From
the Institute of Phytomedicine
University of Hohenheim
Department of Weed Science
Prof. Dr. R. Gerhards

Effects of weeds on yield and determination of economic thresholds for site-specific weed control using sensor technology

Dissertation
Submitted in fulfillment of the requirements for the degree Doktor der Agrarwissenschaften Dr.sc.agr./Ph.D. in Agricultural Sciences
to the Faculty of Agricultural Sciences University of Hohenheim

First submitted: September 2013
Revisions submitted: October 2014

by Master of Science ETH in Agroecosystem Science
Martina Keller
born 6 of February 1982
in St. Gallen, Switzerland

This thesis was accepted as a doctoral dissertation in fulfillment of the requirements for the degree "Doktor der Agrarwissenschaften" (Dr. sc. agr. / Ph.D. in Agricultural Sciences) by the Faculty of Agricultural Sciences at the University of Hohenheim, on January 14, 2014.

Date of oral Examination:	February 25, 2014
Dean:	Prof. Dr. M. Brockmeier
Examination Commitee:	
Supervisor and Review:	Prof. Dr. R. Gerhards
Co-Reviewer:	Prof. Dr. H.-P. Piepho
Additional Examiner:	Prof. Dr. H.W. Griepentrog
Head of the Comittee:	Prof. Dr. S. Böttinger

Unkraut vergeht nicht

(German proverb)

Erklärung

gemäß § 8.2.2. der Promotionsordnung der Universität Hohenheim zum Dr.sc.agr.

Hiermit erkläre ich an Eides statt, dass die vorliegende Arbeit mit dem Titel:

"Effects of weeds on yield and determination of economic thresholds for site-specific weed control using sensor technology"

von mir selbst verfasst und lediglich unter Zuhilfenahme der angegebenen Quellen und Hilfsmittel angefertigt wurde und ich mich keiner unzulässigen Hilfe Dritter bedient habe. Wörtlich oder sinngemäss aus anderen Werken übernommene Inhalte wurden als solche gekennzeichnet.

Insbesondere erkläre ich, dass ich nicht früher oder gleichzeitig einen Antrag auf Eröffnung eines Promotionsverfahrens unter Vorlage der hier eingereichten Dissertation gestellt habe und ich nicht die Hilfe einer kommerziellen Promotionsvermittlung oder -beratung in Anspruch genommen habe.

[Martina Keller] Winterthur, October 2014

Abstract: Weeds can cause high yield losses. Knowledge about the weeds occurring, their distribution within fields and their effects on the crop yield is important to achieve effective weed control. The critical period for weed control (CPWC) and the economic threshold (ET) are important key concepts and management tools in weed control. While the former helps to time weed control in crops of low competitiveness, the latter provides a decision aid to determine whether weed control is necessary. This decision is generally taken at the field level.

Weeds have been found to be distributed heterogeneously within fields. Site-specific weed control (SSWC) addresses this sub-field variation by determining weed distribution as input, by taking control decisions in the decision component and by providing control measures as output at high spatial resolution. Sensor systems for automated weed recognition were identified as prerequisite for SSWC since costs for scouting are too high. While experiences with SSWC using sensor data as input are still scarce, studies showed that considerable herbicide savings could be achieved with SSWC.

ETs can serve as thresholds for the decision component in SSWC systems. However, the commonly used ETs were suggested decades ago and have not been updated to changing conditions since. The same is the case for the CPWC in maize in Germany. In addition, the approaches to determine the CPWC are usually not based on economic considerations, which are highly relevant to farmers. Thus, the objectives of this thesis are:

1. To test different models and to provide a straightforward approach to integrate economical aspects in the concept of the CPWC for two weed control strategies: Herbicide based (Germany) and hoeing based (Benin);

2. To determine the effect of weeds on yield and to calculate ETs under current conditions which can be used for SSWC;

3. To evaluate the use of bi-spectral cameras and shape-based classification algorithms for weed detection in SSWC; and

4. To determine changes in weed frequencies, herbicide use and yield over the last 20 years in southwestern Germany.

Datasets in maize from Germany and Benin served as input for the CPWC analyses. The log-logistic model was found to provide a similar fit as the commonly used models but its parameters are biologically meaningful. For Germany, analyses using a full cost model revealed that farmers should aim at applying herbicides early before the 4-leaf stage of maize.

In Benin, where weed control is mainly done by hoeing, analyses showed that one well-timed weeding operation around the 10-leaf stage could already be cost-effective. A second weeding operation at a later stage would assure profit.

The precision experimental design (PED) was employed to determine the effect of weeds, soil properties and herbicides on crop yield in three winter wheat trials. In this design, large field trials' geodata of weed distribution, herbicide application, soil properties and yield are used to model the effects of the former three on yield. *Galium aparine*, other broad-leaved weeds and *Alopecurus myosuroides* reduced yield by 17.5, 1.2 and 12.4 kg ha^{-1} $plant^{-1}$ m^2 determined by weed counts. The determined thresholds for SSWC with independently applied herbicides were 4, 48 and 12 plants m^{-2}, respectively. Bi-spectral camera based weed–yield estimates were difficult to interpret showing that this technology still needs to be improved. However, large weed patches were correctly identified.

ETs derived of field trials' data carried out at several sites over 13 years in the framework of the 'Gemeinschaftsversuche Baden-Württemberg' were 9.2-9.8 and 4.5-8.9 % absolute weed coverage for winter wheat and winter barley and 3.7% to 5.5% relative weed coverage for maize. Overall, the weed frequencies in winter cereals were found to be more stable than the weed frequencies in maize during the observation period. In maize, a frequency increase of thermophilic species was found. Trends of considerable yield increases of 0.16, 0.08 and 0.2 t ha^{-1} for winter wheat, winter barely and maize, respectively, were estimated if weeds were successfully controlled.

In order to evaluate the use of bi-spectral cameras and shapebased classification algorithms for weed detection in SSWC, herbicides were applied site-specifically using weed densities determined by bi-spectral camera technology in a winter wheat and maize field. Threshold values were employed for decision taking. Using this approach herbicide savings between 58 and 83 % could be achieved. Such reductions in herbicide use would meet the demand of society to minimize the release of plant protection products in the environment. Misclassification occurred if weeds overlapped with crop plants and crop leaf tips were frequently misclassified as grass weeds. Improvements in equipment, especially between the interfaces of camera, classification algorithms, decision component and sprayer are advisable for further trials.

In conclusion, the derived ETs can be easily implemented in a straightforward SSWC system or can serve as decision aid for farmers in winter wheat and winter barley. Further model testing and adjusting would be necessary. For maize, the use of ETs at the field level is not suggested by this study, however the need for early weed control is clearly demonstrated. Bi-spectral camera technology combined with classification algorithms to detect weeds is promising for research use and for SSWC, but still requires some technical improvements.

Kurzfassung: Unkräuter können hohe Ertragsverluste verursachen. Kenntnis über die vorkommenden Unkräuter, deren Verteilung in den Feldern und deren Wirkung auf den Ertrag sind wichtig, um eine wirksame Unkrautkontrolle zu erzielen. Die kritische Periode (KP) und Schadensschwelle (SSW) sind Schlüsselkonzepte und wichtige Kontrolmaßnahmen in der Unkrautkontrolle. Erstere hilft die Unkrautkontrolle in Kulturen mit geringer Konkurrenzkraft zu determinieren, letztere ermöglicht eine Entscheidungshilfe um zu bestimmen, ob eine Kontrollmaßnahme notwendig ist. Diese Entscheidung wird meist für das ganze Feld getroffen.

Unkräuter weisen jedoch eine heterogene Verteilung im Feld auf. Die teilschlagspezifische Unkrautkontrolle (SSWC) berücksichtigt diese Variabilität innerhalb eines Feldes, in dem sie die Unkrautverteilung als Input bestimmt, in der Entscheidungskomponente entscheidet, ob eine Kontrollmaßnahme notwendig ist und diese auch mit einer hohen räumlichen Auflösung als Output ausführt. Sensoren für eine automatisierte Unkrauterkennung sind als notwendig für SSWC identifiziert worden, da die Kosten zu hoch sind, um die Unkrautverteilung von Hand zu bestimmen. Obwohl noch relativ wenig Erfahrung mit SSWC unter Verwendung von Sensordaten vorliegt, konnte in Studien nachgewiesen werden, dass beträchtliche Herbizideinsparungen mit SSWC erzielt werden können. SSWs können als Schwellenwerte innerhalb der Entscheidungskomponente eines SSWC-Systems dienen. Die zurzeit verwendeten SSWs wurden jedoch vor Jahrzehnten vorgeschlagen und seitdem nicht konsequent an die sich ändernden Bedingungen angepasst. Das Gleiche ist der Fall für die KP in Mais in Deutschland. Außerdem werden zur Bestimmung der KP normalerweise keine ökonomische Aspekte herangezogen, was jedoch sehr relevant für die Landwirte ist. Daher waren die Ziele dieser Arbeit:

1. Verschiedene Modelle zu testen und einen einfachen Ansatz zu finden, um ökonomische Aspekte in das Konzept der KP für zwei Strategien zu integrieren: Herbizid basiert (Deutschland) und basierend auf Hacken (Benin).

2. Die Unkrautwirkung auf den Ertrag zu bestimmen und SSWs unter aktuellen Bedingungen zu berechnen, die dann auch für SSWC genutzt werden können.

3. Den Einsatz von Bispektralkameras und formbasierter Klassifizierungsalgorithmen für die Unkrauterkennung in SSWC zu evaluieren.

