total equivalent density of five weed species, using density equivalent of individual weed species. When observed data in 2013 was fitted by the model, weed-free soybean yield and weed competitivity were 1.7312 t ha^{-1} and 0.1349, respectively. When observed data in 2014 was fitted by the model, weed-free soybean yield and weed competitivity were 1.7001 t ha^{-1} and 0.1709, respectively. The model well described the soybean yield influenced by the multiple weed interferences (Figure 1-5 and Table 1-5), indicating that multivariate rectangular hyperbola model can be used for predicting soybean yield under a practical soybean field.

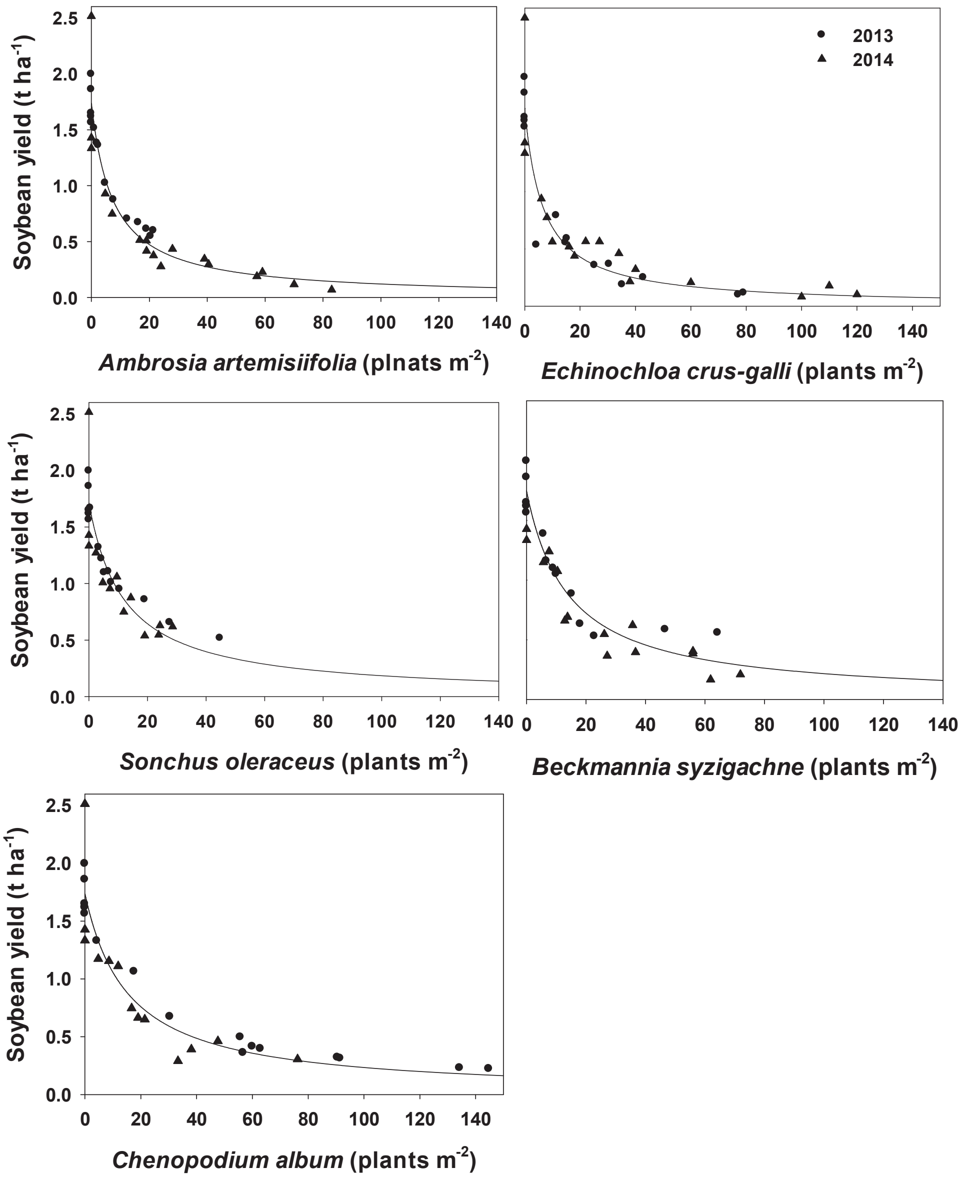


Figure 1-4. Observed and regressed soybean yield as a function of weed density of *Ambrosia artemisiifolia*, *Sonchus oleraceus*, *Chenopodium album*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* in the result of analyses of the pooled 2-year data. The continuous lines are fitted values calculated using equation 1.

Table 1-3. Parameter estimates for the regression of soybean seed yield as a result of competition between soybean and *Ambrosia artemisiifoli*a, *Sonchus oleraceus*, *Chenopodium album*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* in the year of 2013, 2014, and pooled 2-year data.

Weed species	Parameter						R^2		
	Y_0			β					
	2013	2014	Pooled	2013	2014	Pooled	2013	2014	Pooled
Ambrosia artemisiifolia	1.719	1.747	1.737	0.1116	0.1571	0.1335	0.952	0.852	0.907
	(0.0467)	(0.141)	(0.065)	(0.0136)	(0.0415)	(0.0192)			
Sonchus oleraceus	1.710	1.706	1.712	0.0739	0.0897	0.0828	0.918	0.706	0.808
	(0.053)	(0.163)	(0.071)	(0.0109)	(0.0290)	(0.0138)			
Chenopodium album	1.731	1.757	1.736	0.0497	0.0773	0.0642	0.973	0.785	0.886
	(0.049)	(0.166)	(0.074)	(0.0059)	(0.0240)	(0.0105)			
Echinochloa crus-galli	1.718	1.744	1.726	0.1770	0.1371	0.1505	0.936	0.838	0.889
	(0.081)	(0.147)	(0.077)	(0.0387)	(0.0364)	(0.0256)			
Beckmannia syzigachne	1.738	1.764	1.751	0.0653	0.0855	0.0760	0.913	0.811	0.859
	(0.068)	(0.154)	(0.089)	(0.0105)	(0.0229)	(0.0118)			

Table 1-4. Density equivalent of individual weed species in comparison of a reference weed species, *Ambrosia artemisiifolia* based on the year of 2013, 2014, and the pooled 2-year data.

Weed species	Density equivalent		
	2013	2014	pooled
Ambrosia artemisiifolia	1.00	1.00	1.00
Sonchus oleraceus	0.66	0.57	0.62
Chenopodium album	0.45	0..49	0.48
Echinochloa crus-galli	1.59	0.87	1.13
Beckmannia syzigachne	0.59	0.54	0.57

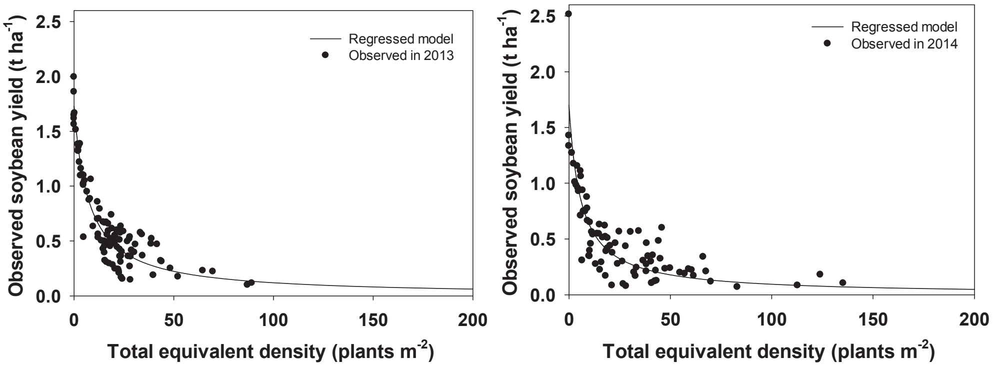


Figure 1-5. Observed and regressed soybean yields as a function of total equivalent density in 2013 and 2014 using multivariate rectangular hyperbolic model. The total equivalent density was calculated using process of multiplying actual weed density in soybean field to density equivalent of single weed species. The continuous lines are fitted values calculated using the equation 5.

Table 1-5. Parameter estimates for the regression of soybean yield as a result of competition between soybean and multiple weed interferences in 2013 and 2014. The numbers in parentheses are standard error.

Observed soybean yield	Parameter estimates		d.f.	RMS	R^2
	Y_0	β			
2013	1.7312 (0.0499)	0.1349 (0.0096)	80	0.1427	0.895
2014	1.7001 (0.0948)	0.1709 (0.0200)	82	0.1860	0.781

Discussion

Model application for the competition between soybean and multiple weed interferences

Previous studies had been conducted to investigate competition between crop and weed under field conditions in which tested weed species were artificially sown with crops. In such field conditions, the modelling of crop-weed competition could be easier to test experimentally, but may not represent practical field situations. Neither weed species in soil emerge uniformly and contemporarily nor the seedling of weed species occur directly in distance adjacent to crops. Oveisi et al. (2013) suggested that crop yield loss model based on artificial weed infestation was not accurate for natural condition. This study showed that rectangular hyperbolic model can well describe soybean yield caused by densities of single weed species and their weed combinations which were naturally established in soybean field. In particular, multivariate rectangular hyperbolic model can be useful for predicting soybean yield under natural field conditions. The model is originally derived from Kim et al.'s model (2006), which omitted the interaction of multiple weed species, thus making it simpler. Although the interaction parameter is required to well describe crop yield loss at high densities of multiple weed species, it may be rather impractical to cover multiple weed interferences under field conditions. This study showed that variability between observed and regressed yields was least noticeable in high densities of multiple weed species. It means that the interaction parameter of multiple weed species was not required in this study.

Therefore, this study would be a practical case study to validate Kim et al.'s model (2006).

Estimation of economic thresholds

The model tested here can be used to determine the economic thresholds for weed interferences in soybean production in Primorsky-krai, Russia. According to many studies (Marra MC & Carlson GA, 1983; Cousens, 1987; Zanin et al, 1993), economic thresholds of weed species can be predicted by comparing the cost of controlling weed species with the benefit gained by herbicide application. Economic threshold (ET) of weed species is calculated as follows,

$$\mathrm{ET} = \frac{C_h + C_a}{Y_0 P \beta H}$$

Where C_h is herbicide cost (US\$ ha^{-1}), C_a is application cost (US\$ ha^{-1}), Y_0 is weed-free crop yield (t ha^{-1}), P is value per unit of crop (US\$ t^{-1}), ß is weed competitivity, a proportional loss per unit weed density, and H is herbicide efficacy calculated as efficacy (%)/100, a proportional weed reduction by the herbicide treatment. Under multiple weed interferences in a natural field condition, the estimated parameters of the model tested in this study may determine the economic thresholds for herbicide use. If Y_0 were 1.7312 t ha^{-1}, P were 560 US\$ t^{-1}, H were 0.90, ß were 0.1349, and C_h and C_a were 65.3 US\$ ha^{-1} and 6.0 US\$ ha^{-1} in 2013, respectively, the economic thresholds of 0.61 plants m^{-2} would be expected. If P, H, C_h, and C_a were still same as those in 2013 and Y_0 and ß were 1.7001 t ha^{-1} and 0.1709 in 2014, respectively, the economic thresholds of 0.49 plants m^{-2} would be expected. Therefore, using the actual or estimated data for weed management, the economic threshold concept can support decision-making for herbicide use in soybean production.

Further studies

This study showed that estimated weed-free soybean yield did not differ significantly between years at the field of Bogatyka although the observed value in 2014 showed a larger variation than in 2013. Actually, the variation of weed-free soybean yield may depend on weather conditions. Many studies (Coble et al, 1981; Baysinger & Sims, 1991; Webster et al, 1994; Cowbrough et al, 2003) reported that a variation in yearly precipitation was attributed to difference in growth and development of soybean during the whole growing season. In this study, estimated weed competitivity of single weed species did not vary significantly between years within the same area. In other studies (Fellows et al, 1992; Dieleman et al, 1995; Bensch et al, 2003), weed competitivities were not significantly different within the given weed species across years in soybean. In addition, the estimate in weed competitivity may not be affected by the spatial distribution of weeds within an area. According to Cowbrough et al (2003), weed competitivities were considerably similar in aggregated and uniformed distributions. However, under different environment conditions, both weed-free soybean yield and weed competitivity may be changed. In a study of Moon et al (2010), the two parameter estimates of Kim et al.'s model showed much larger regional variation due to site-specific factors in crop-weed competition. Although the model described the competition effect of multiple weed interferences on soybean yield under same field conditions in this study, further studies should be conducted to validate the two parameters in other regions. Such further works can support decision-making more effectively for herbicide use in soybean cultivation across Primorsky-krai, Russia.

References

Baysinger JA and Sims BD. 1991. Giant ragweed (*Ambrosia trifida*) interference in soybeans (*Glycine max*). Weed Science 39(3): 358-362.

Bensch CN, Horak MJ, and Peterson. 2003. Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranthus (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Science 51:37-43.

Berti A and Zanin G. 1994. Density equivalent: a method for forcasting yield loss caused by mixed weed populations. Weed Research 34: 327-332.

Coble HD, Williams FM, and Ritter RL. 1981. Common ragweed (*Ambrosia artemisiifolia*) interference in soybean (*Glycine max*). Weed Science 29(3): 339-342.

Cousens R. 1985. A simple model relating yield loss to weed density. Annals of Applied Biology 107(2): 239-252.

Cousens R. 1987. Theory and reality of weed control thresholds. Plant Protect. Q. 2: 13-20.

Cowan P, Weaver SE, and Swanton CJ. 1998. Interference between pigweed (*Amaranthus* spp.), barnyardgrass (*Echinochloa crus-galli*), and soybean (*Glycine max*). Weed Science 46: 533-539.

Cowbrough MJ, Brown RB, and Tardif FJ. 2003. Impact of common ragweed (*Ambrosia artemisiifolia*) aggregation on economic thresholds in soybean. Weed Science 51(6): 947-954.

Crook TM and Renner KA. 1990. Common lambsquarters (*Chenopodium album*) competition and time of removal in soybeans (*Glycine max*). Weed Science 38: 358-364.

Dieleman A, Hamill AS, Weise SF, and Swanton CJ. 1995. Empirical models of pigweed (*Amaranthus* spp.) interference in soybean (*Glycine max*). Weed Science 43(4): 612-618.

Fellows GM and Roeth FW. 1992. Shattercane (*Sorghum bicolor*) interference in soybean (Glycine max). Weed Science 40(1): 68-73.

Genstat Committee. 2002. Reference Manual (Genstat Release 6.1). VSN International, Oxford, UK.

Kim DS, Marshall EJP, Brain P, and Caseley JC. 2006. Modeling interactions between herbicide dose and multiple weed species interference in crop-weed competition. Weed Research 46: 175-184.

Marra MC and Carlson GA. 1983. An economic threshold model for weeds in soybeans (*Glycine max*). Weed Science 31(5): 604-609.

Moon, BC, Cho SH, Kwon OD, Lee SG, Lee BW, and Kim DS. 2010. Modelling rice competition with *Echinochloa crus-galli* and *Eleocharis kuroguwai* in transplanted rice cultivation. Journal of Crop Science and Biotechnology 13(2): 121-126.

Oveisi M, Mashhadi HR, Yousefi AR, Alizade H, Baghestani MA, and Gonzalez-Andujar JL. 2013. Predicting maize yield in a multiple species competition with *Xanthium strumarium* and *Amaranthus retroflexus*: Comparing of approaches to modeling herbicide performance. Crop Protection 45: 15-21.

Song JS, Jung JH, Kwon JH, Lim SH, and Kim DS. 2013. Weed survey in soybean fields of Seoul Feed Farm in Primorsky-krai, Russia.

Proceedings of the Korean Society of Weed Science 33(1): 147-148 (In Korean).

Swinton SM, Buhler DD, Forcella F, Gunsolus JL, and King RP. 1994. Estimation of crop yield loss due to interference by multiple weed speices. Weed Science 42: 103-109.

Vail GD and Oliver LR. 1993. Barnyardgrass (*Echinochloa crus-galli*) interference in soybeans (*Glycine max*). Weed Technology 7(1): 220-225.

Weaver SE. 2001. Impact of lamb's-quarters, common ragweed and green foxtail on yield of corn and soybean in Ontario. Canadian Journal of Plant Science 81(4): 821-828.

Webster TM, Loux MM, Regnier EE, and Harrison SK. 1994. Giant ragweed (*Ambrosia trifida*) canopy architecture and interference studies in soybean (*Glycine max*). Weed Technology 8(3): 559-564.

Yousefi AR, Gonzalez-Andujar JL, Alizadeh H, Baghestani MA, Rahimian Mashhadi H, and Karimmojeni. 2012. Interactions between reduced rate of imazethapyr and multiple weed species-soybean interference in a semi-arid environment. Weed Research 11: 174-182.

Zanin G, Berti A, and Toniolo L. 1993. Estimation of economic thresholds for weed control in winter wheat. Weed Research 33: 459-467.

CHAPTER II. Modelling the effect of N fertilizer on soybean-weed competition

ABSTACT

The effect of N fertilizer on soybean-weed competition was investigated to predict soybean yield as influenced by weed interference in a soybean field located in Bogatyrka (N43°49', E131°36'), Primorsky-krai, Russia. Rectangular hyperbolic model fitted soybean yield as a function of total equivalent density of multiple weed species including *Ambrosia artemisiifolia*, *Beckmannia syzigachne*, and *Echinochloa crus-galli* at different levels of nitrogen fertilizer (0, 12, 24, 36, 72 kg ha^{-1}). The weed-free soybean (Y_o) increased with increasing N fertilizer from 0 to 36 kg ha^{-1}, but decreased at 72 kg ha^{-1}, indicating that the inverse quadratic model could well describe the relationship between Y_o and nitrogen level. The weed competitivity (β) also responded to nitrogen level in the inverse quadratic function. Therefore, a combined model was developed by incorporating two inverse quadratic models for parameters Y_o and β in the rectangular hyperbolic model. The combined rectangular hyperbolic model well described soybean yield influenced by weed competition and nitrogen level. The model can support the decision-making for herbicide use under different nitrogen use scheme in soybean cultivation in Primorski-Krai, Russia.

Keywords: crop-weed competition, modeling, nitrogen fertilizer, inverse quadratic model, soybean, multiple weeds

Introduction

Nitrogen fertilizer plays an important role in agriculture. The application of nitrogen fertilizer improves crop productivity. However, weeds can exploit the nitrogen which is applied for crops when they were not adequately controlled. Although crop productivity positively responds to nitrogen fertilizer, the nitrogen effect on growth and yield of crops could be offset by the weeds outcompeting crops for the nitrogen. Many studies reported that the crop yield loss increased as weeds favored the nitrogen over the crops (Buchanan and Mclaughlin, 1975; Wells, 1979; Ampong-Nyarko and Datta, 1992; Dhima and Eleftherohorinos, 2001; Naderi and Ghadiri, 2011).

Soybean depends on nitrogen fertilizer less than other crops. Soybean can use the nitrogen by biologically fixing nitrogen gas in the air. The nitrogen fixation is helpful for soybean, but in practice is not enough to attain the maximum soybean yield. On an average, 40-50% of soybean N demand was not met by biological nitrogen fixation (Salvagiotti et al., 2008). Thus, nitrogen fertilizer is needed for improving soybean productivity. The nitrogen fertilizer might also increase weed biomass and allow soybean yield to decrease severely by the weed.

