University of Hohenheim

Institute for Phytomedicine

Department of Weed Science

Development of an automated sensor based system for weed harrowing in cereals

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 Science
University of Hohenheim

First submitted: September 2011

Revision submitted: October 2012

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Date of oral Examination:	February 1st., 2012
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I confirm that all this work is my own except where indicated and that I did not use any other than the stated resources. I have completed the dissertation independently, according to the doctoral regulations of the University of Hohenheim, § 8.2.2.

[Victor Rueda Ayala] Stuttgart, October 2012

Abstract Site-specific weed control techniques have gained interest within the precision farming community over the last years. Managing weeds on a subfield level requires the varying weed density within a field to be measured. Decision models aid in the selection and adjustment of the treatments depending on the weed infestation, and the spatial and temporal variability of weeds. Also soil characteristics, and growth stages of crop and weeds are decisive parameters for precision weed management. Therefore, the general aim of the study was to develop a prototype harrow with an automatic adjustment of the intensity, under the approach of site-specific weed management, to obtain the highest weed control with the least possible crop damage. The specific objectives of this study were:

- to determine the efficacy of weed harrowing in cereals through experiments on selectivity in Germany.
- to study the crop tolerance and crop recovery to burial in soil due to harrowing
- to study the crop resistance to weed harrowing
- to assess the contributions to crop yield as a result of controlling weeds by harrowing
- to assess the soil resistance to harrowing
- to work out algorithms for automatic adjustment of the harrowing intensity according to
  - site-specific soil-, crop- and weed variability assessed before harrowing
  - harrowing intensities that produced the highest yield gain in the experiments done during 2007–2010.

Site-specific techniques for the detection and management of weeds are nowadays available to facilitate development of these techniques for herbicide application or mechanical weeding. Side effects of herbicides and increasing prevalence of organic farming are the motivation to make further developments in mechanical weed control. Mechanical weed control is mainly associated with cultivating tillage, but also primary and secondary tillage influence weeds. Cultivating tillage is performed in growing crops with harrows, hoes, brushes and a number of special tools for intra-row weed control. Harrows and rotary hoes are used for whole crop treatment, but it is essential to find the right timing and intensity to obtain the best selectivity and yield response. Different implements attached to the same vehicle are combined together attempting more selective weed control, like the in-row cultivator, the rotary harrow, and the precision hoe. Lately, there are prototypes intending automatic adjustment of the aggressiveness for the spring-tine harrow and autonomous guidance for hoes. The control mechanisms of all cultivating tillage methods are burring in soil, uprooting, and tearing plants into pieces.

Success of inter- and intra-row cultivation is highly influenced by selectivity. More specifically, this study was about finding the best intensity which delivers the highest selectivity of harrowing and the highest contributions to yield gain. Therefore, crop tolerance and weed control experiments in winter and spring cereals were carried out, to determine the influence of different harrowing intensities on selectivity, weed control, crop tolerance and recovery, and yield gain. Furthermore, those parameters were investigated at different crop growth stages in autumn (Denmark) and spring (Germany). Selectivity was chosen as a measure of the relationship between weed control and crop soil cover, with crop recovery as a measure of how crop yield was affected by soil cover in the absence of weeds. Selectivity was unaffected by crop growth stage in autumn and spring. In autumn, 80% weed control was associated with 6% crop soil cover, whereas in spring, 80% weed control corresponded to 26% crop soil cover. Crop recovery was higher in late growth stages in autumn and spring. With 25% crop soil cover, crop yield losses occurred in the ranges of 1–4% in autumn and 0.3–0.8% in spring. Weed control experiments revealed that the maximum crop yield response to harrowing was comparable with herbicide treatment. The average yield gain was 13% in autumn (Denmark) and 27% in spring (Germany). This studies contribute with parameter estimates that can be used in future models to evaluate the optimum harrowing intensity.

The biggest challenge for weed harrowing in wheat and barley is to carry out a site-specific weed control according to the variability in conditions of soil, weeds and crop growth stage; selectivity of harrowing and yield response may also be considered. Therefore, we developed an algorithm to automatically adjust the harrowing intensity by following three steps. First, in previous experiments different intensities were tested, and the best results in terms of weed control efficacy and yield gains, were assigned as the optimal intensity levels. Second, we formulated thirty six simple rules which combined assessments of leaf cover (I_{LC}), weed density (I_{WD}) and soil density (I_{SD}), to infer the output variable intensity (O_{HI}). Third, we tested the system in two field experiments. In experiment A the harrowing intensity was varied along the plot, according to the assessed crop-weed-soil variability, and compared with three constant intensities and one untreated control. In experiment B different modes of varying the intensity were tested: according to soil density, weed variability, or a combination of both. The system requires more validation experiments in field with variable soil types and variable weed competition. Our perspective is that real-time intensity adjustment might be achievable if cameras are attached in the front and at the rear or sides of the harrow. Then feedback of the remaining weed competition might be used as new input to the model, which would indicate the necessity of cultivating a second or more passes.