4. Änderungen im Vorkommen von Unkräutern und Herbizideinsatz und Ertragssveränderungen in den letzten 20 Jahren in Südwestdeutschland zu untersuchen.

Datensätze von Maisversuchen aus Deutschland und Benin wurden für die Auswertungen zur KP herangezogen. Das log-logistische Model wies eine vergleichbare Güte auf

wie die üblicherweise benutzten Modelle, wobei das genannte Modell jedoch über biologisch interpretierbare Parameter verfügt. Für Deutschland zeigte ein Vollkostenmodell, dass die Landwirte die chemische Unkrautkontrolle zu einem sehr frühen Zeitpunkt vor dem 4-Blattstadium des Maises durchführen sollten. In Benin, wo die Unkrautkontrolle vor allem mit Hacken erfolgt, zeigten die Auswertungen, dass bereits ein Hackdurchgang um das 10-Blattstadium zu einem Gewinn führen kann und ein weiterer Durchgang diesen sichert.

Der 'Precision Experimental Design' Ansatz (PED) wurde verwendet, um den Ertragseffekt von Unkräutern, Bodeneigenschaften und Herbizidanwendung in drei Winterweizenversuchen zu bestimmen. In diesem Ansatz, werden Geodaten von grossflächigen Feldversuchen bzw., deren Unkrautverteilung, Herbizidanwendung, Bodeneigenschaften und Ertrag verwendet um den Effekt der ersteren drei auf den Ertrag zu modellieren. *Galium aparine*, andere breitblättrige Unkräuter und *Alopecurus myosuroides* reduzierten den Ertrag um 17.5, 1.2 und 12.4 kg ha^{-1} $Pflanze^{-1}$ m^2 berechnet anhand der manuell bestimmten Verunkrautung. Die Schadensschwellen für SSWC mit der Möglichkeit Herbizide unabhängig zu applizieren, waren 4, 48 und 12 Pflanzen je m^2, jeweils. Schätzungen der Unkraut–Ertragswirkung anhand der Bispektralkameradaten waren schwierig zu beurteilen. Das zeigt, dass diese Technologie noch weiter verbessert werden muss. Jedoch wurden große Unkrautnester richtig erkannt.

SSWs bestimmt anhand von Feldversuchsdaten, die an verschiedenen Standorten über einen Zeitraum von 13 Jahren innerhalb der Gemeinschaftsversuche Baden-Württemberg durchgeführt worden waren, betrugen 9.2-9.8 und 4.5-8.9% absolute Unkrautbedeckung in Winterweizen und Wintergerste sowie 3.7% bis 5.5% relative Unkrautbedeckung in Mais. Insgesamt konnte gezeigt werden, dass die beobachteten Unkrauthäufigkeiten in Wintergetreide stabiler waren als in Mais in dem beobachteten Zeitraum. In Mais, konnte eine Zunahme der Häufigkeit von thermophilen Arten festgestellt werden. Eine tendenzielle und beträchtliche Ertragszunahme von 0.16, 0.08 und 0.2 t ha^{-1} für Winterweizen, Wintergerste und Mais konnte ermittelt werden, wenn das Unkraut erfolgreich kontrolliert wurde.

Um den Einsatz von Bispektralkameras und formbasierter Klassifizierungsalgorithmen für SSWC zu evaluieren, wurden die Unkrautdichten in einem Winterweizen und in einem Maisfeld mit dieser Technologie bestimmt und Herbizide teilschlagspezifisch appliziert. Schwellenwerte wurden für die Entscheidungsfindung verwendet. Unter Verwendung dieses Ansatzes konnten Herbizideinsparungen von 58 bis 83 % erreicht werden. Derartige Einsparungen würden auch dem gesellschaftlichen Wunsch, die Freisetzung von Pflanzenschutzmitteln in die Umwelt zu minimieren, entsprechen. Eine Fehlklassifizierung trat vor allem auf, wenn es zu Überlappungen zwischen den Unkräutern und Kulturpflanzen gab und oft wurden auch Blattspitzen der Kulturpflanze als Ungräser klassifiziert. Verbesserungen in der

Ausstattung der Geräte ins besondere der Schnittstellen zwischen Bispektralkameras, Klassifizierungsalgorithmen, der Entscheidungskomponente und der Feldspritze sind empfehlenswert für weitere Versuche.

Die bestimmten SSWs können einfach in ein überschaubares SSWC-System eingebaut werden oder auch als Entscheidungshilfe für Landwirte in Winterweizen und Wintergerste dienen. Jedoch sind weitere Tests und Anpassungen notwendig. Für Mais ist von der Verwendung von SSWs auf Ebene 'Feld' abzuraten. Die Notwendigkeit einer frühen Unkrautkontrolle konnte jedoch in dieser Studie deutlich gezeigt werden. Bispektralkamera Technologie kombiniert mit formbasierten Klassifizierungsalgorithmen zur Erfassung der Verunkrautung in Feldern ist erfolgsversprechend für die Anwendung in der Forschung und für SSWC, weitere technische Verbesserungen sind jedoch notwendig.

Acknowledgement:
At this point I would like to thank many people and institutions: Prof. Dr. Roland Gerhards for giving me the opportunity to work on this project; my colleagues Dr. Christoph Gutjahr, Dr. Victor Rueda Ayala and Dr. Martin Weis for their support, teamwork and the fruitful talks and discussions; Dr. Jens Möhring for the enlightening discussions, advises and his patience; Prof. Dr. Hans-Peter Piepho for his amazing lectures on statistics; my colleagues from SenGIS for the great teamwork; Markus Pflugfelder the current and Helmut Kärcher the former manager of the field trial division and the staff from the Ihinger Hof in general; the Carl Zeiss Stiftung for funding; my current colleagues for their support; Vanessa Windhausen, Sarah Bryner and Steve Policar; and my family and my friends for all their help during these challenging years.

This project was funded by the Carl-Zeiss-Stiftung.

Contents

Chapter 1

General introduction

1.1 Structure of the dissertation

In this work several approaches were used to determine the effect weeds on crop yield, to derive economic thresholds (ETs) in winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.) and maize (*Zea mays* L.). A further topic was the critical period for weed control (CPWC) in maize. Changes in weed frequencies, herbicide use and yield trends in these crops were investigated for Baden-Württemberg (southwestern Germany).

This thesis consists of a general introduction (chapter 1) outlining the structure, the objectives and the publications of the thesis. The second chapter 'Publications' (chapter 2) consists of two book chapters (sections 2.1 and 2.2), four research articles (sections 2.3, 2.4, 2.6 and 2.7), and a conference proceeding (section 2.5). The book chapters provide an introduction into the topic of the thesis. The first section (section 2.1) of chapter 2 deals with possibilities to reduce herbicide use and therefore to minimize herbicide release into the environment, wherein SSWC could play an important role. In the second section (section 2.2), the use of sensor technology in weed science especially to derive the relationship between weed infestation and crop yield under practical field conditions is briefly presented. This application is put in the broader context of precision farming, sensor technology and geoinformation systems. These topics are the main research area of the competence centre SenGIS in which this work was embedded.

In section 2.3, different models and economical calculations are employed to derive the CPWC in maize using datasets from Germany and Benin.

In section 2.4 the precision experimental design (PED) is employed and further developed. The PED uses the natural heterogeneity of large field trials to derive the effect of herbicide treatment, weeds and soil properties. One focus of this study is the comparison of weed counts and automated weed detection by a sensor system as input for the PED. With the estimates ETs can be calculated for different approaches for site-specific weed control (SSWC). In section 2.5, the use of bi-spectral camera technology to determine weed distribution for SSWC was evaluated.

As the ETs derived from the PED trials are the results of two trials carried out in two years and in one year an unusual severe drought in spring occurred, the year variation of the weed-crop yield relationship could not be considered. Thus, data of the 'Common field trials Baden-Württemberg' [Gemeinschaftsversuche Baden-Württemberg] was employed for further analyses. In sections 2.6 and 2.7 yield loss models are applied to these data, ETs are computed and yield trends over time are studied. Changes in weed frequency and changes in herbicide use over time are described and discussed. In the general discussion (Chapter 3), the different sections are put in context and are discussed.

1.2 Objectives of the dissertation

The main objective of this thesis was to model the relationship between weeds and crop yield using different input data (archived data, weed counts and sensor technology), methods and approaches. These established relationships and determined economic thresholds (ETs) can be used for simple decision systems in site-specific weed control (SSWC) or to advise farmers. They can also be seen as an update to the traditional ETs determined by Niemann (1981) based among others on the two doctoral theses of Garburg (1974) and Beer (1979); tested by Gerowitt and Heitefuss (1990). Yield curves determined by the PED (Precision Experimental Design) and yield loss curves determined with the data of the 'Common field trials Baden-Württemberg' served to determine ETs. Further aim of working with these data was also to get insights into changes in weed frequencies and used herbicides in southwestern Germany. A further objective of this thesis was to determine the onset of the critical period for weed control (CPWC) in maize under current conditions as the study of Koch and Kemmer (1980), in which the CPWC for Germany was determined, dates back decades. In addition an aim was to compare different equations for modeling the effect of increasing length of weed competition on yield and increasing length of weed-free conditions on yield. Further aim was to provide a straightforward, simple approach to implement economic calculations for herbicide based and an hoeing based weed management systems into the standard method to determine the CPWC.