In far-eastern regions of Russia, soybean has been intensively cultivated during 4 months from May until late September. Due to the short growing season, nitrogen fertilizer was essentially used to grow enough to secure soybean yield. However, soybean yield loss was severely caused by weed interferences of dominant weed species although nitrogen fertilizer increased soybean yield. Additionally, few study has been reported for nitrogen effect on competition between soybean and weed until Shafagh-Kolvanagh et al (2008). Such a study is needed to establish the strategies for the nitrogen application and weed management in the situation where soybean fields are heavily infested with weeds. This study was thus conducted to investigate the effect of nitrogen fertilizer on soybean-weed competition, and predict yield loss effect using an empirical model, which can be utilized to aid decision-support for weed management in a practical field condition where multiple weed species establish and compete with soybean.

Materials and methods

Field experiment

Field experiments were conducted in 2013 and 2014 to evaluate the effect of nitrogen fertilizer on soybean-weed competition in soybean field located in Bogatyrka of Primorsky-Krai in Russia. The soil in the field was the typical Mollisol (Black soil); a soil texture of silty loam with CEC of 22.62 cmol kg^{-1}, organic matter of 29.59 g kg^{-1}, total N of 1.58 g kg^{-1}, inorganic NH^{4+}-N of 0.85 mg kg^{-1}, inorganic NO^{3-}-N of 14.01 mg kg^{-1}, available P of 18.19 mg kg^{-1}, and pH of 6.61. P-K basal fertilizer was yearly applied at a rate of 31-31 kg ha^{-1} before nitrogen application. Nitrogen fertilizer was applied in the form of urea ($CO(NH_2)_2$) at 0, 12, 18, 24, and 36 kg N ha^{-1} and 0, 12, 24, 36, and 72 kg N ha^{-1} on 27 May, 2013 and May 22, 2014, respectively. In each main plot of nitrogen fertilization, the sub-plots were laid-out in complete randomized design. The main plot size was 56 m x 100 m with a 2.0 m buffer zone between them, while the sub-plot size was 2.1 m × 1 m in which three soybean rows were included.

Soybean (cv. Heinong 48) was drilled at 80 kg ha^{-1} with a row width of 70 cm on May 27, 2013 and May 22, 2014. Weed seedlings which had been established naturally in the field were artificially thinned to achieve at target weed densities of three single weed species and their different weed density combinations by late June in 2013 and 2014 (Appendix 2-1). The maximum densities of three single weed species were 49, 71, and 91 (plants sub-$plot^{-1}$) with 17, 13, and 13 (sub-plots) for *Ambrosia artemisiifolia*, *Beckmannia* *syzigachne*, and *Echinochloa crus-galli* in 2013, respectively. In 2014, they were 49, 110, and 139 (plants sub-plot^{-1}) with 17, 18, and 16 (sub-plots), respectively. Density combinations of three weed species were 45 and 35 (sub-plots) in 2013 and 2014, respectively. Background weed species were removed by handing-weeding.

The plots for soybean-weed competition were maintained throughout the whole growing season. Soybean was harvested from the area of 2.1 m^2 in each sub-plot by hand at maturity in October.

Model development

A rectangular hyperbolic model can be used to describe the relationship between crop yield (Y) and initial single weed density (X) (Cousens, 1985) and between crop yield and initial weed densities of more than two weed species (Kim et al., 2006a). The model equations (Equation 1) were used as follows,

$$Y = \frac{Y_0}{1+\beta X} \quad (1\text{-}1)$$

or

$$Y = \frac{Y_0}{1+\beta_1(X_1+\frac{\beta_2}{\beta_1}X_2+\frac{\beta_3}{\beta_1}X_3)} \quad (1\text{-}2)$$

Where Y_0 is weed-free soybean yield (t ha^{-1}) and β is a measure of weed competitivity (β_1, β_2, and β_3 are the competitivities of the three weed species; 1 is a reference weed species).

In Equation 1-2, $X_1 + \frac{\beta_2}{\beta_1} X_2 + \frac{\beta_3}{\beta_1} X_3$ is total equivalent density, which causes soybean yield loss equivalent to that caused by a reference weed species 1. The total equivalent density is the sum of the relative density of individual weed species that was calculated by multiplying actual density of the weed species with its relative competitivity to a reference weed species (Berti and Zanin, 1994).

Soybean yield may be changed when nitrogen fertilizer is applied to the field where weed species are interfered alone or in mixture. Initially, the relationship among soybean yield, weed competitivity, and nitrogen is a little unknown, so is necessary to be parameterized separately at each nitrogen level (*i*) as follows,

$$Y = \frac{Y_{0i}}{1+\beta_i X} \quad (2\text{-}1)$$

or

$$Y = \frac{Y_{0i}}{1+\beta_{1i}(X_1+\frac{\beta_{2i}}{\beta_{1i}}X_2+\frac{\beta_{3i}}{\beta_{1i}}X_3)} \quad (2\text{-}2)$$

The parameter Y_{0i} at different nitrogen levels was further investigated based on increasing nitrogen level (*i*). Weed-free soybean yield (Y_{0i}) may be changed with increasing nitrogen level as inverse quadratic curve. The inverse quadratic curve has been used to describe fertilizer response to the decrease in yield at high nitrogen level (e.g. Thornley, 1978). Thus, the relationship between weed-free soybean yield (Y_{0i}) and applied nitrogen can be described using the inverse quadratic model given as follows,

$$Y_{0i} = \frac{a+bN}{1+cN+dN^2} \quad (3)$$

The parameter (β) may be changed with increasing nitrogen level as inverse quadratic curve. It was unknown how the parameter change with increasing nitrogen in soybean field, so a further work was done for better empirical description.

$$\beta_i = \frac{l+mN}{1+nN+rN^2} \quad (4)$$

Statistical analyses

All measurements were initially subjected to analysis of variance (ANOVA) with the third-order interaction as an estimate of variability as the experiment was not replicated. Non-linear regression analysis was adopted to fit two parameters, Y_0 and β of rectangular hyperbolic model at different nitrogen levels by using inverse quadratic model. The performance of models was evaluated by coefficients of determination of models (R^2) and the root mean square error in prediction (RMS). By incorporating the models selected for two parameters into the rectangular hyperbolic model, the new combined model was evaluated using lack of fit test as follows,

$$F = \frac{\frac{RSS_{i+1} - RSS_i}{df_{i+1} - df_i}}{\frac{RSS_f}{df_f}} \quad (5)$$

Where RSS and df are the residual sum of square and the degree of freedom, respectively, $i + 1$ is the one step further reduced model from its predecessor (i) and f is the full model. If the *F*-value was lower than the tabulated *F*-value (5% level) with (df_{i+1}-df_i, df_f) degrees of freedom, the reduced model could be accepted. All the statistical analyses were conducted using Genstat (Genstat Committee, 2002).

Results

The effect of nitrogen on soybean-weed competition under single weed interferences

The rectangular hyperbolic model was used to model the competition effect of single weed species such as *A. artemisiifolia*, *E. crus-galli*, and *B. syzigachne* on soybean yield at different levels of nitrogen fertilizers. Regardless of weed species, the response of soybean yield to single weed interferences was well described by the rectangular hyperbolic model, so well fitted to the model (Table 2-1). The soybean yield was hyperbolically reduced by increasing plant density of each weed species, and the weed competition effect varied among weed species. Nitrogen application improved soybean yield grown at no weed interference, and additionally increased plant biomass of each weed species with increasing nitrogen level up to 36 kg N ha^{-1}.

Weed-free soybean yield increased with increasing nitrogen level up to 36 kg N ha^{-1}, but it was reduced at 72 kg N ha^{-1}. Within a given nitrogen level, weed-free soybean yield was not significantly different among weed species. With nitrogen fertilizer of 36 kg N ha^{-1}, the weed-free soybean yield (Y_o) increased from around 1.6 t and 1.4 t ha^{-1} to 2.4 t and 2.2 t ha^{-1} in 2013 and 2014, respectively (Table 2-1). However, at 72 kg N ha^{-1} tested only in 2014, weed-free soybean yield was reduced to 0.8 t ha^{-1}.

Single interference of three weed species, *A. artemisiifolia*, *E. crus-galli*, and *B. syzigachne*, caused soybean growth reduction, resulting in significant yield reduction. Nitrogen application also affected soybean-weed competition, so the weed competitivity of each weed species was influenced by nitrogen application. *A. artemisiifolia* showed its weed competitivity of ten-fold and eight-fold increase in 2013 and 2014, as nitrogen fertilizer increased from 0 to 36 N ha^{-1}, respectively, while its weed competitivity decreased to 0.344 at 72 kg N ha^{-1} in 2014. *E. crus-galli* increased its weed competitivity seven and three times more in 2013 and 2014 at 36 N ha^{-1} than in untreated plot, respectively, while its weed competitivity was reduced to 0.121 N ha^{-1} at 72 kg N ha^{-1}. Weed competitivity in *B. syzigachne* increased around two times or less up to 36 kg N ha^{-1}, but decreased to 0.015 at 72 kg N ha^{-1}. The response of weed competitivity to increasing nitrogen level was the most sensitive in *A. artemisiifolia*, followed by *E. crus-galli* and *B. syzigachne* (Table 2-1).

Table 2-1. Parameter estimates for the prediction of soybean yields as a result of competition with *A. artemisiifolia*, *B. syzigachne*, and *E. crus-galli* at different nitrogen levels in 2013 and 2014. The numbers in parentheses are standard error (df = 7~16).

Weed species	Nitrogen (kg N ha^{-1})	Parameter estimates					
		Y_0		β		R^2	
		2013	2014	2013	2014	2013	2014
Ambrosia artemisiifolia	0	1.620 (0.095)	1.443 (0.086)	0.0529 (0.0104)	0.0853 (0.0132)	0.861	0.918
	12	1.732 (0.122)	1.816 (0.138)	0.1303 (0.0324)	0.1181 (0.0249)	0.864	0.843
	18	1.828 (0.061)		0.2205 (0.0266)		0.970	
	24	2.100 (0.104)	1.969 (0.048)	0.2324 (0.0396)	0.2208 (0.0175)	0.952	0.984
	36	2.392 (0.097)	2.169 (0.058)	0.5457 (0.0839)	0.5940 (0.1040)	0.980	0.987
	72		0.8321 (0.079)		0.3440 (0.1070)		0.796
Echinochloa crus-galli	0	1.523 (0.169)	1.397 (0.058)	0.0664 (0.0259)	0.0864 (0.0114)	0.847	0.972
	12	1.742 (0.085)	1.823 (0.163)	0.1358 (0.0353)	0.1485 (0.0582)	0.966	0.865
	18	1.813 (0.064)		0.2392 (0.0297)		0.970	
	24	2.076 (0.170)	1.969 (0.041)	0.4130 (0.1170)	0.3079 (0.0477)	0.861	0.993
	36	2.407 (0.184)	2.160 (0.105)	0.4380 (0.1010)	0.2918 (0.0568)	0.912	0.947
	72		0.8336 (0.099)		0.1213 (0.0497)		0.706
Beckmannia syzigachne	0	1.641 (0.101)	1.401 (0.079)	0.0477 (0.0122)	0.0631 (0.0089)	0.805	0.921
	12	1.728 (0.107)	1.826 (0.157)	0.0406 (0.0079)	0.0894 (0.0251)	0.895	0.818
	18	1.836 (0.086)		0.0449 (0.0065)		0.915	
	24	2.187 (0.141)	1.969 (0.073)	0.0829 (0.0205)	0.0934 (0.0106)	0.884	0.958
	36	2.415 (0.157)	2.171 (0.074)	0.1131 (0.0218)	0.0932 (0.0095)	0.931	0.968
	72		0.8156 (0.059)		0.0148 (0.0041)		0.641

The effect of nitrogen on soybean-weed competition under multiple weed interferences

The multivariate rectangular hyperbolic model was used for describing the relationship between soybean yield and multiple weed interferences at different levels of nitrogen fertilizers. The model was developed based on density equivalent of individual weed species in comparison with a reference weed species, *A. artemisiifolia* (Table 2-2). The response of soybean yield to multiple weed interferences was well described by the model at all levels of nitrogen. The soybean yield hyperbolically decreased with increasing total equivalent density, and the shape of which was affected by the level of nitrogen. Weed-free soybean yield increased from 1.7 to 2.4 t ha^{-1}, while weed competitivity increased from 0.071 to 0.486 with increasing nitrogen level up to 36 kg N ha^{-1} in 2013. Under the same field condition conducted in 2014, weed-free soybean yield increased from 1.4 to 2.1 t ha^{-1}, while weed competitivity increased from 0.119 to 0.476 with increasing nitrogen level up to 36 kg N ha^{-1}. Additionally, with 72 kg N ha^{-1} of nitrogen, weed-free soybean yield of 0.8 t ha^{-1} and weed competitivity of 0.202 were estimated. Nitrogen application at 36 kg N ha^{-1} has the greatest impact on weed-free soybean yield and weed competitivity over two years.

Table 2-2. Density equivalent of individual weed species in comparison with a reference weed species, *Ambrosia artemisiifolia*, at different nitrogen levels in 2013 and 2014.

Year	Weed species	Density equivalent					
		0 N	12 N	18 N	24 N	36 N	72 N
2013	*Ambrosia artemisiifolia*	1.00	1.00	1.00	1.00	1.00	-
	Echinochloa crus-galli	1.26	1.04	1.09	1.78	0.80	-
	Beckmannia syzigachne	0.90	0.31	0.20	0.36	0.21	-
2014	*Ambrosia artemisiifolia*	1.00	1.00	-	1.00	1.00	1.00
	Echinochloa crus-galli	1.01	1.26	-	1.39	0.49	0.35
	Beckmannia syzigachne	0.74	0.76	-	0.42	0.16	0.04

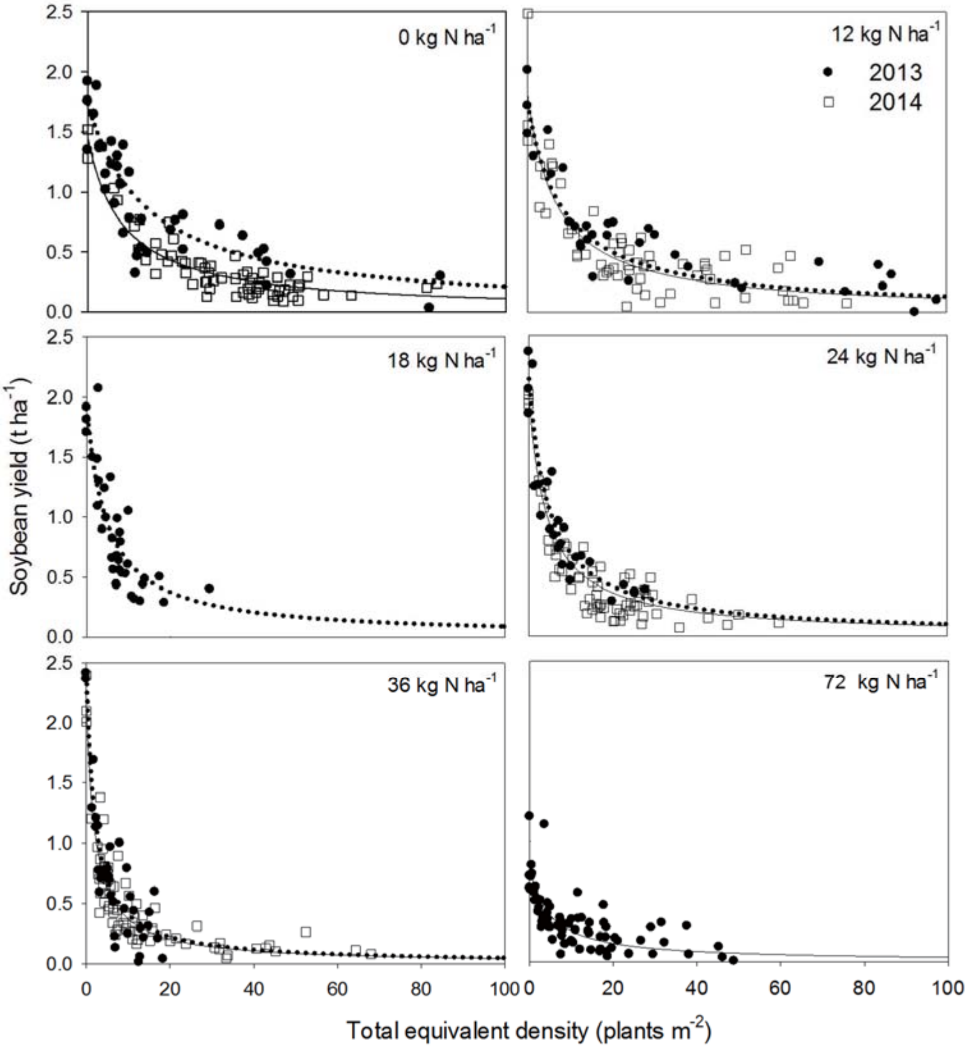


Figure 2-1. Observed and regressed soybean yield as a function of total equivalent density of multiple weeds including *Ambrosia artemisiifolia*, *Beckmannia syzigachne*, and *Echinochloa crus-galli* in 2013 and 2014. The predicted soybean yield (continuous line) was calculated using rectangular hyperbolic model.

Table 2-3. Parameter estimates for the regression of soybean seed yields as a result of competition between soybean and multiple weeds consisting of *Ambrosia artemisiifolia*, *Beckmannia syzigachne*, and *Echinochloa crus-galli* in 2013 and 2014.

Year	Nitrogen ($kg\ N\ ha^{-1}$)	Parameter		R^2
		Y_0	β	
2013	0	1.736 (0.122)	0.0713 (0.0138)	0.761
	12	1.734 (0.087)	0.1208 (0.0153)	0.886
	18	1.910 (0.134)	0.2058 (0.0344)	0.753
	24	2.108 (0.102)	0.2147 (0.0276)	0.906
	36	2.402 (0.153)	0.4861 (0.0647)	0.851
2014	0	1.448 (0.072)	0.1187 (0.0106)	0.853
	12	1.800 (0.106)	0.1441 (0.0184)	0.803
	24	1.993 (0.073)	0.2756 (0.0208)	0.908
	36	2.137 (0.096)	0.4757 (0.0422)	0.865
	72	0.760 (0.056)	0.2018 (0.0377)	0.598

Relationship between weed-free soybean yield and nitrogen

The relationship between weed-free soybean yield and nitrogen level was plotted using inverse quadratic model. The response of weed-free soybean yield to nitrogen level was well described by inverse quadratic model (Figure 2-2 and 2-3). Regression analysis showed that the inverse quadratic model fitted it with a small residual mean square value (Table 2-2 and 2-3). Weed-free soybean yield was estimated to reach 2.4 t and 2.2 ha^{-1} at 36 kg N ha^{-1} in 2013 and 2014, while 0.8 t ha^{-1} of weed-free soybean yield was estimated at 72 N kg ha^{-1} tested only in 2014.