Kurzfassung Teilflächenspezifischen Unkrautbekämpfungsverfahren wurden in den letzten Jahren von Seiten der Precision Farming Gemeinde großes Interesse gewidmet. Das Unkrautmanagement in einem kleineren Maßtab benötigt eine unterschiedliche Unkrautbestandesdichte innerhalb eines Feldes, um Messungen durchführen zu können. Entscheidungsmodelle helfen bei der Auswahl und Anpassung der Behandlungen in Abhängigkeit von der Verunkrautung und der räumlichen und zeitlichen Variabilität von Unkräutern. Auch Bodeneigenschaften und das Entwicklungsstadium der Kulturpflanzen und Unkräuter sind entscheidende Parameter für die Präzisionsunkrautbekämpfung. Aus diesem Grund stellte das allgemeine Ziel der Studie die Entwicklung eines Prototyp-Hackstriegels mit einer automatischen Anpassung der Intensität dar, um den höchsten Unkrautbekaempfungserfolg bei möglichst geringer Schädigung der Kultur zu erreichen, wobei der Ansatz des teilflächenspezifischen Unkrautmanagements berücksichtigt wurde. Die spezifischen Ziele dieser Studie waren:

- die Bestimmung der Wirksamkeit des Striegelns in Getreide durch Experimente zur Selektivität in Deutschland
- die Untersuchung der Kulturtoleranz (Widerstandsfähigkeit) und Kulturwiederherstellung nach der Bedeckung mit Erde durch das Striegeln.
- die Kulturresistenz (Widerstandsfähgigkeit) auf das Striegeln.
- die Evaluierung der positiven Beeinflussung der Erträge als Folge der Unkrautkontrolle durch Striegeln.
- die Bewertung des Bodenwiderstandes beim Striegeln.
- das Finden von Algorithmen für die automatische Anpassung der Striegelintensität in Abhängigkeit.
  - der teilflächenspezifischen Boden-, Kultur- und Unkrautvariabilität vor dem Striegeln.
  - des Striegelintensitätsniveaus, welches den höchsten Ertrags-

gewinn in den von 2007 bis 2010 durchgeführten Experimenten erzielte.

Heutzutage sind teilflächenspezifische Methoden zur Erkennung und Kontrolle von Unkräutern verfügbar, welche eine Weiterentwicklung dieser Technik für die Herbizidapplikation oder mechanischen Unkrautbekämpfung erleichtern. Nebenwirkungen von Herbiziden und eine zunehmende Verbreitung des ökologischen Landbaus stellen die Motivation für weitere Entwicklungen im Bereich der mechanischen Unkrautkontrolle dar. Die mechanische Unkrautbekämpfung wird hauptsächlich mit einer Bodenkultivierung verbunden, aber auch eine primäre und sekundäre Bodenbearbeitung beeinflusst Unkräuter. Die Bodenkultivierung wird in wachsenden Kulturen mit Hackstriegeln, Hacken, Bürsten und einer Vielzahl an Spezialgeräten für die Unkrautkontrolle innerhalb der Reihen durchgeführt. Hackstriegel und Hackfräsen werden für die ganzflächige Behandlung verwendet, wobei der richtige Zeitpunkt und die richtige Intensität essentiell sind, um höchste Selektivität und beste Erträge zu erreichen. Unterschiedliche Geräte, die an ein Fahrzeug gekoppelt sind, können gemeinsam genutzt werden, um somit höhere Bekämpfungserfolge zu erzielen. Beispiele dafür sind die in-row cultivator, die Kreiselegge und die Präzisionshacke. In letzter Zeit wurden Prototypen entwickelt, die eine automatische Anpassung der Aggressivität für die Hackstriegel und eine autonome Orientierung für Hacken zum Ziel haben. Die Unkrautbekämpfungsmechanismen aller Bodenbearbeitungsmethoden basieren auf einer Bedeckung von Pflanzen mit Erde, Entwurzelung und Ausreißen oder das in Stücke schneiden von Pflanzen.