To sum up the main objectives of this thesis were:

1. To test different models and to provide a straightforward approach to integrate economics in the concept of the CPWC for two weed control strategies: Herbicide based (Germany) and hoeing based (Benin);
2. To determine the effect of weeds on yield and to calculate ETs under current conditions which then can be used for SSWC;
3. To evaluate the use of bi-spectral cameras and shape-based classification algorithms for weed detection in SSWC; and
4. to determine changes in weed frequencies, herbicide use and yield over the last 20 years in southwestern Germany.

Secondary objectives of this study were:

i To apply and to further develop the 'Precision Experimental Design' as published by Ritter et al. (2008) and by Gerhards et al. (2012); and ii To compare weed counts by scouting and sensor technology as input for the 'Precision Experimental Design'.

1.3 Publications related to the dissertation

The publications related to, written and contributed to during this dissertation are listed below:

Reviewed publications:

Keller, M., C. Gutjahr, J. Möhring, M. Weis, M. Sökefeld, and R. Gerhards (2014). Estimating economic thresholds for site-specific weed control using manual weed counts and sensor technology: An example based on three winter wheat trials. *Pest Management Science 70*, 200–211. (section 2.4) (Keller et al., 2014)

Keller, M., N. Böhringer, J. Möhring, V. Rueda-Ayala, C. Gutjahr, and R. Gerhards (2014). Long-term changes in weed occurrence, yield and use of herbicides in maize in south-western Germany, with implications for the determination of economic thresholds. *Weed Research 54*, 457–466. (section 2.6) (Keller et al., 2014)

Gerhards, R., C. Gutjahr, M. Weis, M. Keller, M. Sökefeld, J. Möhring, and H.-P. Piepho (2012). Using precision farming technology to quantify yield effects attributed to weed competition and herbicide application. *Weed Research 52*, 6–15. (Gerhards et al., 2012)

Rueda-Ayala, V., M. Weis, M. Keller, D. Andújar, and R. Gerhards (2013). Development and testing of a decision making based method to adjust automatically the harrowing intensity. *Sensors 13*, 6254–6271. (Rueda-Ayala et al., 2013)

Reviewed book chapters:

Weis, M., M. Keller, and V. Rueda Ayala (2012, January). *Herbicides - Environmental Impact Studies and Management Approaches*, Chapter Herbicide Reduction Methods, pp. 95–120. Rijeka, Croatia: Intech. (section 2.1) (Weis et al., 2012)

Keller, M., C. Zecha, M. Jackenkroll, M. Weis, J. Link-Dolezal, R. Gerhards and W. Claupein (2012). *ICT for agriculture, rural development and environment: Where we are? Where we will go?*, Chapter Competence centre SenGIS - exploring methods for georeferenced multi-sensor data acquisition, storage, handling and analysis, 218–229. Prague, Czech Republic, České centrum pro vědu a společnost (Czech Centre for Science and Society). (section 2.2) (Keller et al., 2012)

Reviewed conference proceedings:

Keller, M., C. Zecha, M. Weis, J. Link-Dolezal, R. Gerhards, and W. Claupein (2011, July). Competence centre SenGIS - exploring methods for multisensor data acquisition and handling. J.V. Stafford (Ed), pp. 491–500. Papers presented at the 8th European Conference on Precision Agriculture 2011, Prague, Czech Republic, 11-14 July 2011. (Keller et al., 2011)

Keller, M., G. Gantoli, A. Kipp, C. Gutjahr, and R. Gerhards (2012, March). The effect and dynamics of weed competition on maize in Germany and Benin. H. Nordmeyer and L. Ulber (Eds), pp. 289–299. Papers presented at the 25th German Conference on Weed Biology and Weed Control, Braunschweig, 13-15 March 2012. (Keller et al., 2012)

Gutjahr, C., M. Keller, J. Möhring, M. Weis, M. Sökefeld, H. P. Piepho, and R. Gerhards (2011, July). Measuring yield effect of weeds and herbicide application in small annual grains and maize using the precision experimental design. J.V. Stafford (Ed), pp. 203–212. Papers presented at the 8th European Conference on Precision Agriculture 2011, Prague, Czech Republic, 11-14 July 2011. (Gutjahr et al., 2011)

Sökefeld, M., M. Keller, M. Weis, C. Gutjahr, and R. Gerhards (2012, March). Using bi-spectral imaging technology for simulated online-weed control in winter wheat and maize. H. Nordmeyer and L. Ulber (Eds), pp. 183–190. Papers presented at the 25th German Conference on Weed Biology and Weed Control, Braunschweig, 13-15 March 2012. (section 2.5) (Sökefeld et al., 2012)

Workshop proceedings:

Keller, M., M. Weis and R. Gerhards (2010, August). Biomass estimation from images for greenhouse experiments. In M. Zude and M. Kraft (Eds.), *Proceedings 16. Workshop Computer-Bildanalyse in der Landwirtschaft*, Volume 73 of *Bornimer Agrartechnische Berichte*, Potsdam-Bornim/Braunschweig, 13–20. Leibnitz Institute for Agricultural Engineering (ATB): ATB. 16. Workshop Computer-Bildanalyse in der Landwirtschaft. (Keller et al., 2010)

Accepted:

Keller, M., G. Gantoli, J. Möhring, C. Gutjahr, R. Gerhards, and V. Rueda-Ayala. Integrating Economics in the Critical Period for Weed Control Concept in Corn. Accepted by *Weed Science*. (section 2.3)

Keller, M., N. Böhringer, J. Möhring, V. Rueda-Ayala, C. Gutjahr, and R. Gerhards. Changes in weed communities, herbicides, yield levels and effect of weeds on yield in winter cereals based on three decades of field experiments in south-western Germany. Accepted by *Gesunde Pflanzen*. (section 2.7)

Chapter 2

Publications

2.1 Herbicide reduction methods

Martin Weis[†], Martina Keller[†], Victor Rueda-Ayala[†]

[†] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, Stuttgart, Germany.

Herbicides - Environmental Impact Studies and Management Approaches, InTech, 2012 edited by Ruben Alvarez-Fernandez. 95-120

The original publication is freely available at:
`http://www.intechopen.com/articles/show/title/herbicide-reduction-methods`

Abstract

Chemical weed control is faced by many challenges in the new millennium. For example public awareness of environmental pollution is increasing. This results in stricter regulations for weed control and herbicide use. Furthermore the number of herbicide with new active ingredients put on the market has decreased considerably in the last years. In addition available herbicides become less effective due to emerging resistant weed biotypes. Thus, farmers in several countries are obliged to implement integrated pest management strategies, which do not only rely on chemical weed control. In order to support farmers challenged by these new requirements innovative methods need to be found and developed. For instance, multiple decision support systems have already been developed to maximise the weed control effect

and to optimise the application of herbicides economically. In this chapter approaches to reduce the amount of herbicides applied in the fields are outlined. The potentials and technical possibilities of these different approaches and methods are presented and discussed.

2.2 Competence centre SenGIS - exploring methods for geo-referenced multi-sensor data acquisition, storage, handling and analysis

Martina Keller[†], Christoph Zecha[††], Markus Jackenkroll[†], Martin Weis[†], Johanna Link-Dolezal[††], Roland Gerhards[†], Wilhelm Claupein[††]

[†] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, Stuttgart, Germany.

[††] Department of Agronomy, Institute of Crop Science, University of Hohenheim, Stuttgart, Germany.

ICT for agriculture, rural development and environment: Where we are? Where we will go? České centrum pro vědu a společnost (Czech Centre for Science and Society) Czech Centre for Science and Society edited by Tomas Mildorf and Karel Charvat jr. address = Prague, Czech Republic. 218-229

The original publication is freely available at:
`http://www.ccss.cz/books/ict_agr/ICT_for_Agriculture.pdf`

Abstract

In precision farming challenges are the development of sensor systems for site-specific management, sensor fusion and analyses schemes for related tasks. In research the acquisition and handling of multi-sensor data is becoming more important and it is essential for the development of innovative management techniques. With this background the centre SenGIS was founded. In this chapter the main components of SenGIS, two different types of sensor platforms and a geodatabase, are presented. These platforms are built for sensor measurements under field conditions, enabling the development of sensor fusion approaches and the improvement of decision models. The second component, the geodatabase serves as a prototype and allows the standardised organisation of data, geodata and metadata. Furthermore, three examples of SenGIS interdisciplinary research activities are presented.

2.3 Integrating economics in the Critical Period for Weed Control Concept in corn

Martina Keller[†], Geoffroy Gantoli[†], Jens Möhring[††], Christoph Gutjahr[†], Roland Gerhards[†], and Victor Rueda Ayala[†]

[†] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, Stuttgart, Germany.

[††] Bioinformatic Unit, Institute of Crop Science, University of Hohenheim, Stuttgart, Germany.

Accepted for publication in Weed Science

The original publication will be available at:
`http://wssajournals.org/loi/wees`

Abstract

The effect of weed competition on maize yield was determined and the critical period for weed control (CPWC) was calculated for Germany and Benin. Treatments with weed removal starting at various growth stages of the crop and kept weed-free continuously until harvest represented the "weed-infested interval". Treatments weed removal from sowing until various growth stages of the crop represented the "weed-free interval". Weed interference on yield was modeled employing the Michaelis-Menten, Gompertz, logistic and log-logistic model equations. Cross-validation showed that the log-logistic model fitted the weed-free interval data slightly better than Gompertz model and equally well as the logistic model fitted the weed-infested interval. Economic calculations considered yield revenue and cost increase due to mechanical weeding operations for Benin. In three out of four cases weeding once at the ten-leaf stage of maize was already profitable. One further weeding operation may assure and optimize profit. For Germany economic calculations determined a CPWC starting earlier than the four-leaf stage. This questions and challenges the decade-long propagated CPWC for maize in Germany. Differences between Germany and Benin are likely caused by the high production costs and higher yields in Germany. In this study a simple

approach to integrate economic data in the determination of the CPWC for chemical and nonchemical weed control strategies is provided.