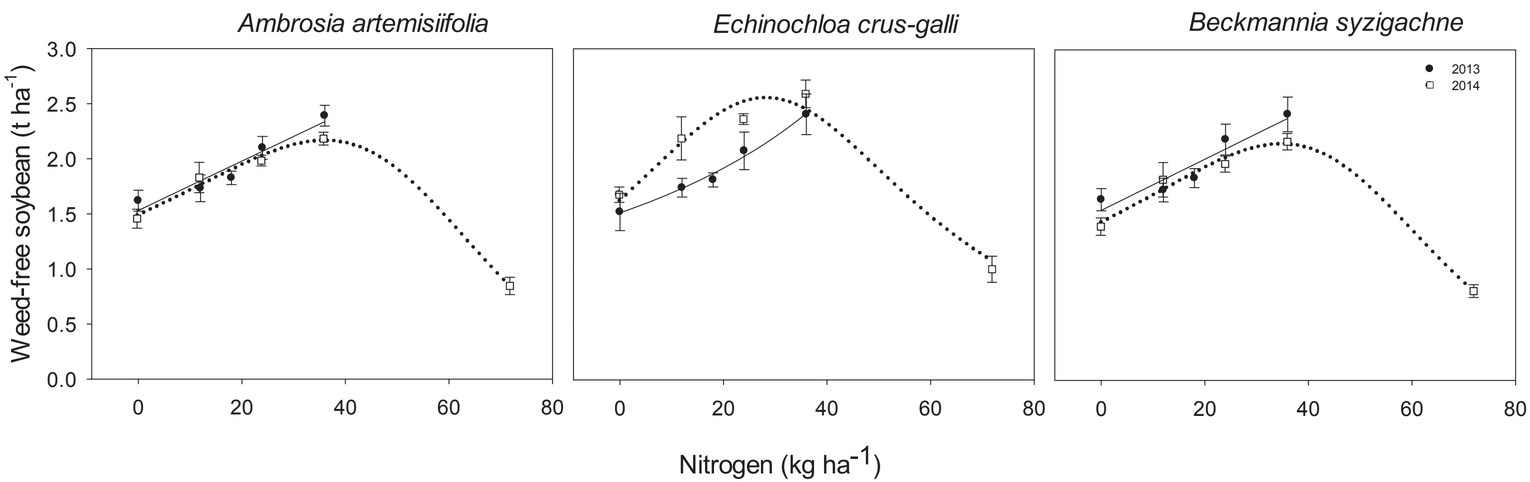


Figure 2-2. Weed-free soybean (Y_o) as affected by nitrogen fertilizer at no single weed interference with *Ambrosia artemisiifolia*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* in 2013 (■) and 2014 (□). The continuous lines are fitted values calculated using the equation (Eqn 3) and parameter estimates in Table 2-1. The vertical bars are the standard errors of Y_o in Table 2-1.

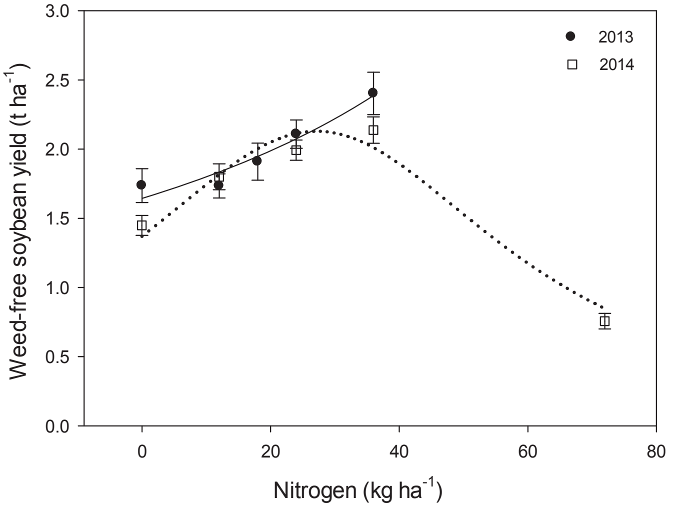


Figure 2-3. Weed-free soybean yield as affected by nitrogen fertilizer at no multiple weed interferences in 2013 (■) and 2014 (□). The continuous lines are fitted values calculated using the equation (Eqn 3) and parameter estimates in Table 2-3. The vertical bars are the standard errors of the estimates of Y_o in Table 2-3.

Table 2-4. Parameter estimates for inverse quadratic model to describe weed-free soybean yield at no single weed interference such as *Ambrosia artemisiifolia*, *Beckmannia syzigachne*, and *Echinochloa crus-galli* in 2013 and 2014. The data of soybean yield used to fit the inverse quadratic model was the parameter estimates in Table 2-1. The numbers in parenthesis are standard errors.

Weed species	Year	Parameter estimates				RMS	R^2
		a	b	c	d		
Ambrosia artemisiifolia	2013	1.5318 (0.1664)	0.0224 (0.6538)	1.35×10^{-17} (0.3943)	2.73×10^{-20} (0.0032)	0.0278	0.9284
	2014	1.4773 (0.0844)	-0.0147 (0.0053)	-0.0242 (0.0020)	0.0002 (0.0001)	0.0083	0.9925
Beckmannia syzigachne	2013	1.5442 (0.2067)	0.0232 (0.7805)	9.98×10^{-18} (0.4654)	3.70×10^{-20} (0.004)	0.0428	0.9003
	2014	1.4446 (0.1063)	-0.0133 (0.0067)	-0.0250 (0.0026)	0.0003 (0.0001)	0.0132	0.9886
Echinochloa crus-galli	2013	1.5145 (0.0778)	2.61×10^{-18} (1.8319)	-0.0108 (1.1983)	1.22×10^{-5} (0.0122)	0.0061	0.9868
	2014	1.3552 (0.0186)	3.34×10^{-19} (0.0183)	-0.0257 (0.0054)	0.0005 (0.0003)	0.0387	0.9655

Table 2-5. Parameter estimates for inverse quadratic model to describe weed-free soybean yield at no multiple weed interference in 2013 and 2014. The data of soybean yield used to fit the inverse quadratic model was the parameter estimates in Table 2-3. The numbers in parenthesis are standard errors.

Year	Parameter estimates				R^2
	a	b	c	d	
2013	1.6443 (0.1452)	$2.49\text{x}10^{-18}$ (0.0049)	-	-	0.9335
2014	1.3691 (0.2017)	$2.73\text{x}10^{-20}$ (0.0194)	-0.0263 (0.0061)	0.0005 (0.0003)	0.9626

Relationship between weed competitivity and nitrogen

The relationship between weed competitivity and nitrogen level was plotted using inverse quadratic model. The response of weed competitivity to nitrogen level was well described by inverse quadratic model (Figure 2-4 and 2-5). Regression analysis showed that inverse quadratic model fitted the response of weed competitivity to nitrogen level with a small residual mean square value (Table 2-6 and 2-7). With the plots interfered with *A. artemisiifolia* alone, weed competitivity reached 0.554 at 36 kg N ha^{-1} in 2013, while that reached 0.429 at 53 kg N ha^{-1} in 2014. With the plots interfered with *E. crus-galli* alone, weed competitivity reached 0.113 at 36 kg N ha^{-1} in 2013, while that reached 0.101 at 24 kg N ha^{-1} in 2014. With the plots interfered with *B. syzigachne* alone, weed competitivity reached 0.562 and 0.316 at 30 kg N ha^{-1} in 2013 and 2014, respectively. With the plots interfered with multiple weed interferences (Figure 2-1), weed competitivity reached 0.484 at 36 kg N ha^{-1} in 2013, while that reached 0.449 at 40 kg N ha^{-1} in 2014.

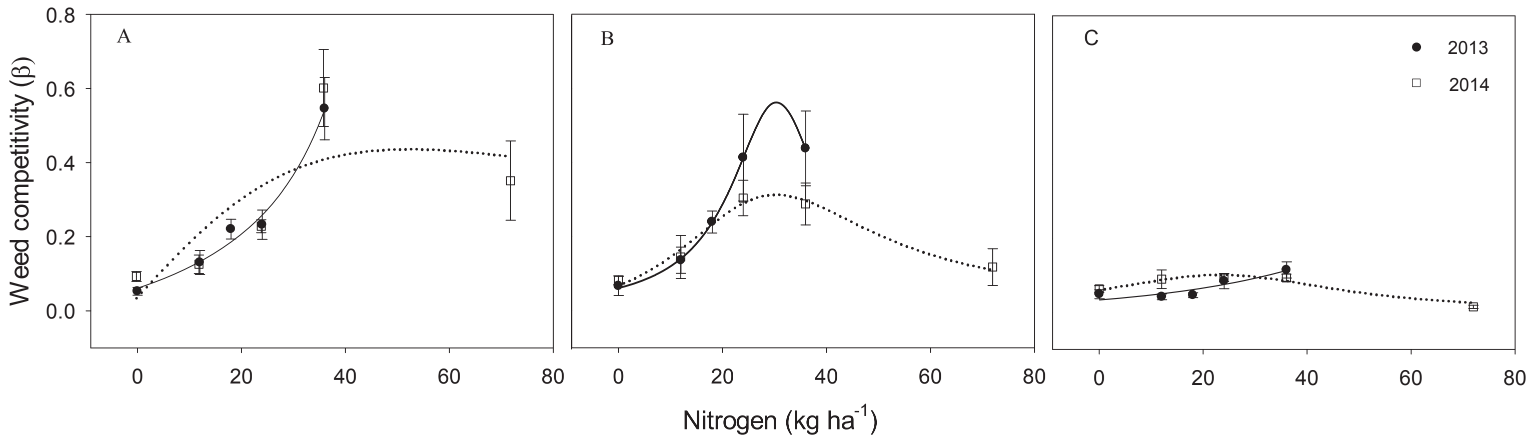


Figure 2-4. Weed competitivity in *Ambrosia artemisiifolia* (A), *Echinochloa crus-galli* (B), and *Beckmannia syzigachne* (C) as affected by nitrogen fertilizer in 2013 (■) and 2014 (□). The continuous lines are fitted values calculated using the equation (Eqn 4) and parameter estimates in Table 2-1. The vertical bars are the standard errors of Y_o in Table 2-1.

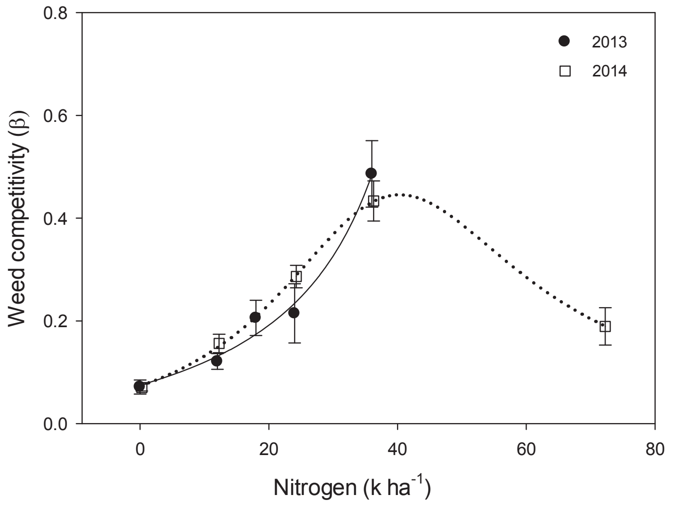


Figure 2-5. Weed competitivity in multiple weeds interferences as affected by nitrogen fertilizer in 2013 (■) and 2014 (□). The continuous lines are fitted values calculated using the equation (Eqn 4) and parameter estimates in Table 2-3. The vertical bars are the standard errors of Y_o in Table 2-3.

Table 2-6. Parameter estimates for inverse quadratic function tested to describe the relationship between weed competitivity and nitrogen in *Ambrosia artemisiifolia*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* in 2013 and 2014. The values in parenthesis are standard errors.

Weed species	Year	Parameter estimates for weed competitivity				RMS	R^2
		l	m	n	r		
Ambrosia	2013	0.0613 (0.0445)	0.0035 (0.0156)	-0.0181 (0.1209)	3.86×10^{-20} (0.0026)	0.0020	0.9858
artemisiifolia	2014	0.0264 (0.2503)	0.0153 (0.0563)	4.61×10^{-20} (0.1623)	0.0003 (0.0009)	0.0635	0.6267
Echinochloa	2013	0.0610 (0.0064)	1.83×10^{-30} (0.0005)	-0.0587 (0.0008)	0.0010 (0.00002)	0.00005	0.9995
crus-galli	2014	0.0710 (0.0278)	0.0026 (0.0023)	-0.0430 (0.0069)	0.0008 (0.0002)	0.0010	0.9757
Beckmannia	2013	0.0385 (0.0225)	3.17×10^{-21} (1.2928)	-0.0184 (1.1024)	9.07×10^{-21} (0.5106)	0.0005	0.8681
syzigachne	2014	0.0605 (0.0153)	1.72×10^{-26} (0.0012)	-0.0345 (0.013)	-0.0345 (0.013)	0.0003	0.9412

Table 2-7. Parameter estimates for inverse quadratic function tested to describe the relationship between parameter weed competitivity and nitrogen in multiple weed interferences in 2013 and 2014. The values in parenthesis are standard errors.

Year	Parameter estimates				RMS	R^2
	l	m	n	r		
2013	0.0748	0.0022	-0.0189	1.01×10^{-19}	0.0001	0.9852
	(0.0389)	(0.0192)	(0.1646)	(0.0035)		
2014	0.0778	0.0014	-0.0382	0.0005	0.00006	0.9992
	(0.0066)	(0.0004)	(0.0007)	(0.00003)		

Combined model for soybean-weed competition under different nitrogen fertilization

The inverse quadratic model was sequentially used by incorporating into a rectangular hyperbolic model to describe the relationships between weed-free soybean yield and nitrogen, and between weed competitivity and nitrogen (Table 2-8). Statistical analysis revealed that the combined rectangular hyperbolic model ($Model_2$) was not worse than the $Model_1$ and Full model regardless of weed species (Table 2-9 and 2-10). When weed-free soybean yield (Y_{0i}) versus nitrogen was replaced by the inverse quadratic model, there was no difference between Full model and $Model_1$ to describe soybean yield affected by weed interference. When weed competitivity (β_i) versus nitrogen was also replaced by the inverse quadratic model, there was no difference between $Model_1$ and $Model_2$ to describe the same soybean yield. The combined model well described both nitrogen and weed competition effects on soybean yield under single weed interferences (Figure 2-6 and Table 2-11) and multiple weed interferences (Figure 2-7 and Table 2-12).

Table 2-8. Summary of models tested for soybean yield.

Model	Model equation
Full Model	$Y = \frac{Y_{0i}}{1+\beta_i X}$
Model 1	$Y = \frac{\frac{a+bN}{1+cN+dN^2}}{1+\beta_i X}$
Model 2	$Y = \frac{\frac{a+bN}{1+cN+dN^2}}{1+(\frac{l+mN}{1+nN+rN^2})X}$

$X = X_1 + \frac{\beta_{2i}}{\beta_i} X_2 + \frac{\beta_{3i}}{\beta_i} X_3$ (X is the sum of the relative densities of three weed species that are calculated by multiplying actual density of each weed species with its relative competitivity to a reference weed species. When $X_1 \neq 0$, $X_2 = 0$, and $X_3 = 0$, X is a density of single weed species.)

Table 2-9. Summary of non-linear regression analysis and F-test to compare models for soybean yield as affected by single weed species including *Ambrosia artemisiifolia*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* and applied nitrogen.

Weed species	Year	Model	Residual		Number of parameters	Test statistics	
			d.f.	SS		Comparison	F-value
		Soybean yield					
Ambrosia artemisiifolia	2013	Full Model	46	1.280	10		
		$Model_1$	47	1.305	9	Full - $Model_1$	0.8984^{NS}
		$Model_2$	48	1.384	8	$Model_2$ - $Model_1$	2.8391^{NS}
	2014	Full Model	70	1.563	10		
		$Model_1$	71	1.588	9	Full - $Model_1$	1.1196^{NS}
		$Model_2$	72	1.635	8	$Model_2$ - $Model_1$	2.1049^{NS}
		Soybean yield					
Echinochloa crus-galli	2013	Full Model	39	2.081	10		
		$Model_1$	40	2.099	9	Full - $Model_1$	0.3373^{NS}
		$Model_2$	41	2.186	8	$Model_2$ - $Model_1$	1.6398^{NS}
	2014	Full Model	58	1.833	10		
		$Model_1$	59	1.868	9	Full - $Model_1$	1.1074^{NS}
		$Model_2$	60	1.983	8	$Model_2$ - $Model_1$	3.6388^{NS}
		Soybean yield					
Beckmannia syzigachne	2013	Full Model	42	1.581	10		
		$Model_1$	43	1.650	9	Full - $Model_1$	1.8330^{NS}
		$Model_2$	44	1.728	8	$Model_2$ - $Model_1$	2.0734^{NS}
	2014	Full Model	68	1.219	10		
		$Model_1$	69	1.257	9	Full - $Model_1$	2.1197^{NS}
		$Model_2$	70	1.258	8	$Model_2$ - $Model_1$	0.0558^{NS}

Table 2-10. Summary of non-linear regression analysis and F-test to compare models for soybean yield as affected by weed density of multiple weeds and applied nitrogen.

Year	Model	Residual		Number of	Test statistics	
		df	SS	parameters	Comparison	F-value
	Soybean yield					
2013	Full Model	161	7.551	10		
	$Model_1$	162	7.670	9	Full - $Model_1$	2.5373^{NS}
	$Model_2$	163	7.829	8	$Model_2$ -Full	2.9658^{NS}
2014	Full Model	329	7.338	10		
	$Model_1$	330	7.349	9	Full - $Model_1$	0.4931^{NS}
	$Model_2$	331	7.375	8	$Model_2$ - $Model_1$	1.2015^{NS}

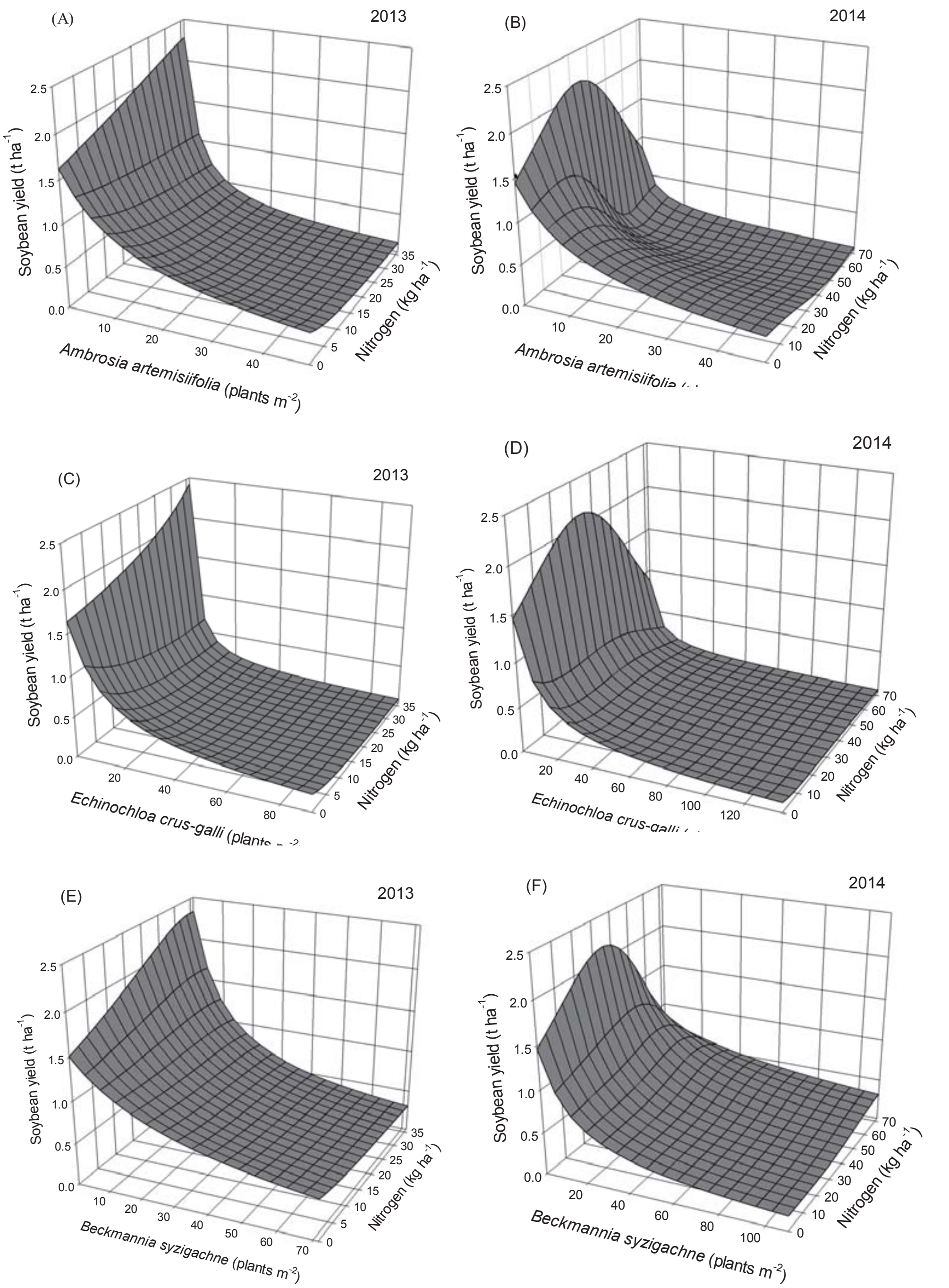


Figure 2-6. Predicted soybean yield as a function of weed density of *Ambrosia artemisiifolia* (A, B), *Echinochloa crus-galli* (C, D), and *Beckmannia syzigachne* (E, F), and amount of applied nitrogen in 2013 (left) and 2014 (right). The predicted soybean yield (mesh) was calculated using $Model_2$.