Der Erfolg einer Bearbeitung zwischen oder innerhalb einer Reihe wird von der Selektivität beeinflusst. Genauer gesagt, wurde diese Studie durchgeführt, um die besten Intensitätsniveaus, mit der besten Striegelselektivität zu finden, welche zu dem höchsten Ertragszuwachs führt. Um diese Parameter zu evaluieren, wurden Kulturtoleranz- und Unkrautbekämpfungsexperiment in Winter- und Sommergetreide durchgeführt, um den Einfluss verschiedener Intensitäten auf die Selektivität, Unkrautbekämpfungserfolg, Widerstandsfähigkeit der Kultur und Ertragsgewinn zu bestimmen. Des Weiteren wurden diese Parameter bei verschiedenen Entwicklungsstadien der Kulturpflanzen im Herbst (Dänemark) und Frühjahr (Deutschland) untersucht. Die Selektivität wurde als Maß für das Verhältnis zwischen Unkrautbekämpfung und Bedeckung der Pflanzen mit Erde gewählt, wobei die Widerstandsfähigkeit der Kultur als Maß dafür diente, wie der Ertrag durch die Bedeckung mit Erde in Abwesenheit von Unkräutern beeinflusst wurde. Die Selektivität wurde weder im Herbst noch im Frühjahr durch das Entwicklungsstadium der Kulturpflanzen beeinflusst. Im Herbst entsprachen 80% Unkrautbekämpfung 6% Bedeckung der Pflanzen mit Erde, während im Frühjahr 80% Unkrautbekämpfung zu 26% Bedeckung führten. Der Kulturwiderstand war bei späten Entwicklungsstadien im Herbst und Frühjahr höher. Bei einer 25%igen Bedeckung der Pflanze mit Erde, lag der Ertragsverlust zwischen 1 bis 4% im Herbst und zwischen 0,3 bis 0,8% im Frühjahr. Die Ergebnisse der Unkrautbekämpfungsexperimente zeigten, dass die maximale Ertragsantwort auf das Striegeln mit der Herbizidbehandlung vergleichbar war. Der durchschnittliche Ertragszuwachs lag bei 13% im Herbst (Dänemark) und 27% im Frühjahr (Deutschland). Diese Studien tragen dazu bei eine optimale Striegelintensität zu evaluieren, da die hier generierten Schätzwerte der Parameter in zukünftigen Studien verwendet werden können.

Die größte Herausforderung beim striegeln in Weizen und Gerste, ist einen standortspezifischen striegeln asuzuführen durch eine Anpassung von Bedingungen von Boden, Unkräutern und Wachstumsstadien der Kulturen. Dabei müssen die Selektivität des Striegels sowie die Beeinflussung des Ertrags berücksichtigt werden. Deshalb entwickelten wir einen Algorithmus zur automatischen Anpassung der Intensität in drei Schritten. Zunächst haben wir, unterschiedliche Intensitäten getestet, wobei die besten Ergebnisse in Bezug auf Selektivität, Ertragszuwachs und Kulturpflanzenschädigung das optimale Niveau darstellten. In einem zweiten Schritt formulierten wir 36 einfache Regeln, aus denen die Ausgabe von variablen Intensitäten mit Hilfe eines Linguistic-Fuzzy-Inferenz-Systems abgeleitet wurden. In einem letzten Schritt, untersuchten wir mithilfe von 2 Experimenten den Striegelerfolg bei variierender Intensität, die entsprechend der Bodenverdichtung, Unkrautvariabilität oder einer Kombination aus beiden Faktoren angepasst wurde. Ein zukünftiges Ziel stellt eine Echtzeit-Intensitätseinstellung dar. Dabei könnte das System eine Kamera enthalten, die hinter dem Fahrzeug angebracht wird, um Daten der nicht bekämpften Unkräuter zu sammeln, welche sofort als neue Eingabe für das Modell dienen. Somit könnte die Notwendigkeit einer zweiten oder mehreren Überfahrten direkt festgestellt werden.

Acknowledgements

I would like to deeply thank all people directly or indirectly involved in this thesis. To Professor Roland Gerhards, who kindly supervised and reviewed the whole work, guided me his with wise and profound understanding, not only for the development of the thesis, but also in personal matters. To Professor Jesper Rasmussen, who firstly accepted share his knowledge with me. Without even knowing me, he accepted to have me in Copenhagen university to do a theoretical and practical experience in the topic of mechanical weeding. Thanks also for being co-author in two of my publications. Special thanks go to the colleagues at the institute and research stations at Hohenheim, namely Martin Weis, Markus Ströbel, Stefan Knapp, Helmut Kärcher, Christoph Gutjahr, and Wilhelm Hermann. Thanks to Martina Keller for her valuable comments to the last part of this thesis. Also my thanks go to Dr. Oerke, Mrs. Sikora, and the colleagues in the University of Bonn, GRK722. Thanks for all the support with the complicated technical matters and also the field work. Of course, the list might be large if I named all people who I am thankful with: colleagues and friends, for their interesting and really rich discussions.