Keywords: Benin, corn-weed competition, Germany, Gompertz, logistic, mechanical weeding, Michaelis-Menten.

2.4 Estimating economic thresholds for site-specific weed control using manual weed counts and sensor technology: An example based on three winter wheat trials

Martina Keller[†], Christoph Gutjahr[†], Jens Möhring[††], Martin Weis[†], Markus Sökefeld[†] and Roland Gerhards[†]

[†] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, Stuttgart, Germany.

[††] Bioinformatic Unit, Institute of Crop Science, University of Hohenheim, Stuttgart, Germany.

Pest Management Science 70, 2014, 200-211

The original publication is available at:
`http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1526-4998`

Abstract

The Precision Experimental Design (PED) employs the naturally occurring heterogeneity in agricultural fields and combines sensor technology with linear mixed models to determine the effect of weeds, herbicide and soil characteristics on crop yield. Such estimates can be further used to calculate economic thresholds. Three field trials in winter wheat are presented using the PED. Densities of weeds were determined by manual sampling and by bi-spectral camera technology. Soil properties and yield were mapped.
In one trial *Alopecurus myosuroides*, *Galium aparine* and other broad-leaved weeds reduced crop yield by 12.4, 17.5 and 1.2 kg ha^{-1} $plant^{-1}$ m^2. For site-specific weed control with independently applied herbicides economic thresholds of 12, 4 and 48 plants m^{-2} were calculated for *Alopecurus myosuroides*, *Galium aparine* and other broad-leaved weeds, respectively. A rather severe drought in spring reduced the effects of weeds on crop yield in one trial, because water became yield limiting. Generally negative herbicide effects on yield were negligible, apart from one trial, in which the application of a herbicide mixture tended to reduce yield by 0.6 t ha^{-1}. Bi-spectral camera technology for automated weed counting were of rather

limited use and still need to be improved. Despite its drawbacks, large weed patches were correctly identified by bi-spectral camera technology.
This paper presents a novel approach to carry out field trials and to determine decision rules for weed control for practical farming.

Keywords: bi-spectral camera, linear mixed models, site-specific herbicide application, weed distribution

2.5 Using bi-spectral imaging technology for simulated on-line-weed control in winter wheat and maize

Markus Sökefeld[†], Martina Keller[†], Martin Weis[†], Christoph Gutjahr[†], and Roland Gerhards[†]

[†] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, Stuttgart, Germany.

Proceedings of the 25th German Conference on Weed Biology and Weed Control, 2012, 183–190.

The original publication is freely available at:
`http://pub.jki.bund.de/index.php/JKA/issue/view/786`

Abstract

Two field trials on site-specific weed control were carried out in winter wheat and maize in spring 2011. Trials were installed at the Ihinger Hof research station of the University of Hohenheim. Bi-spectral cameras were mounted on a sensor platform vehicle for the image acquisition. These bi-spectral cameras take images without disturbances from stones, mulch or soil. Images and the GPS position, where they have been acquired, were stored on-the-go. The images were analyzed later by a weed recognition software. Weed maps of weed species and of weeds grouped according to their herbicide sensitivity were created based on the data.

A one-sided moving average of order five was used to to simulate an online herbicide application. With this approach only the data of weed infestation which were already assessed behind or directly in the current position of the vehicle is used. Visual grid sampling was used to check the calculated weed distribution maps. Herbicide application maps were created by applying thresholds on the weed distribution maps. Based on these maps the herbicide application was conducted by a multiple sprayer. With this sprayer up to three herbicides can be applied independently from each other in a single pass across the field.

The performance of the herbicide application was assessed by visual grid sampling. The site-specific weed control saved 66 % in maize and 83 % and 58 % herbicides in winter wheat respectively compared to a uniform herbicide application. In winter wheat the average efficacy of the site-specific herbicide application was 70 % of the conventional herbicide application system.

Keywords: Bi-spectral cameras, herbicide application, image analysis, site-specific, weed control

2.6 Long-term changes in weed occurrence, yield and use of herbicides in maize in south-western Germany, with implications for the determination of economic thresholds

Martina Keller[†], Norbert Böhringer[†], Jens Möhring [††], Victor Rueda-Ayala[†], Christoph Gutjahr[†], Roland Gerhards[†]

[†] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, Stuttgart, Germany.

[††] Bioinformatic Unit, Institute of Crop Science, University of Hohenheim, Stuttgart, Germany.

Weed Research 54, 2014, 457-466

The original publication is available at:
`http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1365-3180`

Abstract

Yield loss, herbicide efficacy and crop tolerance of maize (*Zea mays*) were investigated between 1981 and 2011 in 393 field experiments in south-western Germany in the Baden-Württemberg region. The collected data was used to calculate yield loss functions and economic thresholds (ETs) and to determine changes in herbicide use and weed frequencies. In total more than 60 weed species were observed in the trials. *Galium aparine* and *Chenopodium album* were the most frequent dicotyledonous weeds, the latter becoming more frequent over time. In about every fifth trial species of the genera *Polygonum*, *Lamium*, *Matricaria* and *Veronica* occurred. *Echinochloa crus-galli* and *Alopecurus myosuroides* were the most frequently observed grass weeds; the former increasing by 1.5% in frequency per year, the latter declining in frequency by 1.1%. Findings indicate a weed community shift towards thermophilic species. In the 1990s, aceto-lactate-synthase and 4-HPPD-inhibitor herbicides became of importance. Since the 1980s bromoxynil and pendimethalin have been important components of weed control. ETs ranged between 3.7% and 5.5% relative weed coverage. No yield increase was found over 24 years if weeds competed with the crop. In contrast yield increased by 0.2 t ha^{-1} $year^{-1}$, if weeds were controlled chemically. Over a period of 30 years yield losses and problematic weed species abundance have increased in maize in Baden-Württemberg, despite the intensive use of effective herbicides.

Keywords: economic threshold, multi-year data, relative weed coverage, yield loss

2.7 Changes in weed communities, herbicides, yield levels and effect of weeds on yield in winter cereals based on three decades of field experiments in south-western Germany

Martina Keller[†], Norbert Böhringer[†], Jens Möhring[††], Victor Rueda-Ayala[†], Christoph Gutjahr[†], Roland Gerhards[†]

[†] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, Stuttgart, Germany.

[††] Bioinformatic Unit, Institute of Crop Science, University of Hohenheim, Stuttgart, Germany.

Accepted for publication in Gesunde Pflanzen

The original publication will be available at:
http://link.springer.com/journal/10343

Abstract

Over the last decades arable cropping practices including chemical weed control changed greatly in south-western Germany. This affected weed-crop interference and weed communities. Changes in applied herbicides, weed frequencies and yield over the last three decades in winter cereals were determined by analyzing data of weed control experiments. Based on 122 trials for winter barley and winter wheat the effect of weeds on crop yield and thereof economic thresholds (ETs) were calculated.

Herbicides belonging to the HRAC-groups C, K, M and O were dominant in the 1980s. Whereas in the last two decades the HRAC-groups A, B and F were predominant. Despite these changes in herbicide use weed communities were rather stable. *Stellaria media* frequency and *Galium aparine* frequency declined. Whereas *Alopecurus myosuroides* frequency increased. However observed densities remained stable. For winter barley and winter wheat ETs ranged from 4.5 to 8.9 % and 9.2 to 9.8 % absolute weed coverage, correspondingly. Yield increased by 0.08 t ha^{-1}a^{-1} for barley and by 0.16 t ha^{-1}a^{-1} for winter wheat, if weeds were controlled. Contrarily in the untreated control plots, where weeds were allowed to compete with the crop, no yield increase could be found. Generally yields in the highest yielding herbicide treatment were 1.5 to 2.3 t ha^{-1} higher than in the untreated plots. These findings clearly confirm the importance of effective weed control in winter cereals.

Keywords: *Alopecurus myosuroides*, economic weed thresholds, multi-site, multi-year, weed coverage, winter wheat, winter barley, yield loss

Chapter 3

General discussion

The aims of this study were to determine and re-evaluate the critical period for weed control (CPWC) in maize using different models and economics, to estimate the effect of weeds on crop yield and to calculate economic thresholds (ETs) in winter wheat, winter barley and maize. For farmers the CPWC and ETs are important tools to time weed control and to determine whether herbicides need to be applied. For the determination of ETs, the so called precision experimental design (PED) was employed and improved (Ritter et al., 2008; Gerhards et al., 2012). Data of several years and several sites of the field trial experiments 'Common field trials Baden-Württemberg' were employed to determine coverage based thresholds for all three crops. This dataset also allowed to gain insights into frequency changes of weeds, into changes in *Alopecurus myosuroides* abundance and into changes in herbicide use over the last decades in Baden-Württemberg. Site-specific weed control (SSWC) was carried out and evaluated in two field trials, whereas weed distribution determined by bi-spectral camera technology and classification algorithms served as input for site-specific herbicide application.