Table 2-11. Parameter estimates for the prediction of soybean yield as a result of competition between soybean and *Ambrosia artemisiifolia*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* in applied nitrogen.

Weed species	Year	Parameter estimate								R^2
		Y_{0i}				β_i				
		a	b	c	d	l	m	n	r	
Ambrosia	2013	1.619	-1.1390	-0.0753	0.00759	0.0527	0.0112	0.042	-0.00129	0.94
artemisiifolia		(0.101)	(0.0215)	(0.0379)	(0.0014)	(0.0109)	(0.0246)	(0.216)	(0.0048)	
	2014	1.452	-0.0120	-0.0248	0.00028	0.0784	-0.0001	-0.036	0.000342	0.94
		(0.091)	(0.0058)	(0.0021)	(0.0001)	(0.0126)	(0.0011)	(0.002)	(0.00003)	
Echinochloa	2013	1.494	-0.1299	-0.0974	0.0009	0.0623	0.01	3.05×10^{-22}	7.42×10^{-6}	0.91
crus-galli		(0.159)	(0.2095)	(0.1415)	(0.0015)	(0.0233)	(0.035)	(0.1859)	(0.0031)	
	2014	1.460	-0.0119	-0.0241	0.0003	0.0876	0.01	6.13×10^{-17}	0.0006	0.93
		(0.115)	(0.0076)	(0.0026)	(0.0001)	(0.0243)	(0.018)	(0.0776)	(0.0006)	
Beckmannia	2013	1.572	-0.0687	-0.0534	0.0004	0.0382	0.0004	1.35×10^{-21}	-0.0004	0.90
syzigachne		(0.101)	(0.0076)	(0.0002)	(0.00006)	(0.0115)	(0.0008)	(0.2137)	(0.0001)	
	2014	1.462	-0.0140	-0.0247	0.0003	0.0671	-0.0007	-0.0303	0.0004	0.92
		(0.099)	(0.0057)	(0.0023)	(0.00010)	(0.0117)	(0.0003)	(0.0099)	(0.0003)	

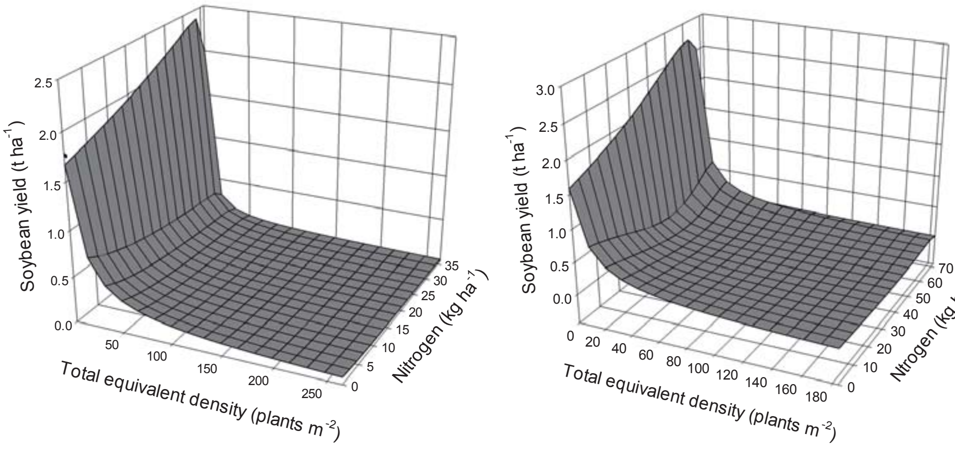


Figure 2-7. Predicted soybean yield as a function of total equivalent density of *A. artemisiifolia*, *B. syzigachne*, and *E. crus-galli* and amount of applied nitrogen in 2013 (left) and 2014 (right). The predicted soybean yield (mesh) was calculated using $Model_2$.

Table 2-12. Parameter estimates for the prediction of soybean seed yields as a result of competition between soybean and multiple weeds.

Year	Parameter estimate								R^2
	Y_{0i}				β_i				
	a	b	c	d	l	m	n	r	
2013	1.7132 (0.1067)	-0.0474 (0.0291)	-0.0362 (0.0113)	0.0002 (0.00001)	0.0801 (0.0151)	0.0068 (0.0180)	1.78×10^{-22} (0.1237)	3.61×10^{-24} (0.002)	0.80
2014	1.5857 (0.0914)	-0.0219 (0.0044)	-0.0214 (0.0024)	0.0001 (0.0001)	0.0902 (0.0096)	-1.20×10^{-21} (0.0007)	-0.0378 (0.0017)	0.0004 (0.00005)	0.85

Discussion

Modelling soybean-weed competition at different N levels

Previous studies for crop-weed competition have been conducted in artificial field experiments where target weed species were sown immediately before sowing crop. This study showed that soybean yield can be hyperbolically affected by weed species naturally established and arranged in rows of soybean. Cousens (1985)' model provided the modelling tool to predict the soybean yield affected by single weed interferences including *A. artemisiifolia*, *E. crus-galli*, and *B. syzigachne* at different nitrogen fertilizations. As a result of the competition between soybean and single weed, the level of soybean yield loss was influenced by weed species and applied nitrogen. *E. crus-galli* was the most competitive among three weed species in the ranges from 0 to 24 kg ha^{-1} of nitrogen fertilization. *A. artemisiifolia* showed a little lower competitivity than *E. crus-galli* at the same nitrogen ranges, but showed the highest competitivity among them at 36 kg ha^{-1} of nitrogen fertilization. *B. syzigachne* showed the lowest competitivity among them at all the nitrogen fertilizations. The result indicated that the weed competitivity to soybean yield was dependent on weed species and applied nitrogen. *A. artemisiifolia* (Leskovsek et al., 2012) and *E. crus-galli* (Chauhan and Abugho, 2013) were known to be nitrophilous weed species as increasing weed biomass with increasing nitrogen level by even at 100 kg ha^{-1}.

Kim et al. (2006a) recently suggested a simplified multivariate rectangular hyperbolic model to describe the effect of multiple weed competition on crop yield. Actually, other modified versions of Cousens (1985)' model (Coble and Mortensen, 1992; Swinton et al., 1994; Cowan et al., 1998) which are basically similar to Kim et al. (2006a)'s model, have commonly been used in practical soybean field conditions. However, the model equations are too complicate to deal with field data compared with Kim et al. (2006a)'s model. This study showed that multivariate rectangular hyperbolic model provided a good description for the relationship between soybean and multiple weed species at different nitrogen fertilizations.

The response of weed-free soybean yield and weed competitivity to nitrogen

This study showed that soybean could be positively responded to a small amount of nitrogen applied before planting in Bogatyrka where early cool season at planting are not always adequate for nodule formation. In the similar weather condition of the northern Great Plains in US, low nitrogen rate of 16 kg ha^{-1} at planting enhanced early vegetative soybean growth and resultant soybean yield compared to untreated plot (Osborne SL & Riedell WE, 2006). In our study, the increase in soybean yield was shown in the range from 12 to 36 kg ha^{-1} of nitrogen fertilization. According to previous studies (Liu et al., 2008; Li, 2005), basal nitrogen fertilizers from 22.5 to 30 kg ha^{-1} were effective for high soybean production in Northeast China which is closely linked to the regions of Russian Far East. As in Figure 2-2 and 2-3, weed-free soybean yield at 72 kg ha^{-1} of nitrogen fertilization decreased with lower number of soybean than that in 36 kg ha^{-1}. Stone et al. (1985) reported that excessive rate over 75 kg ha^{-1} of nitrogen fertilizer could be detrimental to soybean growth as the nitrogen in soil was enough to supply the plant. As a result, optimal rate of nitrogen fertilizer was 36 kg ha^{-1} for maximum soybean yield in far-eastern regions of Russia. Many studies (Afza et al., 1987; Taylor et al., 2005; Osborne & Riedell, 2006; Caliskan et al., 2008) showed that growth and yield of soybean responded to nitrogen level in inverse quadratic function. Our result also showed the inverse quadratic curve was useful for describing the effect of nitrogen on soybean yield at high nitrogen level.

This study indicated that inverse quadratic model provided better description for weed competitivity response to nitrogen than exponential model. Kim et al. (2006b) reported that exponential model well explained the relationship between weed competitivity and nitrogen in wheat. Although weed competitivity to wheat exponentially increased with increasing nitrogen level up to 360 kg ha^{-1}, weed competitivity may decrease as wheat was negatively affected over more than 360 kg h^{-1}. Weed competitivity depends on weed-free crop yield, showing that the reciprocal of weed competitivity is a density of wee species to reduce weed-free crop yield by 50%. Weed competitivity can decrease with decreasing weed-free crop yield at high nitrogen level where weed biomass increases, but conversely crop growth decreases. As the application of nitrogen changes both crop growth and weed biomass, the effect of nitrogen to weed competitivity may be different according to crop species, weed species, and the amount of nitrogen. In this study, the weed competitivity response to nitrogen differed among three weed species alone and in combination, but it was well described by using inverse quadratic model.

Further studies may be required for inverse quadratic model to describe the effect of nitrogen on weed comeptitivity in other crops.

Implementation of the combined model

From the combined models, the results showed that soybean yield inverse-quadratically increased with increasing nitrogen without weed interference, but it also hyperbolically decreased with increasing weed density. According to the combined models, soybean yield can be predicted at a given weed density and nitrogen level. In case of *A. artemisiifolia* interference, soybean yield sharply decreased with increasing weed density at the nitrogen level of 40-50 kg ha^{-1}. At a nitrogen fertilization of 45 kg ha^{-1} and *A. artemisiifolia* density of 1 plants m^{-2}, the combined model predicted soybean yield of 1.00 t ha^{-1}, about 50 % of weed-free plot. In case of E. *crus-galli* interference, soybean yield decreased with increasing weed density and nitrogen level. At the same nitrogen fertilization and weed density as *A. artemisiifolia*, the combined model predicted soybean yield of 1.42 t ha^{-1}, about 80 % of weed-free plot. In case of *B. syzigachne* interference, soybean yield decreased the least with increasing density at the nitrogen level of 40-50 kg ha^{-1}. At the same conditions as other two species, the combined model predicted soybean yield of 1.56 t ha^{-1}, about 93 % of weed-free plot.

With multiple weed interferences consisting of three weed species, soybean yield can be also predicted at a given nitrogen level using the combined multivariate rectangular hyperbolic model. At a nitrogen fertilization of 36 kg ha^{-1}, soybean yield of 2.22 t ha^{-1} was predicted without weed interference, while 50 % of weed-free plot was predicted with a total equivalent density of 1.75 plants m^{-2} in 2014. The total equivalent density can be calculated into actual weed densities (X) of three weed species from the equations of ($X_A + 0.49X_E + 0.16X_B$) in 2014. If *E. crus-galli* and *B. syzigachne* are not observed, actual weed density of *A. artemisiifolia* is predicted as 1.75 plants m^{-2}. If *A. artemisiifolia* and *B. syzigachne* are not observed, actual weed density of *E. crus-galli* is predicted as 3.65 plants m^{-2}. If *A. artemisiifolia* and *E. crus-galli* are not observed, actual weed density of *B. syzigachne* is predicted as 10.94 plants m^{-2}. Thus, considering high soybean yield at a nitrogen fertilization of 36 kg ha^{-1}, the most effective weed management should be selected. In case of heavy infestation of broadleaf weed such as *A. artemisiifolia*, a specific herbicide for targeting broadleaf weeds can be additionally selected. Kim et al (2006b) suggested their combined rectangular hyperbolic model can be used to predict crop yield and recommend the herbicide doses required to restrict crop yield loss caused by weeds at a given nitrogen level. However, Kim et al. (2006b)'s model cannot count the effects of multiple weed interferences on crop yield. This study suggests that the model developed here can be an upgrade version of Kim et al. (2006b)'s model. Although the models developed here were not validated under the other field conditions, they would support the decision-making for weed control under different nitrogen use scheme in soybean production in Primorski-Krai, Russia.

References

Afza R, Hardason G, and Zapata F. 1987. Effect of delayed soil and foliar N fertilization on yield and N_2 fixation of soybean. Plant and Soil 97: 361-368.

Ampong-Nyarko K and Datta SKD. 1993. Effects of nitrogen application on growth, nitrogen use efficiency and rice-weed interaction. Weed Research 33: 269-276.

Berti A and Zanin G. 1994. Density equivalent: a method for forecasting yield loss caused by mixed weed populations. Weed Research 34: 327-332.

Buchanan GA and McLaughlin RD. 1975. Influence of nitrogen on weed competition in cotton. Weed Science 23: 324-328.

Caliskan S, Ozkaya I, Caliskan ME, and Arslan M. 2008. The effect of nitrogen and iron fertilization on growth, yield and fertilizer use efficiency of soybean in a Mediterranean-type soil. Field Crops Research 108: 126-132.

Chauhan BS and Abugho SB. 2013. Effects of water regime, nitrogen fertilization, and rice plant density on growth and reproduction of lowland weed *Echinochloa crus-galli*. Crop Protection 54: 142-147.

Coble HD and Mortensen DA. 1992. The threshold concept and its application to weed science. Weed Technology 6(1): 191-195.

Cousens R. 1985. A simple model relating yield loss to weed density. Annals of Applied Biology 107: 239-252.

Cowan P, Weaver SE, and Swanton CJ. 1998. Interference between pigweed (*Amaranthus* spp.), barnyardgrass (*Echinochloa crus-galli*), and soybean (*Glycine max*). Weed Science 46: 533-539.

Dhima KV and Eleftherohorinos IG. 2001. Influence of nitrogen on competition between winter cereals and sterile oat. Weed Science 49(1): 77-82.

Genstat Committee. 2002. Reference Manual (Genstat Release 6.1). VSN International, Oxford, UK.

Kim DS, Marshall EJP, Brain P, and Caseley JC. 2006a. Modeling interactions between herbicide dose and multiple weed species interference in crop-weed competition. Weed Research 46: 175-184.

Kim DS, Marshall EJP, Caseley JC, and Brain P. 2006b. Modeling the effects of sub-lethal doses of herbicide and nitrogen fertilizer on crop-weed competition. Weed Research 46: 492-502.

Leskovsek et al. 2012. Influence of nitrogen and plant density on the growth and seed production of common ragweed (Ambrosia artemisiifolia). J Pest Sci. 85: 527-539.

Li JR. 2005. The scientific knowledge of applying fertilizer technique for soybean. Journal of Jili Agriculture Science and Technology College 14: 32-35 (in Chinese).

Liu X, Jin J, Wang G, and Herbert SJ. 2008. Soybean yield physiology and development of high-yielding practices in Northeast China. Field Crops Research 105: 157-171.

Naderi R and Ghadiri H. 2011. Competition of wild mustard (*Sinapis arvense* L.) densities with rapeseed (*Brassica napus* L.) under different levels of nitrogen fertilizer. J. Agr. Sci. Tech. 13: 45-51.

Osborne SL and Riedell WE. 2006. Starter nitrogen fertilizer impact on soybean yield and quality in the Northern Great Plains. Agronomy Journal 98: 1569-1574.

Salvagiotti F, Cassman KG, Specht JE, Walters DT, Weiss A, and Dobermann A. 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. Field Crops Research 108: 1-13.

Shalfagh-Kolvanagh J, Zehtab-Salmasi S, Javanshir A, Moghaddam M, and Nasab ADM. 2008. Effect of nitrogen and duration of weed interference on grain yield and SPAD (chlorophyll) value of soybean (Glycine max (L.) Merrill.). Journal of Food, Agriculture and Environment 6: 368-373.

Stone LR, Whitney DA, and Anderson CK. 1985. Soybean yield response to residual NO3-N and applied N. Plant and Soil 84: 259-265.

Swinton SM, Buhler DD, Forcella F, Gunsolus JL, and King RP. 1994. Estimation of Crop yield loss due to interference by multiple weed species. Weed Science 32: 103-109.

Taylor RS, Weaver DB, Wood CW, and van Santen E. 2005. Nitrogen application increases yield and early dry matter accumulation in late-planted soybean. Crop Science 45: 854-858.

Thornley JHM. 1978. Crop response to fertilizers. Annals of Botany 42: 817-826.

Wells GJ. 1979. Annual weed competition in wheat crops: the effect of weed density and applied nitrogen. Weed Research 19: 185-191.

CHAPTER III. Herbicide-based weed management in soybean

ABSTRACT

This study was conducted to establish weed management system with sequential application of pre-emergence (PRE) and post-emergence (POST) herbicides in a soybean field located in Bogatyrka, Primorski-krai, Russia (N43º49’, E131º36’). Without herbicide, soybean was vulnerable to weed interference, and reduced by more than 90% of weed-free plot. When acetochlor was applied at planting, it showed good safety for soybean and good weed control under field condition. When bentazon+acifluorfen, bentazon, and imazamox were applied after 30 days after sowing soybean, they showed good safety for soybean and good weed control. When PRE and POST herbicides were sequentially applied, they showed better performance for weed control compared with PRE and Post herbicide alone. In particular, the sequential application of acetochlor followed by bentazon+acifluorfen and bentazon+imazamox in 2012 and 2013, respectively, was the most effective weed management with good safety for soybean. The sequential application based on acetochlor achieved approximately 1.7 and 1.9 ton ha^{-1} in 2012 and 2013, respectively, similar to those of weed-free plot. Therefore, the sequential applications selected in this study provide an effective weed management

system for soybean cultivation in Primorski-krai, Russia.