This project was funded by the German Research Foundation[1].

[1] Deutsche Forschungsgemeinschaft (DFG), grant No. GK722

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1 General introduction

1.1 Structure of the dissertation

This thesis is composed of three chapters. The first chapter is part of the book *Precision Crop Protection – the Challenge and Use of Heterogeneity*, which I was invited to write (section 2.1. This book chapter gives a description of physical weed management considering the variability of the soil-crop-weed system and the various implements used for mechanical weed control. Objectives to the present dissertation are given immediately below.

Four papers constitute the second chapter. A peer-reviewed paper, for which I contributed with about 30% to the contents to introduce the idea of precision mechanical weed control is included to give an outline of the automatic harrowing and the experiments which were planned. Two publications (sections 2.3 and 2.4) were used to study in detail the important parameters for successful weed harrowing. Results to these experiments were used for the fourth paper, which focused on the development of the algorithm for automatic adjustment the harrowing intensity, according to the site-specific soil-, crop-, and weed variability assessed before harrowing, using a linguistic fuzzy inference system (section 2.5).

The third chapter contains a general discussion and conclusion, including some future perspectives in the field of mechanical weed control and robotic weeding.

1.2 Objective

The general aim of the study was to develop a prototype harrow with an automatic adjustment of the intensity under the approach of site-specific weed management to obtain the highest weed control with the least possible crop damage. The specific objectives of this study were:

1. to determine the efficacy of weed harrowing in cereals through experiments on selectivity in Germany.

2. to study the crop tolerance and crop recovery to burial in soil due to harrowing

3. to study the crop resistance to weed harrowing

4. to assess the contributions to crop yield as a result of controlling weeds by harrowing

5. to assess the soil resistance to harrowing

6. to work out algorithms for automatic adjustment of the harrowing intensity according to

    - site-specific soil- and crop variability, and weed abundance assessed before harrowing

    - harrowing intensities that produced the highest yield gain in the experiments done during 2007–2010.

2 Publications

The publications related to this work are listed as follows:

Reviewed publications: Weis et al. (2008), Rueda-Ayala et al. (2010), and Rueda-Ayala et al. (2011)

Conference proceedings: Rueda-Ayala & Gerhards (2009)

Submitted (in review): Rueda-Ayala et al. (2012)

In this chapter, a brief description of the selected papers is presented. The first section 2.1 is a description of implements used for mechanical weeding, from very simple and old tools to new technologies aiming site-specific weeding and autonomous machines. Furthermore, tools for whole crop cultivation and the most important parameters for success in weed control are analysed. A short review of the innovative technology in physical weed control is also shown (Rueda-Ayala et al., 2010).

A general overview of the prerequisites for site-specific weed management is given in section 2.2 Weis et al. (2008). Possibilities for automated weed detection and a search for decision rules for automatic weed harrowing, according to the variability of the complex soil-crop-weeds are given.

Sections 2.3 (Rueda-Ayala & Gerhards, 2009) and 2.4 (Rueda-Ayala et al., 2011), refer to the detailed study carried out for weed harrowing in cereals, to determine important parameters for successful weed harrowing: selectivity, crop tolerance, crop resistance, crop recovery and crop yield gain. For this purpose, six harrowing experiments in spring and winter cereals (wheat and barley) were carried out during 2007 to

2009 in Germany, and two experiments in winter wheat in during 2008-2009 in Denmark. Linear and non-linear models were fitted to the data, and the major aim was to identify the optimal harrowing intensity in terms of crop yield gain.

Finally, the main goal to the present dissertation is addressed in Section 2.5 (Rueda-Ayala et al., 2012). To increase weed control efficacy by harrowing, the intensity should be adjusted according to the variability of weed infestation, soil density and crop growth stage. Therefore, the best results from previous experiments were used as the optimal intensity levels, and these were automatically varied according to the assessed variability. For this purpose, a linguistic fuzzy inference system was used to determine the harrowing intensity accurately for the leaf cover, weed density and soil density, assessed before harrowing operations.

Please notice: that only the abstracts of the publications are included in the electronic version due to the copyrights of the publishers, except where submitted versions were not yet published.