Timing of weed control in maize

In the literature mainly two approaches have been used to determine the CPWC: multiple comparison techniques and nonlinear regression (Knezevic et al., 2002). For the regression approach mainly the logistic and Gompertz model were employed to model the effect of early weed competition and the effect of late emerging weeds on yield (Knezevic et al., 2002; Bukun, 2004; Gantoli et al., 2013). In this current study the log–logistic and Michaelis-Menten models were tested as alternatives to the commonly used models. The advantage of these two models is that their parameters are biologically meaningful, which helps in finding starting values and assessing the obtained parameter estimates. The log–logistic model was equally well suited as the logistic and Gompertz model for the datasets used. Instead of using an arbitrarily chosen acceptable yield loss level (Knezevic et al., 2002) a full cost model was used for the German datasets in the current study. For Benin, an approach was suggested which takes into account the trade-off between increasing yield due to increasing length of weed-free conditions and the increasing costs due to increasing number of required weeding operations. The decade-long propagated CPWC determined for Germany (Koch and Kemmer, 1980) was re-evaluated and is challenged, as results indicate a much earlier onset of the CPWC. These differences are most likely due to the different approaches used for modeling (Cousens, 1988), the increase in yield and changes in management practices (Duvick, 1997) since the time the study of Koch and Kemmer (1980) was carried out.

Page et al. (2009) found that the very early presence of weeds affects maize growth patterns by altering light composition. Therefore, the effect of early weed competition must not be neglected and is relevant from an economic and agronomic perspective.

In practice, weather conditions limit the time window for herbicide applications and are the main factor for the timing of the chemical weed control measures. Nevertheless, the CPWC provides helpful guidance for farmers. For Germany the effect of late emerging weeds was not studied, as maize plants become much more susceptible to herbicide application from the 6-leaf stage on (Bär et al., 2010). Thus, the time period for the herbicide application is limited. Nevertheless, further studies to determine the end of the CPWC under current conditions could show whether the CPWC is shorter than the average period of time soil herbicides are effective. This would provide guidance as well for timing the weed control measures.

For Benin, further field trials are advisable to test the determined CPWC in the fields. One serious disadvantage of weeding at later stages is the fact that snakes might hide in dense weed canopies and can harm workers (personal communication G. Gantoli). Thus, depending on this hazard one weeding operation should be carried out at a earlier stage when weed coverage is patchy and bare soil is still visible and weeding is less dangerous. Such adjustments to local conditions should be done by local agricultural advisors.

The implementation of the determined CPWC in this study helps to time weed control especially in Benin where yield levels in farmers' field are still very low (Gantoli et al., 2013). The suggested approaches to implement economics into the determination of the CPWC can be easily used for other crops or other production systems.

Use and improvement of the Precision Experimental Design

The PED allows to determine the effect of weed species/weed groups, herbicide application and soil properties on crop yield in a single field (Ritter et al., 2008; Gerhards et al., 2012). These effects cannot be determined in field trials testing different herbicide mixtures like the trials carried out in the framework of the 'Common field trials Baden-Württemberg' (Schwerdtle et al., 1969; Gerhards, 2011; Gerhards et al., 2012). In such trials the effect of removing weed competition due to applying herbicides and a possible negative effect due to herbicide stress on crop plants is confounded (Gerhards et al., 2012). The effect of different weed densities on yield can neither be estimated due to the small number of observations which normally equals the number of replicates. To determine the effect of weed species on yield, trials with varying sown weed densities as treatment were often carried out e.g. Coble and Ritter (1978) and Lindquist et al. (1999). However, it was often reported that sown weeds do not show the same competitiveness as naturally emerged weeds. In contrast, for the PED the naturally occurring weed infestation of a field is used.

In the current study, the estimates derived from the PED could be improved by increasing the number of replicates. One disadvantage of the PED is the dependency on occurring heterogeneity within the field. For example, two trials were carried out in maize in 2010 but the weed infestation was consistently high in both fields and thus only a treatment effect could be estimated (data not included in this thesis) and no further insights could be gained. Another disadvantage are the relatively strong technological requirements (yield, weed and soil mapping sensors, precise GPS signal), and the required large trial size. Due to these requirements, trials could only be carried out in the assigned fields of the well-equipped research stations of the University of Hohenheim, Germany.

With the fast ongoing progress in technology e.g. the availability of virtual reference bases (`http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/services/swipos/gis-geo/vrs.html`), field trials could soon and more easily be installed in fields with variable weed infestation, for example in farmers' fields and could open new opportunities for research.

Usability of bi-spectral camera technology for the Precision Experimental Design

At the beginning of this study it was hypothesized, that weed distribution determined at a higher spatial resolution would be a better input for the PED (Ritter et al., 2008; Gerhards et al., 2012) than weed counts determined in a frame of 0.4 m^{-2} in the center of 9 m $\times$ 9 m grids. However, two field trials carried out in winter wheat could not confirm this hypothesis: Estimates of the effect of weeds on yield using weed distribution data determined by bi-spectral camera technology were difficult to interpret. For automated classification a black and white image (binary image), derived by setting a grey threshold from the difference image of the bi-spectral camera, was used and shape-based algorithms are applied to the objects to compute features for subsequent classification (Weis et al., 2008): Winter wheat leaf tips were often found to be classified as grass weeds and short broad parts of wheat plants classified as dicotyledonous seedlings. Also overlapping occurred resulting in large complex objects which could not be classified properly. These difficulties may have contributed to the poor estimates. While during manual weed counts scientists assess weeds as coloured, three dimensional objects (Weis, 2010) and they have the possibility to touch the plant, move overlapping plant parts, and if they are uncertain to consult weed classifications books. Thus, manual weed counts are based on much more information and thus are much more accurate and even a higher spatial resolution of sampling by the use of bi-spectral cameras could not compensate for this difference. Lemieux et al. (2003) used image analyses to determine relative weed coverage in maize. In their approach they established 32 field trials in farmers' fields each with 24 replicates with two treatments (untreated/sprayed) and determined yield loss functions with high significance. The used approach in the study of Lemieux et al. (2003) is interesting as it also works with the natural variability and several sites and years are included. This is an advantage compared with the PED. Their image analysis method was highly precise, but distinguished only between crop and weeds and furthermore an operator was need for analyses (Lemieux et al., 2003). The high time requirement of 20 minutes per image per operator, is definitively not feasible for the PED with a sampling rate of up to 1'000 images per ha. Yet, if the bi-spectral camera technology used in this current study is further improved or combined with other sensors such as an ultrasonic sensor (Andújar et al., 2012), then automatically derived weed density distributions can serve to determine weed–yield relationships or to determine weed infestation for other research topics.

Usability of bi-spectral camera technology for SSWC

Christensen et al. (2009) identified automated weed detection as crucial component for SSWC. Still, relatively few studies were carried out using sensors to determine weed infestation discriminating between different weeds, and to apply control measures site-specifically - especially in narrow row crops as cereals and distinguishing between different weed groups and crop plants (Berge et al., 2007, 2008, 2012; Gerhards and Oebel, 2006). In the current study, threshold values and moving averages in the direction of driving were used for SSWC. In winter wheat, we applied one herbicide against (i) *Galium aparine* and another herbicide against (ii) other broad-leaved weeds and *Alopecurus myosuroides* independently. Thresholds were chosen rather high to account for noise in the classified images. In the maize field herbicide was applied if weeds were detected in the image. Herbicide savings of 58% to 83% could be achieved similar to the reported savings of Gerhards and Oebel (2006); Nordmeyer (2006a); Gutjahr and Gerhards (2010). Ritter and Gerhards (2007) could already confirm that the longterm use of SSWC does not result in an increase in weed infestation. Hamouz et al. (2013) showed in a recent study that SSWC allowed considerable herbicide savings; even a trend of higher yield in these treatments. Hamouz et al. (2013) explained this tendency by less herbicide stress in the crop, since herbicides were only applied at sites where weeds densities were above the chosen thresholds. In contrast, Simard et al. (2009) experienced an increase in weed infestation and a decrease in herbicide savings over the years when the applied herbicide dependent on relative weed coverage in maize and soybean. This might be ascribed to the relatively high thresholds of 0.2 and 0.4 relative weed coverage in maize (Simard et al., 2009).

The above mentioned difficulties regarding weed classification were encountered in this study as well; they require also attention and efforts in this field of application. The time window for herbicide application (Nordmeyer, 2006b) and especially the time window during which images without too much overlapping of individual weeds can be taken is limited. As a consequence, the technology needs to be robust (Nordmeyer, 2006b) and easy to be handled to avoid malfunctioning during peak periods.

Despite these difficulties, using bi-spectral cameras for SSWC is feasible and corresponds to the political and social expectations towards a sustainable use of plant protection products (Nordmeyer, 2006b; Bundesministerium für Ernährung, 2013). For further trials, it is advisable to improve the interfaces between bi-spectral camera, classification, decision component and sprayer.

Economic thresholds and decision component for SSWC

The derived ET for broadleaved weeds from one trial of the PED were comparable to the ET suggested by Niemann (1981) and tested by Gerowitt and Heitefuss (1990) of 40-50 plants m^{-2} for broadleaved weeds. Whereas the ETs determined in the PED for *Galium aparine* was higher and for *Alopecurus myosuroides* it was lower compared with the established thresholds: 4 versus 0.1-0.5 plants m^{-2}, 12 versus 20-30 grasses m^{-2}, respectively (Gerowitt and Heitefuss, 1990). Differences are most likely due to changes in the cropping systems (varieties, fertilization etc.) and changes of costs and prices (Gerhards et al., 2012). Furthermore, *Galium aparine* can cause nuisance during harvesting which is not accounted for in the calculations of the ETs determined in the current study.