Keywords: weed management, sequential application, economic analysis, economic thresholds, soybean, Primorsky-krai

Introduction

An effective weed management in soybean is essential to protect soybean growth and yield from weed competition during the growing seasons. Soybean is vulnerable to weed interference because of sowing seeds at wide spacing (70 cm rows) to develop branches and expand its canopy fully at the late growth stage. The late canopy closure allows weeds to establish easier in soybean than other crops. To effectively manage weed infestation in soybean, various weed managements, including herbicide application, tillage practices, and crop rotation are used in combination. The weed control methods can be modified based on the field conditions. However, herbicide has been basically incorporated into the weed management practices regardless of region.

Far-eastern regions of Russia is major agriculture area in which soybean, corn, and oats are traditionally cultivated for food and feedstock. In most far-eastern regions, the early-mature soybean has been massively cultivated for soybean oil. A difficulty for soybean cultivation is to manage troublesome weeds naturally established around the Russian Fareast. On average, the grain yield of soybean in far-eastern regions of Russia was lower as 1.05 ton per hectare compared with 1.46 ton per hectare of other provinces in Russia (Russian Statistical Yearbook, 2011). Such a low soybean yield was attributed to poor weed management system, allowing the weeds to cause severe yield loss of soybean. That weed management is based on herbicide treatment; sole application of post-emergence herbicides was lack of controlling troublesome weeds in soybean field of far-eastern regions of Russia.

To prevent soybean yield loss from the weeds, an effective weed management should be established based on the field conditions of far-eastern regions of Russia. Currently, *Ambrosia artemisiifolia*, *Chenopodium album*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* were reported to be dominant weeds in soybean field located in the region (Song et al., 2013). The effective weed management should control the troublesome weeds to an acceptable level. Herbicides which are selected based on the field conditions can be easier method to control the weeds. However, no study has been conducted to screen herbicides for troublesome weeds under field conditions of far-eastern regions of Russia. Based on performance of PRE and POST herbicides alone and in combination, effective weed managements can be selected from the field experiment. Using economic analysis, which depends on soybean yield and price, herbicide cost, and application cost, the herbicide-based weed managements can be chosen to achieve high gross profit. This study was conducted to establish effective and economic weed management which is proper for soybean cultivation in far-eastern regions of Russia.

Materials and Methods

Experimental site

Experiments were conducted in the field located at the Farm Station (43^{o}49'N, 131^{o}36'E) of Bogatyrka of Primorsky-Krai in Russia.

Field experiment with herbicides

Field experiments were conducted in 2012 and 2013. The field had a soil texture of silty loam with CEC of 22.62 cmol kg^{-1}, organic matter of 29.59 g kg^{-1}, total N of 1.58 g kg^{-1}, inorganic NH_4^+-N of 0.85 mg kg^{-1}, inorganic NO_3^--N of 14.01 mg kg^{-1}, available P of 18.19 mg kg^{-1}, and pH of 6.61. The field was used for maize or soybean cultivation in previous years. Soybean (cv. Heinong 48) was drilled at 80 kg ha^{-1} with a row width of 70 cm on May 16, 2012 and May 27, 2013. An N-P-K basal fertilizer was applied at a rate of 12-31-31 kg ha^{-1} before sowing seeds.

5 PRE herbicides, dimethenamid-p (720 g a.i. ha^{-1}), S-metolachlor (750 g a.i. ha^{-1}), acetochlor (900 g a.i. ha^{-1}), pendimethalin (951 g a.i. ha^{-1}), and ethalfluralin (1050 g a.i. ha^{-1}), and 6 POST herbicides, bentazone+acifluorfen (416+208 g a.i. ha^{-1}), bentazone (560 g a.i. ha^{-1}), fluazifop (175 g a.i. ha^{-1}), quizalofop-p-tefuryl (120 g a.i. ha^{-1}), tepraloxydim (90 g a.i. ha^{-1}), and imazamox (40 g a.i. ha^{-1}), were tested alone at their standard and double recommended doses to compare weed-free and untreated controls for the field experiment (Table 3-1). The selected 3 PRE and 5 POST herbicides were sequentially applied in

combination at their standard recommended doses in 2012 and 2013 (Table 3-1). The herbicides are 3 PRE herbicides including S-metolachlor, acetochlor, and dimethenamid-p and 5 POST herbicides including, bentazone+acifluorfen, bentazone quizalofop-p-tefuryl, tepraloxydim, and imazamox. The PRE and POST herbicides alone were applied to the soybean plot of 4.0 m x 5.0 m at planting and 30 (or 60) days after sowing soybean, respectively, while their herbicide combinations were sequentially applied in the same way in 2012 and 2013. Herbicide application was made using a CO_2 pressurized 3m-boom sprayer adjusted to deliver 1,000 L ha^{-1}. During the whole growing season, soybean was grown in the field under rainfed conditions. All the plots were arranged in a randomized block design with three replicates.

Damage of soybean and weed control from each plot were visually evaluated 30 days after application. In autumn of 2012 and 2013, soybean plants were harvested at the soil level and measured for yield components and seed yield. The dry weight was measured after drying in the air.

Table 3-1. Herbicide treatments used in the experiment

Herbicides	Dose (g a.i. ha^{-1})	Application time (days after sowing)
Untreated	-	-
Hand weeding	-	-
Pre-emergence herbicide		
Dimethenamid-p	720, 1440	0
S-metolachlor	750, 1500	0
Pendimethalin	951, 1902	0
Ethalfluralin	1050, 2100	0
Acetochlor	900, 1800	0
Post-emergence herbicide		
Bentazone+acifluorfen	416+208, 832+416	30, 60
Bentazone	560, 1120	30, 60
Fluazifop	175, 350	30, 60
Quizalofop-p-tefuryl	120, 240	30, 60
Tepraloxydim	90, 180	30, 60
Imazamox	40, 80	30, 60
Pre- and Post-emergence herbicides		
Dimethenamid-P fb.	720	1
Bentazone+Acifluorfen	+416+208	30, 60
Dimethenamid-P fb.	720	1
Bentazone+Quizalofop	+560+120	30, 60
Acetochlor fb.	900	1
Bentazone+Acifluorfen	+416+208	30, 60
Acetochlor fb.	900	1
Bentazone+Quizalofop	+560+120	30, 60
S-metochlor fb.	750	1
Bentazone+Acifluorfen+Tepraloxydim	+416+208+90	30, 60
S-metochlor fb.	750	1
Bentazone+Imazamox	+560+40	30, 60
Acetochlor fb.	900	1
Bentazone+Acifluorfen+Tepraloxydim	+416+208+90	30, 60
Acetochlor fb.	900	1
Bentazone+Imazamox	+560+40	30, 60

Statistical analyses

All data were initially subjected to analysis of variance (ANOVA), and mean comparison was made by Duncan's multiple range test ($P < 0.05$). For the field experiment, visual data (visual damage, visual weed control) were analyzed separately with application schemes (PRE, POST, PRE+POST) as a main factor and block as a random factor in 2012 and 2013. Yield data was also analyzed separately with the same application schemes as main factor and block as random factor. All statistical analyses were conducted using Genstat (Genstat Committee, 2002).

Results

Performance of PRE herbicide

In soybean field of Bogatyrka, 5 PRE herbicides were tested to select the herbicide, which has a safety for soybean and a good efficacy for weed species (Figure 3-1). Acetochlor showed the highest efficacy among them, but caused growth stunting at standard recommended dose in 2012 and 2013. Although acetochlor caused some damage, the visual damage was diminished with soybean growth even at double the rate of its recommended dose. In contrast, the other PRE herbicides including dimethenamid-p, pendimethalin, ethalfluralin, and S-metolachlor were safe for soybean, but showed low efficacy at double the rate of their recommended doses in 2012 and 2013.

When assessed at harvest in an untreated plot, soybean yield was significantly reduced to 1.8% and 15% of weed-free plot in 2012 and 2013, respectively. In herbicide-treated plots, acetochlor showed the greatest increase in soybean yield compared to the untreated plot of two-fold and three-fold at standard recommended dose in 2012 and 2013, respectively, and the other PRE herbicides showed no or a little increase even at double the rate of recommended dose. Thus, acetochlor applied prior to the emergence of soybean was more effective in major weed species than the other PRE herbicides, resulting in an increase in soybean yield. However, the yield increase by acetochlor was not acceptable compared to soybean yield of the weed-free plot (Figure 3-2).

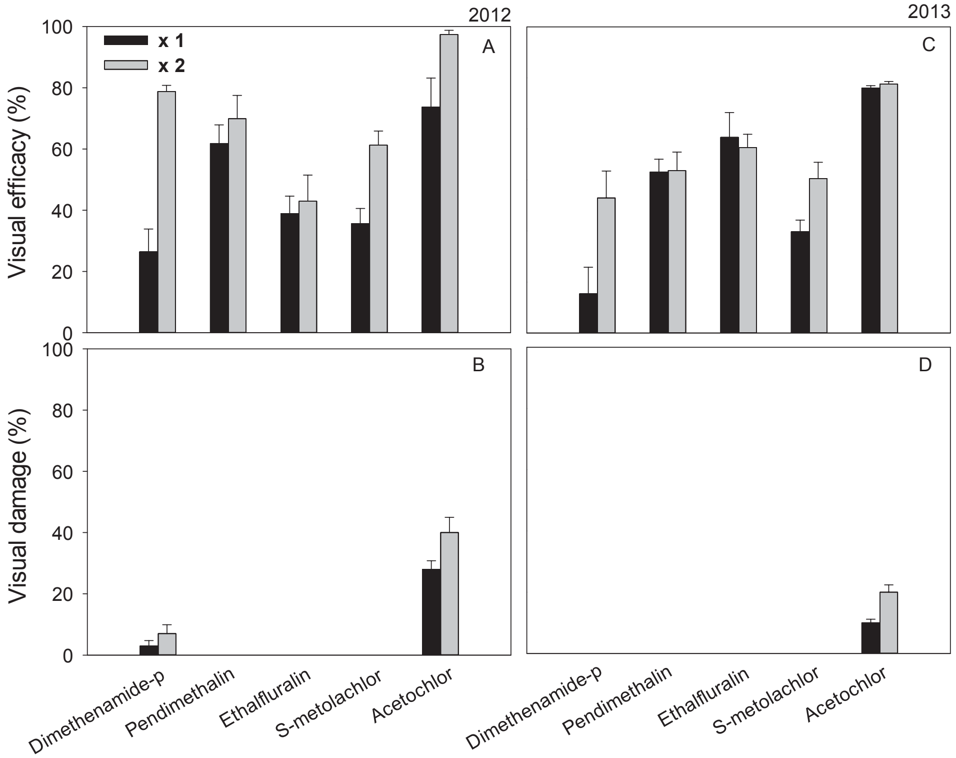


Figure 3-1. Visual damage (B, D) and visual efficacy (A, C) of pre-emergence herbicides at 30 days after application in the field condition of soybean applied at the immediately after sowing in 2012 (A, B) and 2013 (C, D). The vertical bars represent standard deviation of the mean of three replicates.

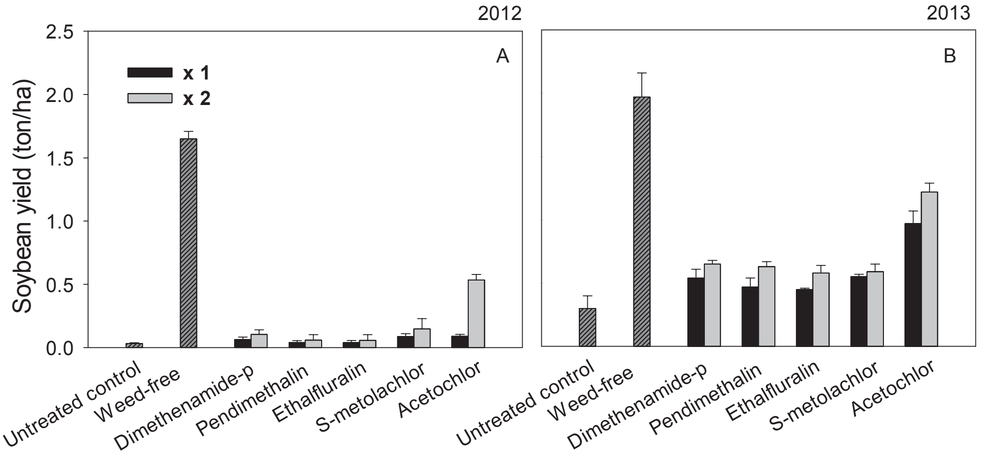


Figure 3-2. Soybean yield (% of weed-free yield) at harvest in the field condition of soybean applied with single application of pre-emergence herbicides in 2012 (A) and 2013 (B). The vertical bars represent standard deviation of the mean of three replicates.

Performance of POST herbicide

6 POST herbicides were tested for selection of herbicide to be safe for soybean and to be effective for major weed species found in soybean field across Primorski-Krai, Russia (Figure 3-3). All the POST herbicides showed good safety for soybean, while the herbicide efficacy varied among weed species. Bentazone+acifluorfen, bentazone, and imazamox were high effective enough to control broadleaf weeds including *A. artemisiifolia*, *C. album*, and *S. oleraceus*, while the other herbicides were not sufficient enough. Fluazifop, quizalofop, tepraloxydim, and imazamox were high effective in grass weeds including *E. crus-galli*, *B. syzigachne*, and *Setaria viridis*. In particular, imazamox showed good efficacy for both broadleaf and grass weeds. The efficacy of all POST herbicides decreases with delaying application timing. When applied at 30 days after sowing in 2012 and 2013, bentazone+acifluorfen, bentazone, and imazamox showed high efficacy for broadleaf weeds, and fluazifop, quizalofop, tepraloxydim, and imazamox showed high efficacy for grass weeds. Conversely, when applied at 60 days after sowing in 2012 and 2013, they showed less efficacies for broadleaf and grass weeds.

When assessed at harvest in herbicide-treated plots, bentazone+acifluorfen showed the greatest increase in soybean yield at standard recommended dose in 2012 and 2013, and followed by imazamox and bentazone (Figure 3-4). However, the increase in soybean yield was reduced as the application timing of POST herbicides was delayed. These results demonstrated that POST herbicides was somehow effective in protecting soybean yield from weed competition, but the efficacies were not sufficient in soybean field across Primorski-Krai. Also, the delayed application of POST herbicides allowed weeds to compete soybean.

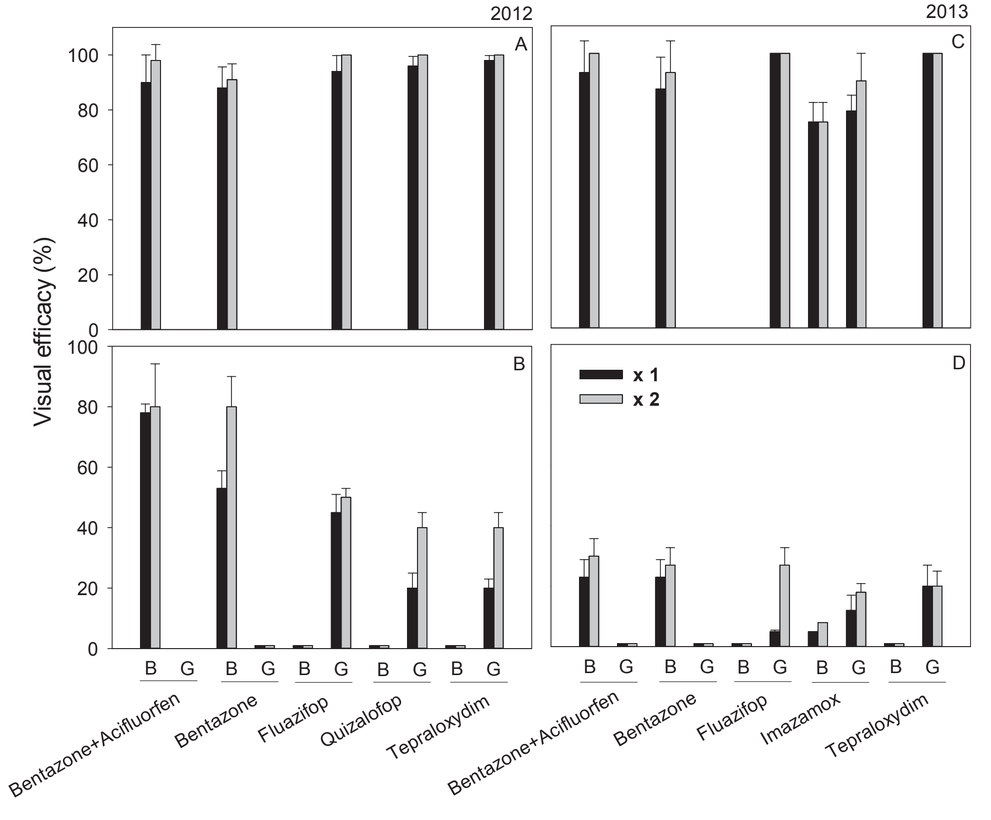


Figure 3-3. Visual damage and visual efficacy of post-emergence herbicides at 30 days after application in the field condition of soybean applied at 30 (A, C) and 60 (B, D) days after sowing 2012 (A, B) and 2013 (C, D). The vertical bars represent standard deviation of the mean of three replicates.

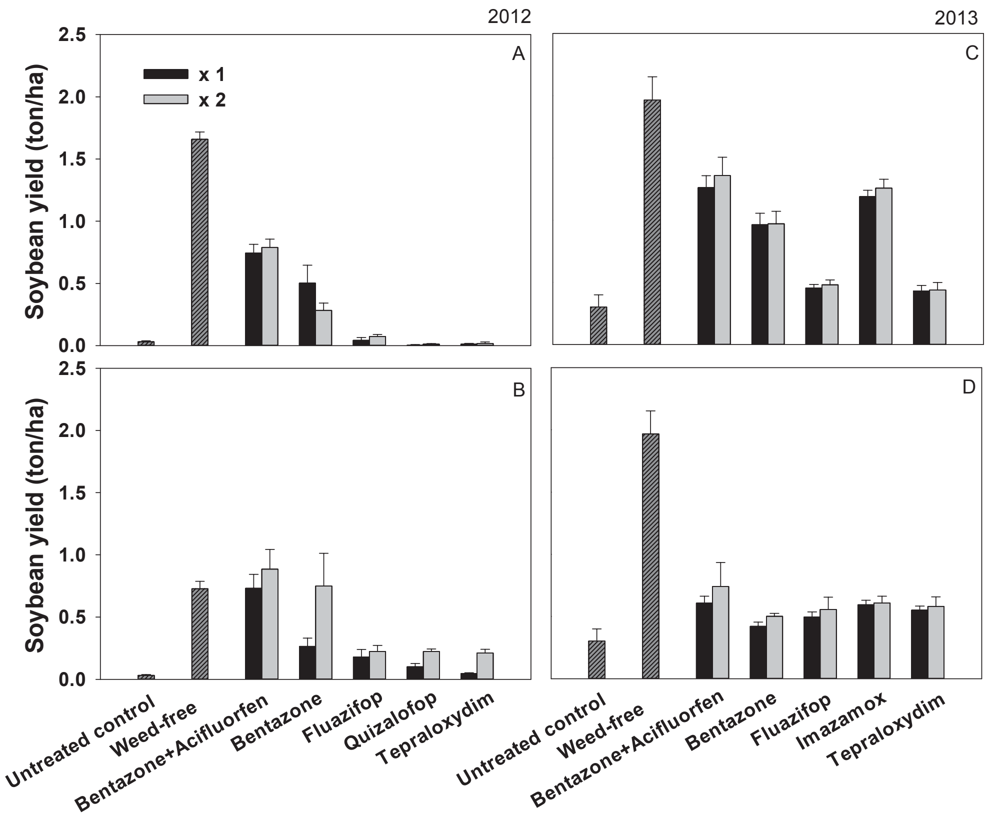


Figure 3-4. Soybean yield (% of weed-free yield) at harvest in the field condition of soybean applied at 30 (A, C) and 60 (B, D) days after sowing with single application of post-emergence herbicides in 2012 (A, B) and 2013 (C, D). The vertical bars represent standard deviation of the mean of three replicates.