Table 2.1: Overview of publications: bibliographic entries in chronological order

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

2.3—Rueda-Ayala & Gerhards (2009) Rueda Ayala, V. P. and R. Gerhards (2009). Selectivity of weed harrow- ing with sensor technology in cereals in Germany. In: E. van Henten, D. Goense and C. Lokhorst, (Eds.) *Precision agriculture '09*, Volume 7, The Netherlands. 7th European Conference on Precision Agriculture (ECPA): Wageningen Academic Publishers, pp. 339–348.

2.1—Rueda-Ayala et al. (2010) Rueda Ayala, V. P., J. Rasmussen and R. Gerhards (2010). *Precision Crop Protection* (1 ed.)., Chapter Mechanical Weed Control. In: Oerke, E.-C., R. Gerhards, G. Menz, and R. A. Sikora (Eds.) Heidelberg, Germany: Springer Verlag, pp. 279–294.

2.4—Rueda-Ayala et al. (2011) Rueda-Ayala, V. P., J. Rasmussen, R. Gerhards and N. E. Fournaise (2011). The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat. *Weed Research 51*, 478–488.

2.5—Rueda-Ayala et al. (2012) Rueda Ayala, V., M. Weis and R. Gerhards (2012). Development and testing of a system to adjust automatically the harrowing intensity. *Weed Technology submitted, under review.*

2.1 Mechanical weed control

Abstract Side effects of herbicides and increasing prevalence of organic farming are the motivation to develop new alternatives to manage weeds. Mechanical weed control is associated with cultivating tillage (e.g. tertiary tillage), but also primary and secondary tillage influence weeds. Cultivating tillage is performed in growing crops with harrows, hoes, brushes and a number of special tools for intra-row weed control. Inter-row cultivations have been used in many decades in row crops with high success, although with some difficulties at intra-row level. Guidance systems have been developed to increase capacity and accuracy to steer the hoes along the rows. The control mechanisms of all cultivating tillage methods are through burring weed seedlings in soil, uprooting, and tearing weeds into pieces. For whole crop and intra-row implements, successful weed control is highly influenced by an appropriate adjustment of the intensity of cultivation. However, variations of soil conditions, crop growth stage and weed abundance have been only recently taken into account. Site-specific weed management aims to identify the spatial and temporal variability of weeds and manage them correspondingly. Improved devices for sensing crops and weeds in real-time and robotics allow more precision when operating mechanical tools, thus improving efficacy of control and reduce operation costs. In this document, implements for mechanical weeding are described together with their options for site-specific weed control strategies. Harrows and rotary hoes are used for whole crop treatment; different implements attached to the same vehicle are combined together attempting more selective weed control. Lately, there are prototypes for automatic adjustment of the intensity of a spring-tine harrow and autonomous guidance for hoes, thus getting closer to a real-time site-specific weed management approach.

Originally published as Rueda-Ayala et al. (2010)

Key words: selectivity, crop yield, image analysis, soil resistance, leaf coverage, weed coverage, fuzzy logic

2.2 Precision farming for weed management: techniques

Abstract Managing weeds on a site-specific level has gained interest in the precision farming community over the last years. It requires objective determination of weed abundance and densities within a field. Decision systems contribute to the selection and adjustment of the treatments to control the weed infestation, according to me assessed variability. The weed control can be done either with herbicides or mechanically. A site-specific herbicide application technology can save large amounts of herbicides used. Mechanical weed control techniques adapting to the weed situation in the field are possible and applicable to a wide spectrum of crops. In this document, site-specific techniques for the detection and management of weeds are presented. A system for the discrimination of weeds and crop plants from images and to generate weed maps automatically, is described. Models for the yield effect of weeds were developed and applied in On-Farm-Research experimental setups. Economic weed thresholds are derived and used for a herbicide application with a patch sprayer.

Key words: site-specific weed control, weed mapping, chemical control, mechanical control, expert systems for weed control

Originally published as Weis et al. (2008)

2.3 Selectivity of weed harrowing with sensor technology in cereals in Germany

Abstract The influence of intensity, timing, and direction of postemergence harrowing was studied in three field experiments in winter and spring cereals. Selectivity of harrowing was studied as originally defined in Denmark. Various intensities were created by increasing number of passes, tine angle and driving speed and then applied at varying crop growth stages. Objective estimation of leaf cover through differential image analysis was used, and a recent proposed statistical procedure was used to analyse leaf cover and weed density was applied. Selectivity was in general influenced by timing of harrowing. Harrowing at late crop growth stages showed improving weed control effects. Leaf cover and weed density decreased exponentially at increasing harrowing intensities due to an increment of crop soil cover. Harrowing across crop rows did not cause impacts on selectivity, while along rows seemed to improve it at early growth stages. Nevertheless, to draw conclusions further research is needed. Intensities which generate the crop soil cover percent associated with the higher selectivity will be taken as the basis to develop algorithms for automatic harrowing.