The determined ETs based on weed densities could be used as thresholds for a simple decision unit for a SSWC system. Conservative thresholds based on the upper confidence limits of the estimated weed effect crop yield may overestimate the effect of weeds on yield in a few cases, but correspond to the more risk adverse attitude of farmers (Coble and Mortensen, 1992). Alternatively to fixed ETs, the expected weed-free yield, expected crop price, herbicide and application costs could be provided by the farmers for the respective field. Based on these input data thresholds could then be calculated for each field using the determined regression coefficients of the weed/weed group yield relationship derived from the PED. These thresholds could also be manually adjusted by the respective farmer taking into account further conditions such as weather, his knowledge of the field history etc. (Gutjahr and Gerhards, 2010).

These thresholds are only based on one trial and thus their general use might be limited. The thresholds determined based on coverage derived from the 'Common Field trials Baden-Württemberg' are based on field trials carried out at several sites for several years covering various conditions. They provide thresholds for mixed weed stands, allowing only to apply a herbicide mixture site-specifically. Grass weeds have a relatively small coverage early in the season, but exhibit high yield loss potential. Whereas the coverage of some dicotyledonous weeds is relatively high, but their competitiveness is limited. If weed coverage is used to decide whether weed control is necessary, these differences cannot be taken into account. Coverage data for *Alopecurus myosuroides*, *Galium aparine*, and other broadleaved weeds were also available in the assembled dataset for winter wheat and winter barley. Unfortunately, the datasets did not allow to estimate the effect of these single weeds and weed group due to high variation within years.

For winter wheat and winter barley, absolute coverage was found to be an equally good better predictor for yield loss as relative weed coverage. In literature, relative weed coverage is reported to be a better predictor of yield loss than weed coverage (Simard et al., 2009; Ali et al., 2013). This could not be confirmed with the current study.

For maize, the determined thresholds in the current study could e.g. be used for a fuzzy system as suggested by Yang et al. (2003). They were considerably lower (factor 10) than the ones employed by Simard et al. (2009). Simard et al. (2009) found their ETs to be too high themselves in their study. Their thresholds were based on the variability of the weed-free yield of maize in the studied region and not on economics.

The amount of herbicide applied can be adjusted to the respective field conditions as suggested by textbooks on weed control (Pallut, 2002) and as suggested for SSWC by Gutjahr and Gerhards (2010). Simple rules such as 'if the crop is highly vigorous or/and if weather conditions are favorable, reduce herbicide amount by for example 20%' could be easily implemented at the field level. At the sub-field level, dose could be reduced, if weed infestation is at the level of the ETs (Pallut, 2002). It is important to note that such reductions may result in loss of efficacy guarantee by the agro-chemical companies (Blackshaw et al., 2006). This is most likely also the case if herbicides are applied site-specifically. In addition, the effect of dose reductions on herbicide resistance development is debated (Blackshaw et al., 2006). Christensen et al. (2003) adjusted doses using dose-response curves assuming a negative linear relationship between weed biomass and yield. Gutjahr and Gerhards (2010) suggested the use of dose-response curves and yield loss curves for dose adjustment for SSWC. This approach requires knowledge of i) yield or yield loss curves using weed coverage as predictor variable for the relevant weeds and ii) dose-response curves of the mainly used herbicides and weeds using weed coverage as response variable. But dose-response curves have often been determined under controlled conditions and results are only transferable to a limited extent to the fields (Medd et al., 2001; Heini, 2012). Thus, this current study suggests to apply ETs or calculate field based ETs, using the yield loss regression coefficients, expected weed-free yield, costs and crop price. Further it is recommanded to focus on integrating the farmers' experience and expertise for further dose adjustments at the field level as suggested by Gutjahr and Gerhards (2010).

Need for regional field trials

Multi-year and multi-site trial data provide a highly valuable source of data for further analyses. For example Fritzsche et al. (2012) used trials from the administrative districts of Northern Germany to determine yield functions and to get information about *Alopecurus myosuroides* and *Apera spica venti* densities; Milberg and Hallgren (2004) used herbicide trials to explore patterns in yield loss in cereals in Sweden. The 'Common field trials Baden-Württemberg' experiments have a long tradition. In the trials, the efficacy, crop tolerance and yield of herbicide mixtures are assessed at several sites in the region by experienced agricultural advisers of the public sector. Apart from the results related to the defined research questions, the aggregated data gave highly valuable insights into changes in weed frequencies, yield trends and more in the current study. Unfortunately, during the last years the maize trials were often not harvested any more and thus little yield data was available. This should be seen with concerns as these field trials provide valuable data to give objective recommendations to farmers.

Changes in weed frequencies

In the current study, weed frequencies in winter cereals were found to be more stable than the weed frequencies in maize. This can be certainly ascribed to the fact that maize is a relatively 'new' crop in southwestern Germany (Mehrtens et al., 2005). An increase in thermophilic weeds could be observed in this crop. This might already be a consequence of climate change (Edler et al., 2012). In winter wheat and winter barley, a significant increase in *Alopecurus myosuroides* frequencies was found, but no indication of increase in number of heads m^{-2} determined in the last 40 years could be detected. The increase in frequency can be certainly attributed to the increasing share of winter crops in the crop rotation, the trend to sow early in autumn and reduced tillage. Furthermore the outsourcing of harvesting, sowing etc. to regional contractors results in further spreading of weeds between farms and fields (Gehring et al., 12a,b, 2012). Re-diversification of crop management could complement chemical weed control. Lutman et al. (2013) showed that ploughing could reduce the *A. myosuroides* population by 69% compared with non-inversion tillage; delayed sowing could result in a reduction of about 50%, and growing more competitive cultivars could decrease *A. myosuroides* heads m^{-2} by 22%.

The used weed frequency data differs from commonly used data to track changes in weed frequencies over years in Europe e.g. Chancellor and Froud-Williams (1984); Hyvönen et al. (2003); Andreasen and Streibig (2011). In these studies usually special surveys were carried out and the main scope was to identify all occurring weeds. In contrast, in the 'Common field trials of Baden-Württemberg' the efficacy of herbicides on weeds which are important in that crop were the focus of the trials. This may have led to not recording very rare weed species. Regarding the important weeds of the region the data is highly relevant and representative, especially because data from over 20 years and many sites could be used. This study could be easily and should be repeated in some years to identify further changes.

The need for effective weed control

Regarding herbicide use, the importance of ALS-inhibitors since the 90s for weed control in winter cereals and maize became very apparent. ALS-inhibitors are considered favorable due to their broad-spectrum weed control, low amount of active ingredient needed, their crop tolerance and low mammalian toxicity among others. Apart from the positive properties ALS-inhibitors exert a strong selection pressure resulting in a relatively fast spread of ALS resistant weed biotypes (Tranel and Wright, 2002). Basing weed control mainly on herbicides and on one or two herbicide groups is precarious: For resistance management the use of other AI is crucial for example the use of flufenacet (K3), prosulfocarb (N) and the group

F1 in winter cereals (Gehring et al., 12a,b, 2012).

Generally, the broad use of herbicides in agriculture has been controversially debated and has been heavily criticized during the last decades. With the review process of plant protection products carried out in the European Union many of the active substances being on the market in at least one Member State before 1993 were eliminated (European commission and Directorate-General for Health & Consumers, 2009; Kraehmer and Stuebler, 2012). The consolidation process among the agro-chemical companies resulted in less Research and Development resources (Rueegg et al., 2007). The registration costs for new plant protection products increased considerably in the last years and thus agro-chemical companies started to invest more in biotechnology and in seed production than in the plant protection area (Rueegg et al., 2007; Kraehmer and Stuebler, 2012). As a result, the available active ingredients are becoming less and the launches of new active ingredients is expected to be rather small (Rueegg et al., 2007). Depicting yield with and without weed interference over two decades, it could be easily shown how important effective weed control is to put 'breeding progress' into effect in farmers' fields for maize, winter wheat and winter barely. Having effective herbicides available and keeping them effective is thus of high importance.

In conclusion, the determined ETs and CPWC in this study can serve as decision aids for farmers at the field level. The determined ETs and yield effect can be easily implemented in a SSWC system. SSWC could contribute to a sustainable use of herbicides in combination with important tools of integrated weed management practices such as crop rotation, sowing dates, mechanical weed control, ploughing etc. The careful use of herbicides is important to keep these valuable tools effective and available and ensure yield and yield increase. For SSWC to become common practice most likely financial support for further research and development and political incentives at the early phase of the product life cycle of SSWC-system would be necessary.