Performance of sequential PRE & POST herbicide application

Three PRE (dimethenamid-p, S-metolachlor, and acetochlor) and four POST herbicides (bentazone+acifluorfen, bentazone+acifluorfen+tepraloxydim, bentazone+quizalofop, bentazone+imazamox) were sequentially applied in soybean plot. Most of them showed acceptable efficacy for both broadleaf and grass weeds. In particular, sequential application based on acetochlor showed greater efficacies against grass weeds than did acetochlor only. The acetochlor-based sequential application with bentazone+acifluorfen, bentazone+imazamox, and bentazone+acifluorfen+tepraloxydim showed the greatest efficacies against both grass and broadleaf weeds (Table 3-5). In sequential herbicide application plots, weed efficacies varied among herbicide combinations and their application timings. In same sequential applications with bentazone+acifluorfen and bentazone+quizalofop in 2012, weed efficacy decreased with delaying the POST herbicides. In same sequential applications with bentazone+acifluorfen+tepraloxydim and bentazone+imazamox in 2013, weed efficacy was high even when the POST herbicides applied at 60 days after sowing.

At harvest, acetochlor-based sequential application showed higher soybean yield than other sequential applications in 2012 and 2013. With the same PRE herbicide, bentazone+acifluorfen and bentazone+imazamox showed the highest soybean yield in 2012 and 2013, respectively (Table 3-6). Under field conditions in Primorski-krai, sequential application of PRE and POST herbicides was the most effective weed management to control major weed species.

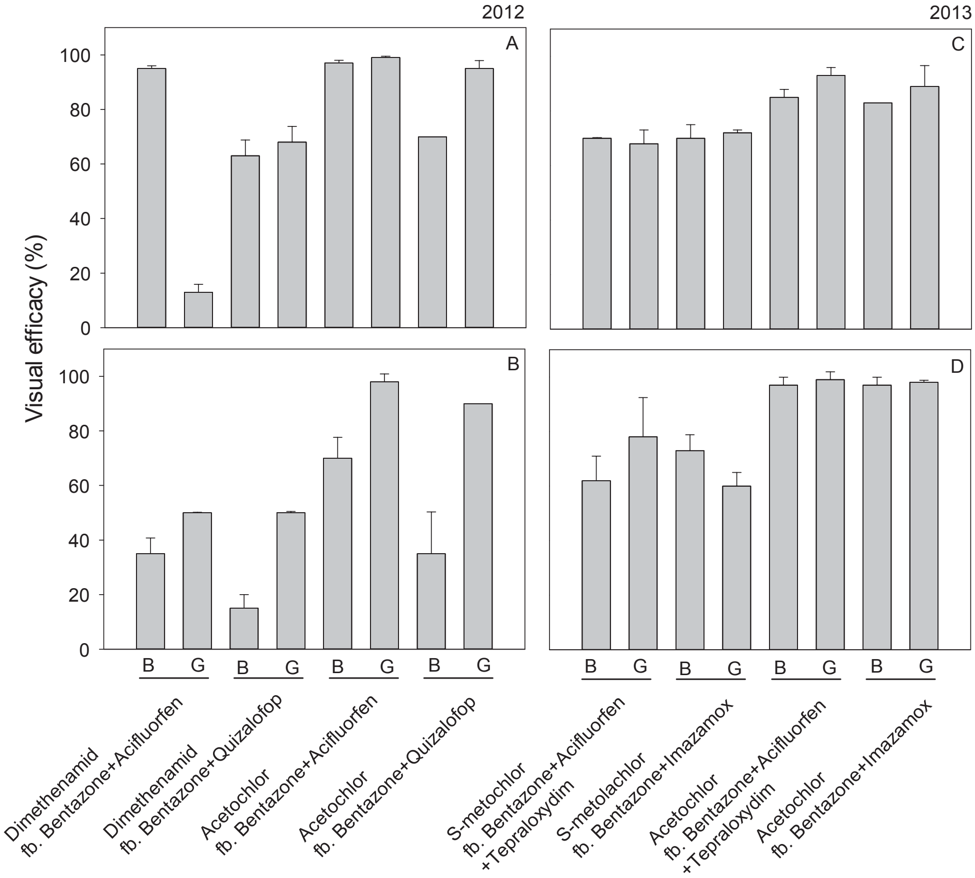


Figure 3-5. Visual efficacy of sequential application at 30 days after application in the field condition of soybean applied with pre-emergence herbicides followed by post-emergence herbicides at 30 (A, C) and 60 (B, D) days after sowing 2012 (A, B) and 2013 (C, D). The vertical bars represent standard deviation of the mean of three replicates.

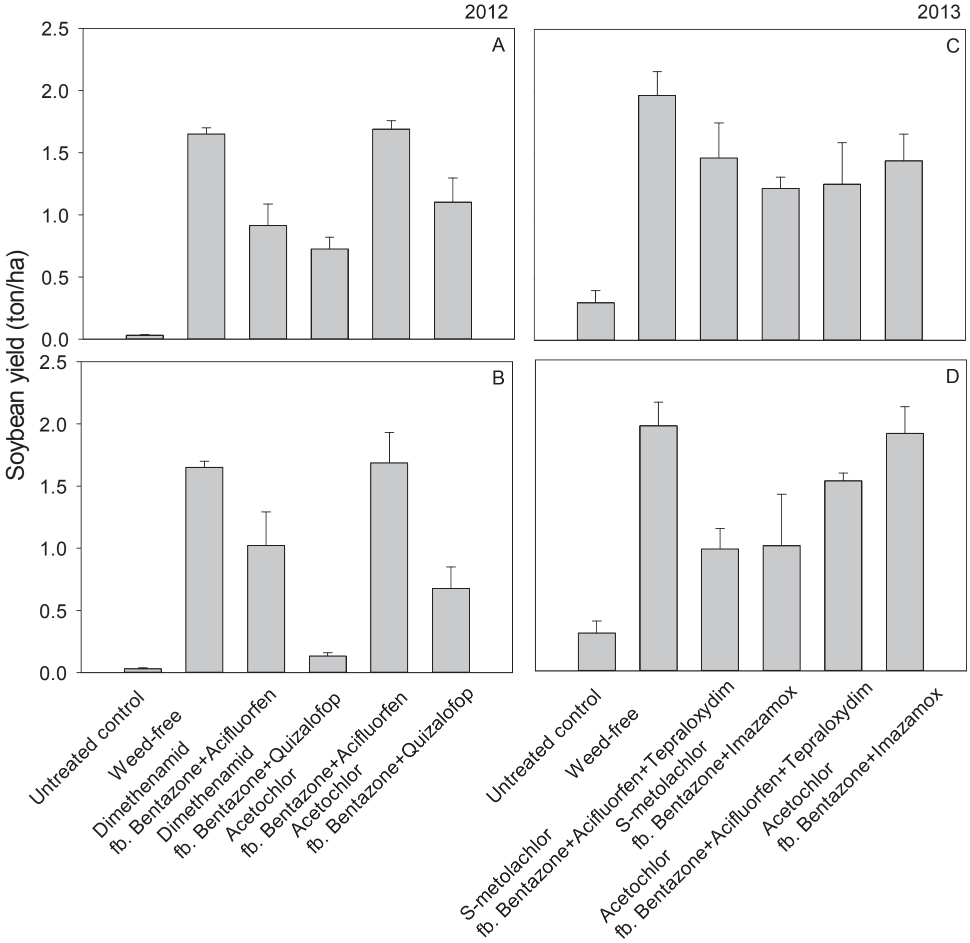


Figure 3-6. Soybean yield (% of weed-free yield) at harvest in the field condition of soybean applied with sequential application of pre-emergence herbicide followed by post-emergence herbicides at 30 (A, C) and 60 (B, D) days after sowing 2012 (A, B) and 2013 (C, D). The vertical bars represent standard deviation of the mean of three replicates.

Economic analysis for herbicide-based weed control

Several weed managements were evaluated using an economic analysis for weed control (Table 3-2). When no weed management was performed, gross revenue was reduced to 14.1 US$ ha^{-1} and 195 US$ ha^{-1} in 2012 and 2013, respectively. With sole application of PRE and POST herbicides, bentazone+acifluorfen showed the greatest increase in gross revenue compared to the untreated plot of approximately 25-fold and 4-fold in 2012 and 2013, respectively. With sequential application of PRE and POST herbicides, acetochlor-based sequential application achieved the greatest gross revenue, resulting in at least 517.0 US$ ha^{-1} and 994.5 US$ ha^{-1} in 2012 and 2013, respectively. In Russia, herbicide cost for soybean production varied between 5.1 and 57.5 US$ ha^{-1}, and between 25.7 and 87.1 US$ ha^{-1} in 2012 and 2013, respectively. A gross profit of weed managements was estimated depending on gross revenue, herbicide cost, and application cost. Compared to the untreated plot, all of weed managements increased gross profit although the cost for weed control should be added. When bentazone+acifluorfen was applied alone, the gross profit was greater than that of other PRE and POST herbicides. When acetochlor-based sequential applications were treated, the gross profit of them was the greatest among other weed managements. In the same sequential applications with acetochlor, bentazone+acifluorfen and bentazone+imazamox achieved the greatest gross profit of 730.7 US$ ha^{-1} and 1161.5 US$ ha^{-1} in 2012 $and 2013, respectively.

Table 3-2. Economic analysis for weed management based on sequential applications of pre-emergence and post-emergence herbicides in 2012 and 2013

Year	Weed management	Yield (ton/ha)	Unit price ($/ton)	Gross revenue ($/ha)	Herbicide cost ($/ha)	Application cost ($/ha)	Gross profit ($/ha)
2012	Untreated control	0.03	470	14.1	0	0	14.1
	Acetochlor	0.51	470	239.7	24.2	6.1	209.4
	Bentazone+acifluorfen	0.74	470	347.8	33.3	6.1	308.4
	Bentazone	0.50	470	235.0	5.1	6.1	223.7
	Dimethenamid fb. bentazone+acifluorfen	0.91	470	427.7	56.5	6.1	365.0
	Acetochlor fb. bentazone+acifluorfen	1.69	470	794.3	57.5	6.1	730.7
	Acetochlor fb. bentazone+quizalofop	1.10	470	517.0	49.0	6.1	461.9
2013	Untreated control	0.30	650	195.0	0	0	195.0
	Acetochlor	0.94	650	611.0	25.7	5.9	579.4
	Bentazone+acifluorfen	1.26	650	819.0	33.4	5.9	779.7
	Imazamox	1.19	650	773.5	37.0	5.9	730.6
	Acetochlor fb. bentazone+acifluorfen +tepraloxydim	1.53	650	994.5	87.1	5.9	901.5
	Acetochlor fb. bentazone+imazamox	1.90	650	1235.0	67.6	5.9	1161.5

Discussion

Soybean production based on sequential application

This study demonstrated that sequential application can be more effective weed management for soybean production than any sole application in Primorsky-Krai, Russia. Previous studies also suggested that various herbicides should be sequentially used for soybean to make it superior to weeds (Johnson BJ, 1971; Anderson & McWhorter, 1976; Watts et al., 1997; Soltani et al., 2009). In particular, timely application of herbicides was effective to control the major troublesome weed species; an annual broadleaf weed, *A. artemisiifolia* and an annual grass weed, *E. crus-galli*. *Ambrosia artemisiifolia* and *Echinochloa crus-galli* were commonly found in soybean across Primorsky-Krai (Song et al., 2013), causing soybean yield loss by 80% of weed-free plot (Vail & Oliver, 1993; Cowbrough et al., 2003). Thus, advanced weed management is essential to prevent soybean yield loss from such weed species in that regions. Among sequential treatments, acetochlor-based sequential applications provided the best strategy for improving soybean yield. Acetochlor was proved to be high effective in both broadleaf and grass weeds when applied immediately after sowing soybean (Sweat et al., 1998; Han et al., 2002; Pornprom et al., 2010). Once weed seedling was little established after application of acetochlor, most of PRE herbicides showed good efficacy to weed species. Previous studies also reported that acetochlor-based sequential applications with various POST herbicides provided season-long weed control (Mickelson JA & Harvey RG, 2000).

This study also showed that acetochlor-based sequential applications could provide greater gross profit compared to the untreated plot. Herbicide application may be a big cost for soybean production. However, this study showed that herbicide application increased soybean yield, resulting in the increase in gross profit compared to the untreated plot. Gross profits in acetochlor-based sequential applications were 461.9-730.7 US\$ ha^{-1} and 901.5-1161.5 US\$ ha^{-1} in 2012 and 2013, respectively, while gross profits in the untreated plot were 14.1 US\$ ha^{-1} and 195.0 US\$ ha^{-1} in 2012 and 2013, respectively. The gross profit mainly depends on soybean price and cost of weed control. Hamill et al. (2004) reported that gross profits across years varied with 608, 781, and 340 Can\$ ha^{-1} in soybean, Ontario, where the same soybean price was 240 Can\$ ha^{-1} and cost of weed control were 87.22, 38.14, and 57.25 Can\$ ha^{-1} on average in 1999, 2000, and 2001, respectively. Reddy and Whiting (2000) reported that the gross profit of 356.38 US\$ ha^{-1} was estimated in conventional herbicide program, based on cost of weed control of 163US\$ ha^{-1} and soybean price of 200US\$ ha^{-1}. In this study, much higher gross profit was estimated due to the high soybean price in Primorsky-Krai, Russia.

Estimation of economic thresholds for weed control

Economic thresholds (ET) of weed species can been used to decide on the needs for weed control in crop field on the basis of economic considerations (Marra et al, 1983; Cousens, 1987). ET of weed species is calculated as follows,

$$\mathrm{ET} = \frac{C_h + C_a}{Y_o P \beta H}$$

Where C_h is herbicide cost (US\$ ha^{-1}), C_a is application cost (US\$ ha^{-1}), Y_o is weed-free crop yield (t ha^{-1}), P is value per unit of crop (US\$ t^{-1}), ß is weed competitivity, a proportional loss per unit weed density, and H is herbicide efficacy calculated as efficacy (%)/100, a proportional weed reduction by the herbicide treatment.

Previous studies (Hager & Renner, 1994; Moon et al., 2010) reported that Cousens (1985)' model was useful for determining ET of single weed species to achieve economic return of weed control in crops. The concept of ET can be extended to estimate ET of multiple weed interferences to crops in practical field conditions. A multivariate rectangular hyperbolic model (Kim et al., 2006) provided an information for crop yield loss based on converted density of multiple weed species using density equivalent. If 0.1507 of a proportional loss per unit converted density of multiple weed species is used, ET will be estimated between 0.39 and 0.75 plants m^{-2} with aetochlor-based sequential applications as shown in Table 3-3. Therefore, acetochlor-based sequential applications can be recommended at a converted density of multiple weed species more than 0.39 plants m^{-2} to economic return of weed control in soybean field of far-eastern regions of Russia.

Table 3-3. Estimation of economic thresholds after acetochlor-based sequential applications in 2012 and 2013.

Year	herbicide	Parameter estimates and economic thresholds (ET)						
		C_h (\$ ha^{-1})	C_a (\$ ha^{-1})	Y_0 (ton ha^{-1})	P (\$ ton^{-1})	L	H	ET (No m^{-2})
2012	A	57.5	6.1	1.65	470	0.1507	0.84	0.65
	B	49.0	6.1	1.65	470	0.1507	0.63	0.75
2013	C	87.1	5.9	1.97	650	0.1507	0.98	0.49
	D	67.6	5.9	1.97	650	0.1507	0.98	0.39

C_h: herbicide cost; C_a: application cost; A: acetochlor fb. bentazone+acifluorfen, B: acetochlor fb. bentazone+quizalofop, C: acetochlor fb. bentazone+acifluorfen+tepraloxydim, D: acetochlor fb. bentazone+imazamox; Y_0: weed free soybean yield; P: value per unit of soybean; L: proportional yield loss per unit converted density of multiple weed species; H: proportional reduction in weed density by herbicide treatment calculated as efficacy/100.

Effective and economic weed management in soybean

This study suggested that sequential application of PRE and POST herbicides could be the most effective and economic weed management in soybean field of Bogatyrka. In particular, acetochlor-based sequential application with bentazon+acifluorfen and bentazon+imazamox achieved soybean yield of 1.68 ton ha^{-1} and 1.90 ton ha^{-1} in 2012 and 2013, respectively, by more than 96% of weed-free plot. The acetochlor-based sequential applications provided greatest gross profit of 730.7 US\$ ha^{-1} and 1161.5 US\$ ha^{-1} in 2012 and 2013, respectively. To achieve the target yield and gross profit under weed-infested soybean field, the acetochlor-based sequential applications can be recommended at a converted density of multiple weed species more than 0.39

plants m^{-2}. In conclusion, herbicide-based weed management developed here can be well utilized to prevent loss in soybean yield and gross profit from weeds in soybean field of far-eastern regions of Russia. Further works are necessary to investigate the effectiveness of the herbicide-based weed management in other regions of Russian Far East.

References

Anderson JM and McWhorter. 1976. The economics of common cocklebur control in soybean production. Weed Science 24(4): 397-400.

Cowbrough MJ, Brown RB, and Tardif FJ. 2003. Impact of common ragweed (*Ambrosia artemisiifolia*) aggregation on economic thresholds in soybean. Weed Science 51(6): 947-954.

Cousens R. 1985. A simple model relating yield loss to weed density. Annals of Applied Biology 107: 239-252.

Cousens R. 1987. Theory and reality of weed control thresholds. Plant Protec. Q. 2: 13-20.

Genstat Committee. 2002. Reference Manual (Genstat Release 6.1). VSN International, Oxford, UK.

Hager A and Renner K. 1994. Common ragweed (*Ambrosia artemisiifolia*) control in soybean (*Glycine max*) with bentazon as influenced by imazethapyr or thifensulfuron tank-mixes. Weed Technology 8(4): 766-771.

Hamill AS, Weaver SE, Sikkema PH, Swanton CJ, Tardif FJ, and Ferguson GM. 2004. Benefits and risks of economic vs. efficacious approaches to weed management in corn and soybean. Weed Technology 18(3): 723-732.

Han J, Liu H, Guo P, and Hao C. 2002. Weed control in summer-sown soybeans with flumioxazin plus acetochlor and flumiclorac-pentyl plus clethodim. Weed Biology and Management 2: 120-122.

Johnson BJ. 1971. Effects of sequential herbicide treatments on weeds and soybeans. Weed Science 19(6): 695-700.

Kim DS, Marshall EJP, Brain P, and Caseley JC. 2006. Modeling interactions between herbicide dose and multiple weed species interference in crop-weed competition. Weed Research 46: 175-184.

Marra MC and Carlson GA. 1983. An economic threshold model for weeds in soybeans (*Glycine max*). Weed Science 31(5): 604-609.

Mickelson JA and Harvey RG. 2000. Woolly cupgrass (*Eriochloa villosa*) management in corn (*Zea mays*) by sequential herbicide applications and cultivation. Weed Technology 14: 502-510.