Key words: image analysis, weed harrowing, timing, wheat, barley, soil coverage, site-specific mechanical weed control

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Originally published as Rueda-Ayala & Gerhards (2009)

2.4 The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat

Abstract Crop tolerance and weed control experiments in winter wheat were carried out to determine the influence of post-emergence weed harrowing at different crop growth stages on selectivity, crop recovery and crop yield. The importance of growth stage was investigated in autumn (Denmark) and spring (Germany). The relationship between weed control and crop soil cover described the selectivity of harrowing. Crop recovery was used as a measure of how crop yield was reduced by soil cover due to harrowingin the absence of weeds. Selectivity was unaffected by crop growth stage in autumn and spring, though more research is needed. In autumn, 80% weed control was associated with 6% crop soil cover, whereas in spring, 80% weed control corresponded to 26% crop soil cover. Crop recovery was higher at late growth stages in autumn and spring, in both locations. About 25% crop soil cover caused crop yield losses between the ranges of 1–4% in autumn and 0.3–0.8% in spring. Weed control experiments revealed that the yield gain from harrowing was comparable with herbicide treatment. The average yield gain was 13% in autumn, Denmark and 27% in spring, Germany. This study contributes with parameter estimates that can be used in future models to evaluate the optimum harrowing intensity and may be used as input in decision system for automation of harrowing.

Key words: weed harrowing, winter wheat, image analysis, crop recovery, crop tolerance, weed competition

Originally published as Rueda-Ayala et al. (2011)

2.5 Development and testing of a system to adjust automatically the harrowing intensity

Abstract Efficacy of weed harrowing in wheat and barley can be increased when the intensity is adapted to the site-specific conditions of soil, weeds and crop growth stage. In this study, an algorithm for automatic control of the intensity was built using three steps. First, in previous experiments different intensities were tested, and the best results in terms of weed control efficacy and yield gains, became optimal intensity levels. Secondly, to build the algorithm we formulated thirty six simple rules which combined the fuzzy sets leaf cover (I_{LC}), weed density (I_{WD}) and soil density (I_{SD}), to infer the output variable intensity (O_{HI}) in a linguistic fuzzy inference system (LFIS). The third step was to test the system in two field experiments. In experiment A the harrowing intensity was varied along the plot, according to the assessed crop-weed-soil variability, and compared with three constant intensities and one untreated control. In experiment B different modes of varying the intensity were tested, i.e. according to soil density, weed variability, or a combination of both. Higher weed control was achieved with the tested intensities, compared with the untreated plots. The variable intensities tended to increase weed control, although not improving crop yield. Absence of weed competition might have hidden the weed control effects on yield. Future validation experiments are necessary in field with variable soil types and variable weed competition. A real-time intensity adjustment should be achievable if cameras are attached in the front and at the rear or sides of the harrow. Then feedback of the remaining weed competition might be used as new input to the model, which would indicate the necessity of cultivating a second or more passes.

Originally submitted to Weed Technology Journal as Rueda-Ayala et al. (2012)

Key words: selectivity, soil covering, crop-weed-soil variability, fuzzy logic, site-specific harrowing

2.5.1 Introduction

Mechanical weed control provides a good option for reducing weed pressure without harming the environment, in both organic and conventional farming. Harrowing is a common strategy to control weeds, typically employed in cereals and legumes with a flexible tine harrow. Commonly, a constant harrowing intensity is applied across the whole field, regardless of variations in weed distribution an soil structure. Weed harrowing controls weeds by uprooting or by covering weed seedlings with soil, however the crop may also be affected (Kurstjens & Kropff, 2001). Variations in soil conditions lead to uneven weed control success (Søgaard, 1998). The heterogeneous spatial distribution of weed populations might cause underestimation of potential yield loss in areas with high weed densities or overestimation in areas with low or none weed densities (Weis et al., 2008). Thus, choosing one harrowing intensity for the whole field may result in crop damage due to an aggressive treatment in areas with low weed infestations, with young and small weeds or with light soil density. Equally, a lighter intensity may generate yield losses due to a insufficient weed control in high weed infested patches. To increase the harrowing efficacy and balance the trade–off between crop damage and weed control, the applied intensity should be adapted to the variability of soil, weeds and crop within a field. During the last decade precision farming has aimed to establish a site-specific weed management strategy, therefore weed harrowing can be done site-specifically if variable conditions in the field are taken into account (Gerhards & Christensen, 2006).