Chapter 4

Appendix

Curriculum vitae

Table 4.1: Curriculum vitae of Martina Keller, born on February 6th., 1982 in St. Gallen, Switzerland

Date	Position/ Studies	Projects, Publications & Degree
[2013–present]	Weed scientist, extension team vegetables, Agroscope, Switzerland	diverse projects
[2009–2014]	Ph. D candidate Agricultural sciences, Institute for Phytomedicine, Department of Weed Science, University of Hohenheim, Germany	Publications: (see chapter 1.3)
[2008–2009]	Trainee in the Plant Protection Chemistry group, Agroscope (ACW) Wädenswil, Switzerland	Trace analyses of glyphosate in WWTP and assistance in soil degradation studies of artificial sweeteners (Buerge et al., 2011)
[2006–2008]	Studies in Agricultural Science, Institute of Agricultural Sciences, ETH Swiss Federal Institute of Technology Zurich, Switzerland	MSc ETH degree in Agroecosystem Science with honour. Results of Master thesis published in Keller et al. (2012)
[2003–2006]	Studies in Agricultural Science, Department of Agricultural Science, ETH Swiss Federal Institute of Technology Zurich, Switzerland	BSc degree in Agricultural Science ETH.
[2002–2003]	Studies in Pharmaceutical Sciences, Department of Chemistry and Applied Biosciences, ETH Swiss Federal Institute of Technology Zurich, Switzerland	
[2001–2002]	Trainee at Empa - Swiss Federal Laboratories for Materials Science and Technology, Switzerland	
[1989–2001]	Primary school and grammar school, Switzerland	University-entrance diploma

Bibliography

Ali, A., J. C. Streibig, and C. Andreasen (2013). Yield loss prediction models based on early estimation of weed pressure. *Crop Protection 53*, 125–131.

Andreasen, C. and J. C. Streibig (2011). Evaluation of changes in weed flora in arable fields of Nordic countries - based on Danish long-term surveys. *Weed Research 51*, 214–226.

Andújar, D., M. Weis, and R. Gerhards (2012, December). An ultrasonic system for weed detection in cereal crops. *Sensors 12*(12), 17343–17357.

Beer, E. (1979). *Ermittlung der Bekämpfungsschwellen und wirtschaftlichen Schadensschwelle von monokotylen und dikotylen Unkräutern in Winterweizen und Wintergerste anhand von Daten aus der amtlichen Mittelprüfung (Determination of control thresholds and economic thresholds for monocotyledonous and dicotyledonous weeds in winter wheat and winter barley using data from governmental trials)*. Ph. D. thesis, Institut für Pflanzenpathologie und Pflanzenschutz der Georg-August-Universiät Göttingen.

Berge, T., A. Aastveit, and H. Fykse (2008, Dec). Evaluation of an algorithm for automatic detection of broad-leaved weeds in spring cereals. *Precision Agriculture 9*, 391–405.

Berge, T., S. Goldberg, K. Kaspersen, and J. Netland (2012). Towards machine vision based site-specific weed management in cereals. *Computers and Electronics in Agriculture 81*, 79–86.

Berge, T. W., H. Fykse, and A. H. Aastveit (2007). Patch spraying of weeds in spring cereals: Simulated influences of threshold level and spraying resolution on spraying errors and potential herbicide reduction. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science 57*(3), 212–221.

Blackshaw, R., J. O'Donovan, K. N. Harker, G. Clayton, and R. N. Stougaard (2006). Reduced herbicide doses in field crops: A review. *Weed Biology and Management 6*, 10–17.

Buerge, I. J., M. Keller, H.-R. Buser, M. D. Müller, and T. Poiger (2011). Saccharin and other artificial sweeteners in soils: Estimated inputs from agriculture and households, degradation, and leaching to groundwater. *Environmental Science & Technology 45*(2), 615–621.

Bukun, B. (2004). Critical periods for weed control in cotton in turkey. *Weed Research 44*, 404–412.

Bundesministerium für Ernährung, L. u. V. (2013). Nationaler Aktionsplan zur nachhaltigen Anwendung von Pflanzenschutzmittel (National plan of action for sustainable use of plant protection products. Technical report, Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz.

Bär, H., K. Ewert, K. Gößner, R. Götz, M. Kraatz, B. Krueger, S. Kupfer, E. Meinlschmidt, M. Naujok, E. Naumann, S. Pelzer, B. Politz, G. Schröder, A. Thate, C. Tümmler, G. Viehweger, and E. Weiske (2010). Hinweise zum sachkundigen Einsatz von Pflanzenschutzmitteln im Ackerbau und auf dem Grünland 2010 (Recommendations for sound use of plant protection product in fields and meadows 2010). Landesamt für Verbraucherschutz, Landwirtschaft und Flurneuordnung, Abteilung Pflanzenschutzdienst, Frankfurt.

Chancellor, R. J. and R. Froud-Williams (1984). A second survey of cereal weeds in central southern England. *Weed Research 24*, 29–36.

Christensen, S., T. Heisel, A. M. Walter, and E. Graglia (2003). A decision algorithm for patch spraying. *Weed Research 43*, 276–284.

Christensen, S., H. Søgaard, P. Kudsk, M. Nørremark, I. Lund, E. Nadimi, and R. Jørgensen (2009). Site-specific weed control technologies. *Weed Research 49*(3), 233–241.

Coble, H. and R. Ritter (1978, Nov.). Pennsylvania smartweed (*Polygonum pensylvanicum*) interference in soybeans (*Glycine max*). *Weed Science 26*(6), 556–559.

Coble, H. D. and D. A. Mortensen (1992). The threshold concept and its application to weed science. *Weed Technology 6*, 191–195.

Cousens, R. (1988). Misinterpretations of results in weed research through inappropriate use of statistics. *Weed Research 28*(4), 281–289.

Duvick, D. N. (1997). The contribution of breeding to yield advances in maize (*Zea mays* l.). *Advances in Agronomy 86*, 83–145.

Edler, B., K. Peters, J. Isselstein, J. Bürger, H.-H. Seinmann, and B. Gerowitt (2012). Unkräuter im Wandel - Welche Auswirkungen haben veränderte klimatische Bedingungen auf ausgewählte Unkräuter Norddeutschlands (Weeds and Climate Change ? Impact of alternating climatic conditions on selected weeds in Northern Germany). In *58. Deutsche Pflanzenschutztagung, 10. - 14. September 2012, Technische Universität Braunschweig*, Volume 438, pp. 134–135. Julius-Kühn-Archiv.

European commission and Directorate-General for Health & Consumers (2009). EU action on pesticides "our food has become greener". Technical report, European commission and Directorate-General for Health & Consumers.

Fritzsche, R., E. Seemann, B. werner, F. de Mol, and B. Gerowitt (2012, March). Gaining extra information from herbicide trials - analysing field trias of the region Hannover from 2003 to 2009. See Nordmeyer and Ulber (2012), pp. 409–416.

Gantoli, G., V. Rueda Ayala, and R. Gerhards (2013). Determination of the critical period for weed control in corn (*Zea mays* L.). *Weed Technology 27*, 63–71.

Garburg, W. (1974). *Untersuchungen zur Ermittlung der ökonomischen Schadensschwelle und der Bekämpfungsschwelle von Unkräutern im Getreide (Investigations to determine the economic thresholds and control thresholds for weeds in cereals)*. Ph. D. thesis, Institut für Pflanzenpathologie und Pflanzenschutz der Georg-August-Universiät Göttingen.

Gehring, K., R. Balgheim, and C. Schleich-Saidfar (12a, March). Prinzipien einer Anti-Resistenzstrategie bei der Bekämpfung von *Alopecurus myosuroides* und *Apera spica-venti* aus Sicht des Pflanzenschutzdienstes (Principles of resistance management for the control of *Alopecurus myosuroides* and *Apera spica-venti* in the view of the official plant protection service. See Nordmeyer and Ulber (2012), pp. 89–101.

Gehring, K., S. Thyssen, and T. Festner (12b, March). Herbizidresistenz bei *Alopecurus myosuroides* Huds. in Bayern (Herbicide resistance of *Alopecurus myosuroides* Huds. in Bavaria. See Nordmeyer and Ulber (2012), pp. 127–132.

Gerhards, R. (2011). Gemeinschaftsversuche Baden-Württemberg 2011, Berichte aus dem Fachgebiet Herbologie der Universität Hohenheim (Common field trials Baden-Württemberg 2011, reports from the Weed Science group, University of Hohenheim).

Gerhards, R., C. Gutjahr, M. Weis, M. Keller, M. Sökefeld, J. Möhring, and H.-P. Piepho (2012). Using precision farming technology to quantify yield effects attributed to weed competition and herbicide application. *Weed Research 52*(1), 6–15.

Gerhards, R. and H. Oebel (2006, June). Practical experiences with a system for site-specific weed control in arable crops using real-time image analysis and GPS-controlled patch spraying. *Weed Research 46*(3), 185–193.

Gerowitt, B. and R. Heitefuss (1990). Weed economic thresholds in the F. R. Germany. *Crop Protection 9*, 323–331.

Gutjahr, C. and R. Gerhards (2010, August). *Precision Crop Protection - the Challenge and Use of Heterogeneity* (1 ed.), Chapter Decision rules for site-specific weed management, pp. 223–239. Volume 1 of Oerke et al. Oerke et al. (2010).

Gutjahr, C., M. Keller, J. Möhring, M. Weis, M. Sökefeld, H. P. Piepho, and R. Gerhards (2011, July). Measuring yield effect of weeds and herbicide application in small annual grains and maize using the precision experimental design. See Stafford (2011), pp. 203–212. Papers presented at the 8th European Conference on Precision Agriculture 2011, Prague, Czech Republic, 11-14 July 2011.

Hamouz, P., K. Hamouzová, J. Holec, and L. Tyser (2013). Impact of site-specific weed management on herbicide savings and winter wheat yield. *Plant Soil and Environment 59*, 101–107.

Heini, J. (2012, November). *Studies on the efficacy, composition and mode of action of an ethoxylated soybean oil adjuvant for herbicides*. Doctoral thesis, Institute for Phytomedicine, Department of Weed Science, University of Hohenheim, Stuttgart, Germany.