Moon, BC, Cho SH, Kwon OD, Lee SG, Lee BW, and Kim DS. 2010. Modelling rice competition with *Echinochloa crus-galli* and *Eleocharis kuroguwai* in transplanted rice cultivation. Journal of Crop Science and Biotechnology 13(2): 121-126.

Pornprom T, Sukcharoenvipharat W, and Sansiriphun D. 2010. Weed control with pre-emergence herbicides in vegetable soybean (*Glycine max* L. Merrill). Crop Protection 29: 684-690.

Reddy KN and Whiting K. 2000. Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. Weed Technology 14(1): 204-211.

Russian Statistical Yearbook. 2011. Annual statistics. Russian statistical yearbook. Rosstat.

Song JS, Jung JH, Kwon JH, Lim SH, and Kim DS. 2013. Weed survey in soybean fields of Seoul Feed Farm in Primorsky-Krai, Russia.

Proceedings of the Korean Society of Weed Science 33(1): 147-148 (In Korean).

Soltani N, Vyn JD, and Sikkema PH. 2009. Control of common waterhemp (*Amaranthus tuberculatus* var. *rudis*) in corn and soybean with sequential herbicide applications. Canadian Journal of Plant Science 89(1): 127-132.

Sweat JK, Horak MJ, Peterson DE, Lloyd RW, and Boyer JE. 1998. Herbicide efficacy on four *Amaranthus* species in soybean (*Glycine max*). Weed Technology 12: 315-321.

Vail GD and Oliver LR. 1993. Barnyardgrass (*Echinochloa crus-galli*) interference in soybeans (*Glycine max*). Weed Technology 7(1): 220-225.

Watts JR, Murdock EC, Stapleton GS, and Toler JE. 1997. Sicklepod (*Senna obtusifolia*) control in soybean (*Glycine max*) with single and sequential herbicide application. Weed Technology 11: 157-163.

OVERALL CONCLUSION

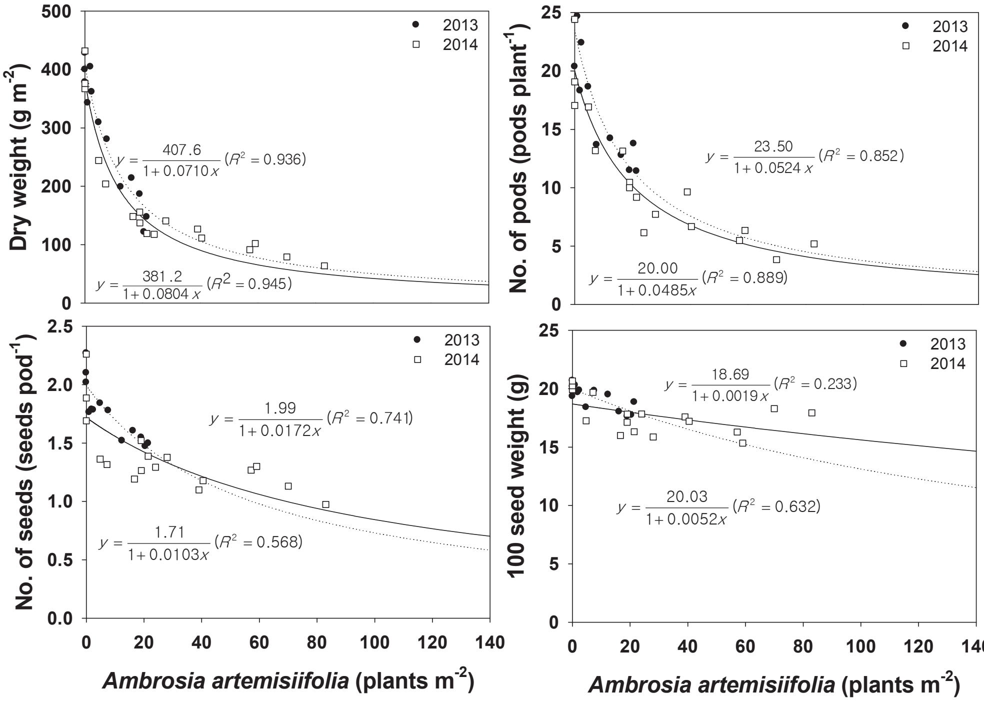
This study was conducted from 2012 to 2014 to model the effects of single and multiple weed interferences and nitrogen fertilizer on soybean yield under and to establish effective and economic weed management system based on the competition models and the sequential herbicide application to support decision-making of weed management for soybean cultivation in Primorsky-krai, Russia.

To model the effect of weed interference on soybean yield under recommended nitrogen fertilization, rectangular hyperbolic model was evaluated for soybean yield in a range of plant density of major weed species found in Primorsky-krai, Russia. The major weed species such as *Ambrosia artemisiifolia*, *Sonchus oleraceus*, *Chenopodium album*, *Echinochloa crus-galli*, and *Beckmannia syzigachne* were naturally established in experimental soybean field of Bogatyrka. Then, they were thinned by hand-weeding to the target densities for individual weed species and their weed combination on June. After thinning weed species by June, the density treatments were maintained throughout the growing season. The rectangular hyperbolic model well described soybean yield influenced by competition of individual weed species. *E. crus-galli* was the most competitive of five weed species, and followed by *A. artemisiifolia*, *S. oleraceus*, *B. syzigachne*, and *C. album*. Using individual equivalent density of five weed species, multivariate rectangular hyperbolic model well described soybean yield influenced by competition of multiple weed species. Therefore, the models could support decision-making for herbicide use under single and multiple weed interferences in soybean cultivation in Primorsky-krai, Russia.

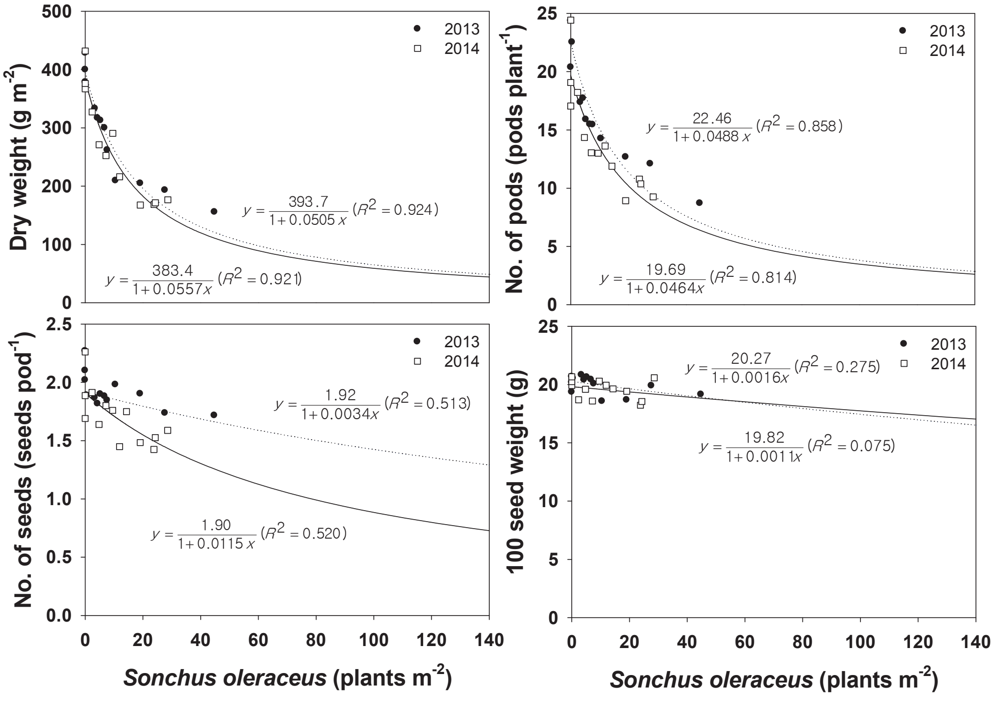
To model the effect of nitrogen fertilizer on soybean-weed competition, inverse quadratic models were incorporated for the two parameters Y_o and β into the rectangular hyperbolic model, and thus a new combined model was developed. The new model was incorporated by two inverse quadratic models for weed-free soybean yield and weed competitivity of rectangular hyperbolic model. Three weed species such as *A. artemisiifolia*, *E. crus-galli*, and *B. syzigachne* were tested solely and in combination to the model. Under different nitrogen levels, the model well described soybean yield influenced by plant density of individual weed species. Additionally, the model well described the both effects of multiple weed interference and nitrogen fertilizer on soybean yield. Therefore, the model could support decision-making for herbicide use under different nitrogen use schemes in soybean cultivation in Primorsky-Krai, Russia.

To establish effective and economic weed management in soybean, 5 PRE herbicides and 6 POST herbicides were tested solely and in combination for crop safety and weed control at 30 days after application and for soybean yield and gross profit at harvest. In an untreated plot, soybean growth was reduced by weed competition, resulting in soybean yield of 1.8% and 15% compared to the weed-free plot in 2013 and 2014, respectively. Acetochlor effectively controlled both grass and broadleaf weeds with good crop safety, but the PRE application was not satisfactory to prevent loss in soybean yield and gross profit from weed infestation. POST herbicides such as bentazon+acifluorfen, bentazon, and imazamox showed an acceptable level of weed control with good crop safety, but the POST application allowed soybean yield and gross profit to be reduced by weeds. Sequential application of PRE and POST herbicides showed better weed control (90% less weeds than the untreated plot) with good crop safety than did their sole application, resulting in better soybean yield and gross profit. In particular, sequential application of acetochlor followed by bentazon+acifluorfen and bentazon+imazamox achieved approximately 1.68 and 1.90 ton ha^{-1} in 2012 and 2013, respectively, more than 96% of weed-free plot. Therefore, the results suggest that the sequential application of PRE and POST herbicides are essential for soybean cultivation in Primorsky-krai, Russia.

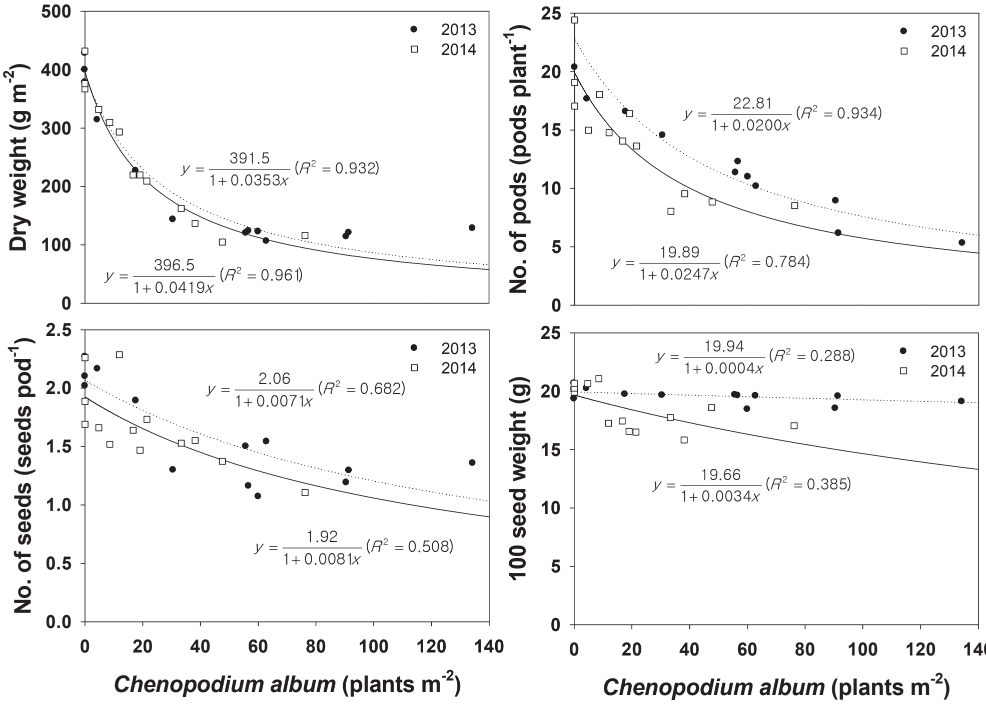
In conclusion, to achieve a target soybean yield and gross profit from weed competition, effective and economic weed management should be established in soybean cultivation in Primorsky-krai. Based on weed competition model, economic threshold (ET) of weed species could be determined to support decision-making for herbicide use. Sequential application of PRE and POST herbicides should be used to adjust ET of weed species below 1.0 (plant m^{-2}). The models and parameter estimates generated from this study can be useful for decision-support of weed control in soybean cultivation, and the herbicide-based weed management with the sequential herbicide application may play an essential role in weed management for soybean in Primorski-krai, Russia.



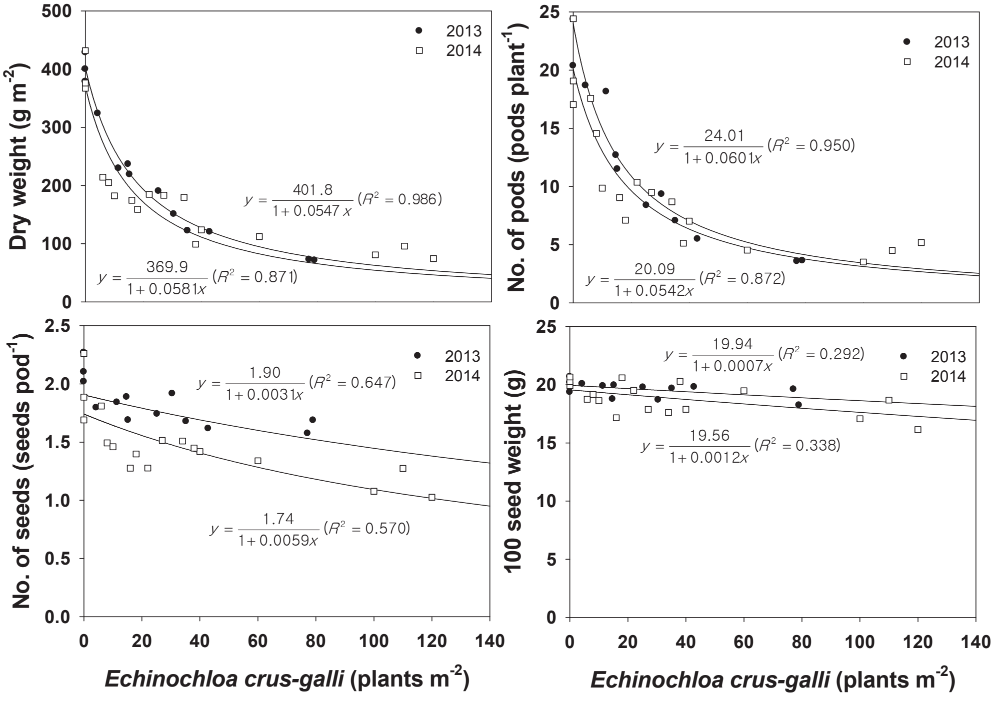
APPENDIX 1-1. Relationship between plant densities of *Ambrosia artemisiifolia* and yield components (no. of pods, no. of seeds, 100-seed weight, and dry weight) in 2013 and 2014. Continuous lines were regressed by rectangular hyperbola.



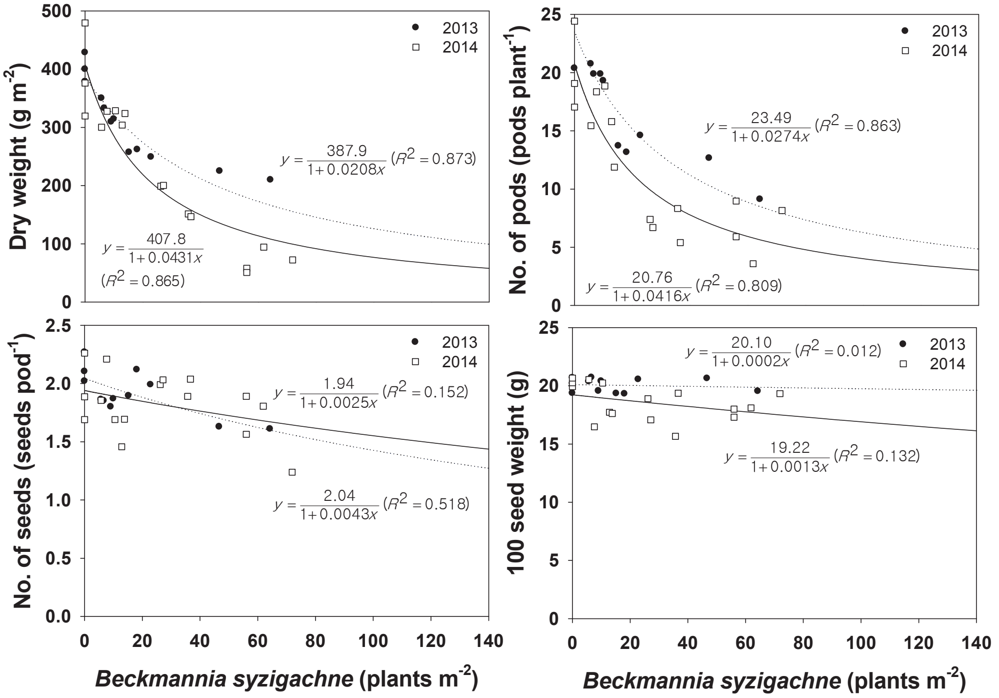
APPENDIX 1-2. Relationship between plant densities of *Sonchus oleraceus* and yield components (no. of pods, no. of seeds, 100-seed weight, and dry weight) in 2013 and 2014. Continuous lines were regressed by rectangular hyperbola.



APPENDIX 1-3. Relationship between plant densities of *Chenopodium album* and yield components (no. of pods, no. of seeds, 100-seed weight, and dry weight) in 2013 and 2014. Continuous lines were regressed by rectangular hyperbola.