In early postemergence harrowing crop plants are usually bigger than weed seedlings, meaning that weed contribution to the green leaf cover is insignificant (Rasmussen & Nørremark, 2006). Hence, the percentage of crop canopy buried in soil after harrowing has been defined as crop soil cover (Rasmussen et al., 2007). A range of crop soil cover around 25% has been recommended to obtain low yield losses due to crop damage and high levels of weed control (Rasmussen et al., 2008, 2010). However, the degree of crop soil cover depends not only on soil conditions, but it is also directly related to the applied harrowing intensity (Cirujeda et al., 2003). Crop soil cover is objectively calculated from measurements of leaf cover (index) after the crop is harrowed, through digital image analysis (Rasmussen et al., 2007). A determined percentage of weed control achieved with a percentage of crop soil cover is the crop-weed selectivity, without considering crop and weed recovery aspects (Rasmussen, 1990). Selectivity is an important relationship for evaluating success of weed harrowing and should be accounted for decision making of the harrowing intensity (Rasmussen et al., 2010, Rueda-Ayala & Gerhards, 2009).

Harrowing intensity refers to the levels of cultivation aggressiveness achieved with the harrow. Higher harrowing intensity levels are achieved by decreasing the tine angle relative to a perpendicular axis to the field surface, by increasing the depth of the implement, by increasing driving speed or through various consecutive passes on the same day of cultivation (Cirujeda et al., 2003, Engelke, 2001, Rasmussen et al., 2007). Although in practice there are systems to vary the harrowing intensity, a decision system is not yet available to adjust the intensity according to the field variability. For instance, in weed patches and/or dense soil structures the intensity should be higher to achieve an acceptable weed control. Contrarily, in areas with low or no weed competition, and/or loose soil structures, a lower harrowing intensity or none at all might be recommendable. Selectivity cannot be incorporated into such a decision system, because it is a relationship determined after harrowing. However, leaf cover and weed density, which are used to determine the selectivity, can serve as command variables in a decision support system to control the harrowing intensity. Furthermore, assessment of these variables can be automated (e.g. with bispectral cameras), which results in a reliable and objective determination of the crop and weed status in a field (Weis, 2010).

In this study, we considered the necessity to assess the crop-weed-soil variability as the base to adjust the harrowing intensity. High, medium, and low levels of leaf cover, weed density and soil density were determined; leaf cover was assumed to correspond to the crop growth stage. The different levels of harrowing intensity varied from light to very strong treatments. Leaf cover, weed density and soil density measured and analysed in previous studies, and the crop yield response to harrowing, were used in this paper as input for the decision system. Our hypotheses were: (i) Leaf cover, weed density and soil density and the applied harrowing intensities in a previous experimental phase, can be used to create an algorithm for automatic control of the harrowing intensity. For this purpose, simple rules were formulated in a linguistic fuzzy inference system (LFIS) to combine input from the bispectral cameras and a soil sensor. (ii) Harrowing according to the assessed variability is achievable, and site-specific harrowing effectively diminishes crop damage due to harrowing, while maintaining high levels of weed control and perhaps increasing crop yield. For this purpose application maps were created with the algorithm and applied in two field experiments.

2.5.2 Materials and Methods

2.5.2.1 Data source

Based on results of previously carried out experiments in winter and spring cereals, barley (*Hordeum vulgare*) and wheat (*Triticum aestivum* L.), we aimed to build a decision system for automatic harrowing. Those experiments aimed to determine the influence of crop growth stage and harrowing intensity on selectivity and on crop yield. They took place during the period from 2007 to 2009, at different sites with varying soil conditions and weed densities (Table 2.2). Further details on experiments 1 to 4, are given in Rueda-Ayala & Gerhards (2009), and Rueda-Ayala et al. (2011). Experiments 5 and 6, come from not previously published data (Meiser, 2009), but the variable assessment and analysis procedure were the same as for experiments 1 to 4.

Table 2.2: Experimental site and treatment description for the trials conducted during 2007–2009, to analyse selectivity and yield response to harrowing. Different tine angles, driving speeds (in km h^{-1}) and number of passes constituted the harrowing intensities, which were applied all at differing crop growth stages (BBCH-code). Experiments were placed at various location with differing soil types and weed populations.