Hyvönen, T., E. Ketoja, and J. Salonen (2003). Changes in the abundance of weeds in spring cereal fields in finland. *Weed Research 43*, 348–356.

Keller, M., N. Böhringer, J. Möhring, V. Rueda-Ayala, C. Gutjahr, and R. Gerhards (2014). Long-term changes in weed occurrence, yield and use of herbicides in maize in south-western Germany, with implications for the determination of economic thresholds. *Weed Research 54*, 457–466.

Keller, M., G. Gantoli, A. Kipp, C. Gutjahr, and R. Gerhards (2012, March). The effect and dynamics of weed competition on maize in Germany and Benin. See Nordmeyer and Ulber (2012), pp. 289–299.

Keller, M., C. Gutjahr, J. Möhring, M. Weis, M. Sökefeld, and R. Gerhards (2014). Estimating economic thresholds for site-specific weed control using manual weed counts and sensor technology: An example based on three winter wheat trials. *Pest Management Science 70*, 200–211.

Keller, M., A. Oberson, K. E. Annaheim, F. Tamburini, P. Mäder, J. Mayer, E. Frossard, and E. K. Bünemann (2012, June). Phosphorus forms and enzymatic hydrolyzability of organic phosphorus in soils after 30 years of organic and conventional farming. *Journal of Plant Nutrition and Soil Science 175*(3), 385–393.

Keller, M., M. Weis, and R. Gerhards (2010, August). Biomass estimation from images for greenhouse experiments. In M. Zude and M. Kraft (Eds.), *Proceedings 16. Workshop Computer-Bildanalyse in der Landwirtschaft*, Volume 73 of *Bornimer Agrartechnische Berichte*, Potsdam-Bornim/Braunschweig, pp. 13–20. Leibnitz Institute for Agricultural Enineering (ATB): ATB. 16. Workshop Computer-Bildanalyse in der Landwirtschaft, 04 May 2010.

Keller, M., C. Zecha, M. Jackenkroll, M. Weis, J. Link-Dolezal, R. Gerhards, and W. Claupein (2012). *ICT for agriculture, rural development and environment: Where we are? Where we will go?*, Chapter Competence centre SenGIS ? exploring methods for georeferenced multi-sensor data acquisition, storage, handling and analysis, pp. 218–229. Prague, Czech Republic: České centrum pro vědu a společnost (Czech Centre for Science and Society) Czech Centre for Science and Society.

Keller, M., C. Zecha, M. Weis, J. Link-Dolezal, R. Gerhards, and W. Claupein (2011, July). Competence centre SenGIS – exploring methods for multisensor data acquisition and handling. See Stafford (2011), pp. 491–500. Papers presented at the 8th European Conference on Precision Agriculture 2011, Prague, Czech Republic, 11-14 July 2011.

Knezevic, S. Z., S. P. Evans, E. E. Blankenship, R. C. Van Acker, and J. L. Lindquist (2002). Critical period for weed control: the concept and data analysis. *Weed Science 50*, 773–786.

Koch, W. and A. Kemmer (1980). Schadwirkung von Unkräutern gegenüber Mais in Abhängigkeit von Konkurrenzdauer und Unkrautdichte (Negative effect of weeds on maize in dependence of the length of weed competition and weed density). *Med. Fac. Landbouww. Rijksuniv. Gent 45*(4), 1199–1109.

Kraehmer, H. and H. Stuebler (2012, March). Technical demands and political restrictions for weed control. See Nordmeyer and Ulber (2012), pp. 15–19.

Lemieux, C., L. Vallée, and A. Vanasse (2003). Predicting yield loss in maize fields and developing decision support for post-emergence herbicide applications. *Weed Research 43*, 323–332.

Lindquist, J., D. Mortensen, P. Westra, W. Lambert, T. Bauman, J. Fausey, and J. Kells (1999). Stability of corn (*Zea mays*) - foxtail (*Setaria spp.*) interference relationships. *Weed Science 47*(2), 195–200.

Lutman, P., R. S. Moss, S. Cook, and S. Welham (2013). A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*. *Weed Research 53*, 299–313.

Medd, R. W., R. J. Ven de Ven, D. Pickering, and T. Nordblom (2001). Determination of environment-specific dose-response relationships for clodinafop-propargyl on *Avena* spp. *Weed Research 41*, 351–368.

Mehrtens, J., M. Schulte, and K. Hurle (2005). Unkrautflora in Mais Ergebnisse eines Monitorings in Deutschland (Weed flora results from a survey in Germany). *Gesunde Pflanzen 57*, 206–218.

Milberg, P. and E. Hallgren (2004). Yield loss due to weeds in cereals and its large-scale variability in Sweden. *Field Crops Research 86*, 323–332.

Niemann, P. (1981). *Schadschwellen bei der Unkrautbekämpfung (Economic thresholds for weed control*, Volume 257 of *Angewandte Wissenschaft - Schriftenreihe des Bundesministers für Ernährung, Landwirtschaft + Forsten*. Münster Hiltrup: Landwirtschaftsverlag.

Nordmeyer, H. (2006a, July). Patchy weed distribution and site-specific weed control in winter cereals. *Precision Agriculture 7*(3), 219–231.

Nordmeyer, H. (2006b). Teilflächenunkrautbekämpfung im Rahmen des Reduktionsprogramms chemischer Pflanzenschutz (Site-specific weed control in the framework of the reduction program of the chemical plant protection). *Journal of Plant Diseases and Protection Special Issue XX*, 165–172.

Nordmeyer, H. and L. Ulber (Eds.) (2012, March). *Proceedings of the 25th German Conference on Weed Biology and Weed Control*, Volume 434 of *Julius-Kühn-Archiv*, Braunschweig, Germany. JKI: Julius-Kühn-Institut.

Oerke, E.-C., R. Gerhards, G. Menz, and R. A. Sikora (Eds.) (2010, August). *Precision Crop Protection - the Challenge and Use of Heterogeneity* (1 ed.), Volume 1. Dordrecht, Heidelberg, London, New York: Springer Verlag.

Page, E. R., M. Tollenaar, E. A. Lee, L. Lukens, and C. J. Swanton (2009). Does the shade avoidance response contribute to the critical period for weed control in maize (*Zea mays*)? *Weed Research 49*, 563–571.

Pallut, B. (2002). *Unkraut – Ökologie und Bekämpfung (Weeds – ecology and control)*, Chapter Massnahmen der Unkrautbekämpfung - Integrierte Bekämpfung (Control measures - integrated control), pp. 224–226. Eugen Ulmer GmbH & Co.

Ritter, C., D. Dicke, M. Weis, H. Oebel, H. Piepho, A. Büchse, and R. Gerhards (2008, Jun). An on-farm approach to quantify yield variation and to derive decision rules for site-specific weed management. *Precision Agriculture 9*(3), 133–146.

Ritter, C. and R. Gerhards (2007). Can short-term gains in site-specific weed management be sustained over multiple years? In *Proceedings of the 2nd Conference on Precision Crop Protection*, Bonn, Germany.

Rueda-Ayala, V., M. Weis, M. Keller, D. Andújar, and R. Gerhards (2013). Development and testing of a decision making based method to adjust automatically the harrowing intensity. *Sensors 13*, 6254–6271.

Rueegg, W. T., M. Quadranti, and A. Zoschke (2007). Herbicide research and development: challenges and opportunities. *Weed Research 47*, 271–275.

Schwerdtle, F., A. Kemmer, and H. Schulz (1969). Gemeinschaftsversuche Baden-Württemberg 1969 (Common field trials Baden-Württemberg 1969). Technical report, Fachgruppe Pflanzenproduktion Stuttgart-Hohenheim.

Simard, M., B. Panneton, L. Longchamps, C. Lemieux, A. Légère, and G. D. Leroux (2009, March). Validation of a management program based on a weed cover threshold model: Effects on herbicide use and weed populations. *Weed Science 57*(2), 187–193.

Stafford, J. V. (Ed.) (2011). *Precision agriculture 2011*, Ampthill, UK/Prague, Czech Republic. ECPA: Czech Centre for Science and Society. Papers presented at the 8th European Conference on Precision Agriculture 2011, Prague, 11-14 July 2011.

Sökefeld, M., M. Keller, M. Weis, C. Gutjahr, and R. Gerhards (2012, March). Using bispectral imaging technology for simulated online-weed control in winter wheat and maize. See Nordmeyer and Ulber (2012), pp. 183–190.

Tranel, P. and T. Wright (2002). Resistance of weeds to als-inhibiting herbicides: what have we learned? *Weed Science 50*, 700–712.

Weis, M. (2010, November). *An image analysis and classification system for automatic weed species identification in different crops for precision weed management*. Ph. D. thesis, Institute for Phytomedicine, Department of Weed Science, University of Hohenheim, Stuttgart, Germany.

Weis, M., C. Gutjahr, V. Rueda Ayala, R. Gerhards, C. Ritter, and F. Schölderle (2008, December). Precision farming for weed management: techniques. *Gesunde Pflanzen 60*, 171–181.

Weis, M., M. Keller, and V. Rueda Ayala (2012, January). *Herbicides - Environmental Impact Studies and Management Approaches*, Chapter Herbicide reduction methods, pp. 95–120. Rijeka, Croatia: Intech.

Yang, C.-C., S. O. Prasher, J.-A. Landry, and H. S. Ramaswamy (2003). Development of a herbicide application map using artificial neural networks and fuzzy logic. *Agricultural Systems 76*, 561–574.