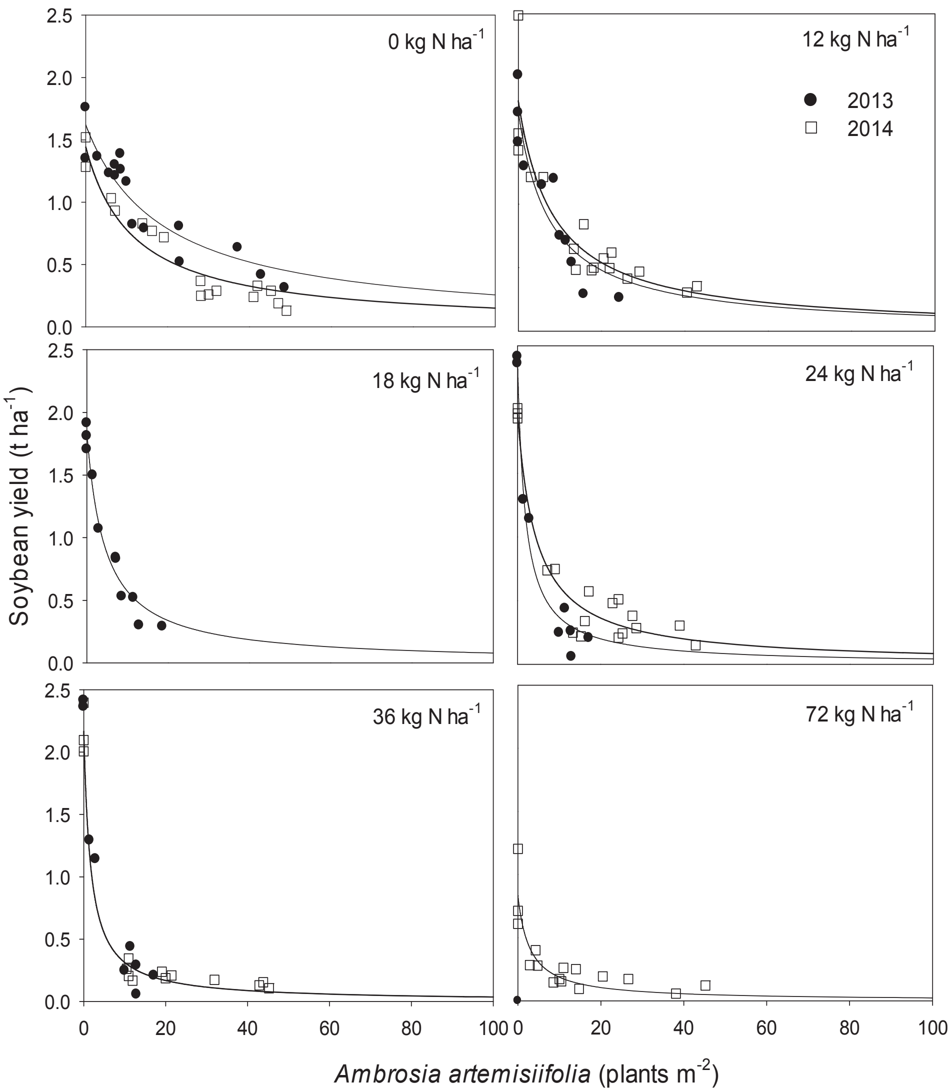
APPENDIX 1-4. Relationship between plant densities of *Echinochloa crus-galli* and yield components (no. of pods, no. of seeds, 100-seed weight, and dry weight) in 2013 and 2014. Continuous lines were regressed by rectangular hyperbola.



APPENDIX 1-5. Relationship between plant densities of *Beckmannia syzigachne* and yield components (no. of plants, no. of pods, no. of seeds, 100-seed weight, and dry weight) in 2013 and 2014. Continuous lines were regressed by rectangular hyperbola.

APPENDIX 2-1. Weed species and densities for soybean-weed competition studies in 2013 and 2014.

Year	Weed species	Nitrogen (kg ha^{-1})	A range of densities (plants plot^{-1})	Number of plots
2013	*Ambrosia artemisiifolia*	0	0 ~ 49	17
		12	0 ~ 24	11
		18	0 ~ 19	11
		24	0 ~ 20	9
		36	0 ~ 17	10
	Beckmannia syzigachne	0	0 ~ 26	11
		12	0 ~ 71	11
		18	0 ~ 49	13
		24	0 ~ 23	9
		36	0 ~ 31	10
	Echinochloa crus-galli	0	0 ~ 91	9
		12	0 ~ 91	9
		18	0 ~ 27	10
		24	0 ~ 16	11
		36	0 ~ 23	13
2 014	*Ambrosia artemisiifolia*	0	0 ~ 49	17
		12	0 ~ 43	17
		24	0 ~ 43	17
		36	0 ~ 45	14
		72	0 ~ 45	16
	Beckmannia syzigachne	0	0 ~ 110	18
		12	0 ~ 56	13
		24	0 ~ 70	15
		36	0 ~ 100	16
		72	0 ~ 100	18
	Echinochloa crus-galli	0	0 ~ 100	11
		12	0 ~ 139	13
		24	0 ~ 139	13
		36	0 ~ 139	16
		72	0 ~ 139	15

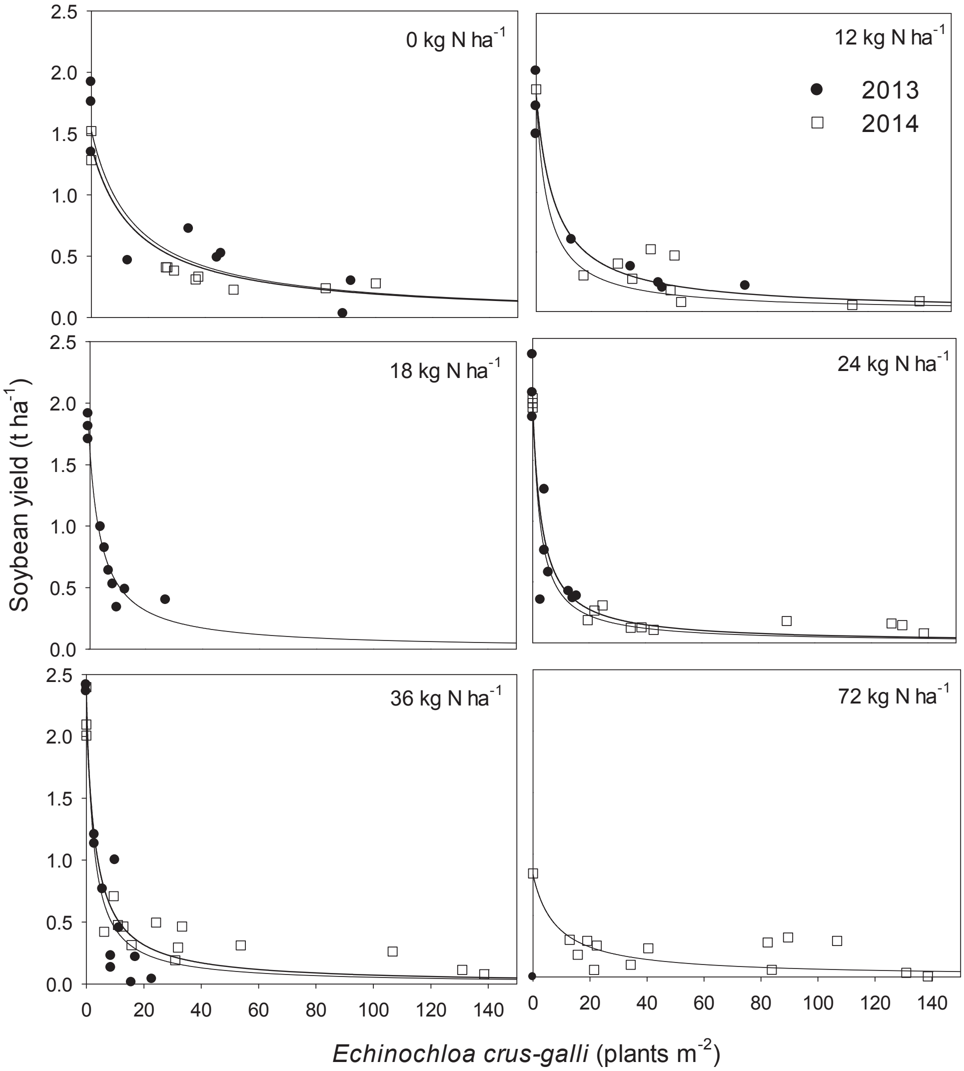


APPENDIX 2-2. Observed and regressed soybean yield as a function of weed density of *Ambrosia artemisiifolia* at different nitrogen fertilizers in 2013 and 2014. The predicted soybean yield (continuous line) was calculated using rectangular hyperbola.

APPENDIX 2-3. Parameter estimates for the functions tested to describe the relationship between parameter β and nitrogen in *Ambrosia artemisiifolia*. The values in parenthesis are standard errors.

Year	Type of response*	Parameter estimates				RMS	R^2
		l	m	n	r		
2013	Constant	0.2364 (0.0839)	-	-	-	0.0352	0
	Linear	-0.0007 (0.0588)	0.0132 (0.0027)	-	-	0.0053	0.886
	Exponential	0.0629 (0.0112)	1.0616 (0.0059)	-	-	0.0008	0.982
	Inverse quadratic	0.0613 (0.0445)	0.0035 (00156)	-0.0181 (0.1209)	3.86×10^{-20} (0.0026)	0.0020	0.985
2014	Constant	0.2724 (0.0922)	-	-	-	0.0425	0
	Linear	0.1438 (0.1310)	0.0045 (0.0035)	-	-	0.0364	0.358
	Exponential	0.1917 (0.1170)	1.0113 (0.0119)	-	-	0.0414	0.270
	Inverse quadratic	0.0264 (0.2503)	0.0153 (0.0563)	4.61×10^{-20} (0.1623)	0.0003 (0.0009)	0.0635	0.626

*Linear response: l+m×nitrogen, Exponential response: $l\times m^{nitrogen}$, Inverse quadratic response: (l+ m×nitrogen)/(1+n×nitrogen+ r×nitrogen^2)

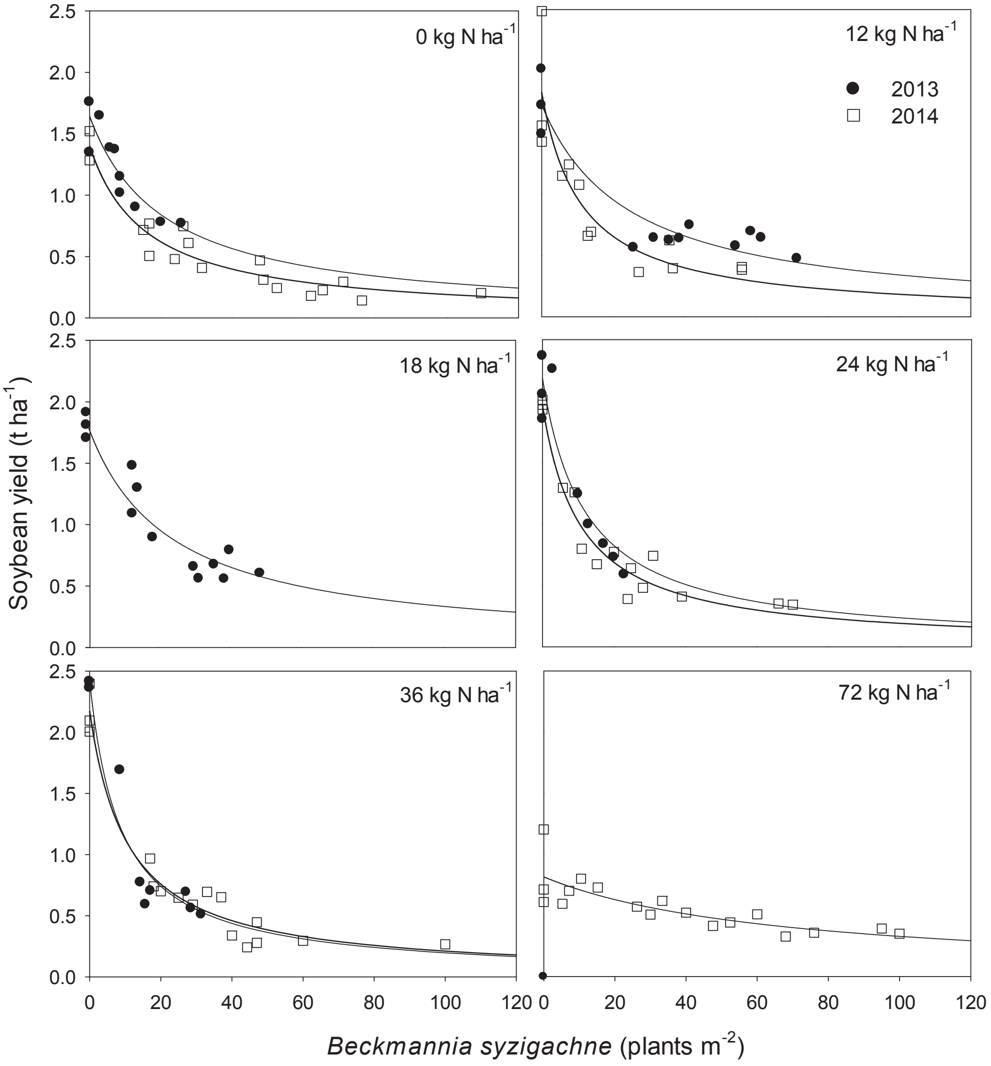


APPENDIX 2-4. Observed and regressed soybean yield as a function of weed density of *Echinochloa crus-galli* in 2013 and 2014. The predicted soybean yield (continuous line) was calculated using rectangular hyperbola.

APPENDIX 2-5. Parameter estimates for the functions tested to describe the relationship between parameter β and nitrogen in *Echinochloa crus-galli*. The values in parenthesis are standard errors.

Year	Type of response*	Parameter estimates				RMS	R^2
		l	m	n	r		
2013	Constant	0.2585 (0.0736)	-	-	-	0.0271	0
	Linear	0.0497 (0.0500)	0.0116 (0.0023)	-	-	0.0038	0.8936
	Exponential	0.1155 (0.0435)	1.0404 (0.0132)	-	-	0.0066	0.8176
	Inverse quadratic	0.0610 (0.0064)	1.83×10^{-30} (0.0005)	-0.0587 (0.0008)	0.0010 (0.00002)	0.00005	0.9995
2014	Constant	0.1912 (0.0455)	-	-	-	0.0104	0
	Linear	0.1829 (0.0805)	0.0003 (0.0021)	-	-	0.0137	0.0061
	Exponential	0.1853 (0.0793)	1.0011 (0.0109)	-	-	0.0138	0.0044
	Inverse quadratic	0.0710 (0.0278)	0.0026 (0.0023)	-0.0430 (0.0069)	0.0008 (0.0002)	0.0010	0.9757

*Linear response: l+m×nitrogen, Exponential response: $l \times m^{nitrogen}$, Inverse quadratic response: (l+ m×nitrogen)/(1+n×nitrogen+ r×nitrogen^2)



APPENDIX 2-6. Observed and predicted soybean yield as a function of weed density of *Beckmannia syzigachne* in 2013 and 2014. The predicted soybean yield (continuous line) was calculated using rectangular hyperbola.

APPENDIX 2-7. Parameter estimates for the functions tested to describe the relationship between parameter β and nitrogen in *Beckmannia syzigachne*. The values in parenthesis are standard errors.

Year	Type of response*	Parameter estimates				RMS	R^2
		l	m	n	r		
2013	Constant	0.0658 (0.0140)	-	-	-	0.0010	0
	Linear	0.0301 (0.0153)	0.002 (0.0007)	-	-	0.0004	0.7238
	Exponential	0.0322 (0.0082)	1.0352 (0.0091)	-	-	0.0002	0.8425
	Inverse quadratic	0.0385 (0.0225)	$3.17\text{x}10^{-21}$ (1.2928)	-0.0184 (1.1024)	$9.07\text{x}10^{-21}$ (0.5106)	0.0005	0.8681
2014	Constant	0.0708 (0.0151)	-	-	-	0.0011	0
	Linear	0.0708 (0.0268)	$7.03\text{x}10^{-20}$ (0.0007)	-	-	0.0015	0
	Exponential	0.0904 (0.0247)	0.991 (0.0096)	-	-	0.0010	0.3268
	Inverse quadratic	0.0605 (0.0153)	$1.72\text{x}10^{-26}$ (0.0012)	-0.0345 (0.013)	-0.0345 (0.013)	0.0003	0.9412

*Linear response: l+m×nitrogen, Exponential response: $l \times m^{nitrogen}$, Inverse quadratic response: $(l+ m\times nitrogen)/(1+n\times nitrogen+ r\times nitrogen^2)$

APPENDIX 2-8. Parameter estimates for the functions tested to describe the relationship between parameter β and nitrogen in multiple weed species. The values in parenthesis are standard errors.

Year	Type of response*	Parameter estimates				RMS	R^2
		l	m	n	r		
2013	Constant	0.2197 (0.0718)	-	-	-	0.0257	0
	Linear	0.0190 (0.0540)	0.0112 (0.0025)	-	-	0.0045	0.8695
	Exponential	0.0647 (0.0108)	1.0573 (0.0056)	-	-	0.0007	0.9809
	Inverse quadratic	0.0748 (0.0389)	0.0022 (0.0192)	-0.0189 (0.1646)	1.01×10^{-19} (0.0035)	0.0001	0.9852
2014	Constant	0.2305 (0.0621)	-	-	-	0.0193	0
	Linear	0.1806 (0.1035)	0.0017 (0.0027)	-	-	0.0227	0.1187
	Exponential	0.1978 (0.0977)	1.0052 (0.0112)	-	-	0.0236	0.0844
	Inverse quadratic	0.0778 (0.0066)	0.0014 (0.0004)	-0.0382 (0.0007)	0.0005 (0.00003)	0.00006	0.9992

ABSTRACT IN KOREAN

러시아 연해주 콩 생산지역에서 콩−잡초 경합피해 예측모델을 이용한 잡초관리시스템 구축

송종석

작물생명과학전공

식물생산과학부

서울대학교 농업생명과학대학

러시아 연해주는 한국의 해외농업의 중심지로서 다수의 영농기업들이 진출하여 콩을 주 작물로 대규모 영농을 하고 있으나 잡초방제의 문제로 수량성이 매우 낮아 손익분기점에 도달하지 못하고 있다. 따라서 본 연구는 연해주 콩 재배지에서 콩−잡초 경합 피해를 수학적 모델을 활용하여 해석하여 요방제 수준을 결정하고, 콩−잡초 경합모델과 제초제 체계처리를 기반으로 한 잡초방제 체계구축을 위해 수행되었다. 표준 질소시비 조건에서 주요 잡초인 돼지풀(0.134), 방가지똥(0.083), 명아주(0.064), 피(0.151), 개피(0.076)의 경합에 의한 콩 수량피해를 rectangular hyperbolic model 의 초종별 경합력으로

해석하였으며, 콩 재배조건에서 다종잡초의 경합피해를 해석하기 위해서 이들 잡초의 개별 경합력을 상대수치화 한 density equivalent 를 활용한 multivariate rectangular hyperbolic model 을 확립하였다. 질소시비 수준에 따른 경합모델을 확립하기 위하여, 다양한 수준의 질소시비 조건에서 돼지풀, 피, 개피의 단초종 또는 다초종 경합피해 해석을 위한 rectangular hyperbolic model 을 구축하고, 질소시비량 증가에 따른 무경합 콩 수량(Y_o)과 경합력(ß)의 변화를 inverse quadratic model 로 해석하고, rectangular hyperbolic model 에 inverse quadratic model 을 결합시킨 통합모델을 구축하였다. 이 통합모델을 단종잡초 또는 다종잡초 경합조건에 적용하여 combined multivariate rectangular hyperbolic model 을 구축하였다. 이들 모델을 기반으로 콩 잡초방제 시스템 구축을 위해 잡초발아 전(PRE) 토양처리제 5 종과 잡초발아 후(POST) 경엽처리제 6 종을 단독 및 체계처리로 평가하여 PRE 로는 acetochlor 를 POST 로는 bentazon+acifluorfen, bentazon+imazamox 를 체계 처리하는 것이 콩 잡초방제 및 수량성 제고에 가장 효율적임을 확인하였다. 제초제기반 잡초방제법에 대한 경제성 분석을 통해 acetochlor fb. bentazon 합제의 제초제 체계처리 시스템을 확립하였다. 잡초경합모델의 결과와 제초제기반 잡초방제시스템을 종합한 결과 제초제처리 의사결정의 기준점이 요방제수준(economic threshold)가 m^2 당 1 개체 이하임을 설정할 수 있었다. 종합적으로 본 연구는 러시아 연해주 콩 재배지역에 적합한 콩-잡초 경합모델을 구축하였으며, 효과적이고 경제적인 제초제 기반 잡초방제 체계를 구축하여 연해주 콩 재배생산에 크게 기여할 것으로 판단되었다.

주요어: 작물-잡초 경합, 잡초방제시스템, 질소시비, 체계처리, 콩, 연해주

학번: 2010-21152