Experiment (Year)	Crop (BBCH)	Location (Soil type)	Dominant weeds	Harrowing intensity: tine angle	speed (km h^{-1})	passes
(2007)						
1*	winter barley	Heidfeldhof	*Lamium purpureum* L.,	lightest,	10	1
	(12, 24)	(silty loam)	*Galium aparine* L.,	light,	10	1
			Alopecurus myosuroides Huds.,	strong,	12	2
			Matricaria inodora L.	strongest	12	2
(2008)						
2*	spring barley	Meiereihof	*Lamium purpureum* L.,	lightest,	8	1–3
	(13, 21, 24)	(silty loam)	*Polygonum convolvulus* L.,	light,	8	1–3
			Amaranthus retroflexus L.,	strong	12	1–3
			Chenopodium album L.			
3†	winter wheat	Heidfeldhof	*Matricaria inodora* L.,	strongest	12	1–4
	(12, 15, 21)	(silty loam)	*Cirsium arvense* (L.) Scop.,			
			Alopecurus myosuroides Huds.,			
			Galium aparine L.			
4†	winter wheat	Ihinger Hof	–	light	8	1–4
	(20)	(loam)				
	(22, 24)				10	1–4
(2009)						
5‡	spring barley	Heidfeldhof	*Lamium purpureum* L.,	lightest,	8	1
	(14)	(silty loam)	*Galium aparine* L.,	light,	8	1
			Cirsium arvense (L.) Scop.,	strong,	8	2
			Avena fatua L.	strongest	8	2
6‡	spring wheat	Meiereihof	*Chenopodium album* L.,	light	8	1–3
	(12, 15)	(sandy loam)	*Veronica hederifolia* L.,			
			Galium aparine L.,	strong	10	1–3
			Alopecurus myosuroides Huds.,			
			Avena fatua L.			

Sources: * Rueda-Ayala & Gerhards (2009); ‡ Rueda-Ayala et al. (2011); ‡ Meiser (2009), not yet published

The experimental sites were located at three research stations of the University of Hohenheim: Heidfeldhof (48°43′ N, 9°12′ E) and Meiereihof (48°43′ N, 9°15′ E), near Stuttgart, and Ihinger Hof (48°45′ N, 8°56′ E), near Renningen. In Rueda-Ayala et al. (2011), only experiments conducted in Germany were used, to keep homogeneous characteristics of harrowing implements and weed- and soil assessments. Harrowing was done with a 6-m-wide flex-tine harrow (Hatzenbichler, Hatzenbichler Austrian Agrotechnik, St. Andrä, Austria. Different tine angles (lightest, light, strong, strongest), were combined with different settings of driving speeds and number of passes, to create increasingly more aggressive intensities, including one untreated control. Decisions about speed, angles and settings were taken according to expert knowledge on the field, at the time of harrowing. The analysis procedures for studying selectivity given in Rasmussen et al. (2008), and Rasmussen et al. (2009) were used. The yield responses to weed control by harrowing was analysed as in Rueda-Ayala et al. (2011).

2.5.2.2 Algorithm for automatic harrowing

A linguistic fuzzy logic control algorithm was created to adjust the harrowing intensity according to three input variables: leaf cover, weed density and soil density, as described below. The applied harrowing intensities on the experiments during the period of 2007 to 2009 which achieved high selectivity, high crop yield gains or negligible crop yield reductions (Table 2.3), were assigned as the optimal intensities to be included into the LFIS via rules (Table 2.4).

Table 2.3: Optimal intensities for the trials conducted during 2007–2009 and their effects on selectivity (calculated crop soil cover corresponding to 80% weed control and yield response (calculated crop soil cover and weed control that attained yield gain. Ranges of leaf cover, weed density and soil density in the untreated plots were used as data source to develop the algorithm for automatic harrowing.

Crop growth stage (BBCH)	Leaf cover (%)	Weed density (plants m^{-2})	Soil density (N)	Intensity* Intensity*	Crop soil cover (%) corresponding to 80% weed control	Crop soil cover (%) that attained yield gain	Weed control (%) that attained yield gain	Yield gain (%)
Experiment 1*								
(12)	*nd*	40–56	*nd*	strong	–	24	94.3	19.2
(14)	18–20	82–93	*nd*	strong	47–50	14.7	41.4	15.5
Experiment 2*								
(24)	24–27	31–41	*nd*	lightest	7–16	11.0	80.0	-3.0
Experiment 3*								
(15)	3–5	58–73	107–147	strongest	22–30	36.0	90.0	37.0
(21)	8–11	148–250	101–142	strongest	22–30	28.0	91.0	45.0
Experiment 4*								
(24)	5–9	–	23–25	light	–	16–31	–	-0.4
Experiment 5*								
(14)	4–6	28–63	9–20	strong	40–50	*nd*	*nd*	*nd*
Experiment 6*								
(12)	6–7	58–147	*nd*	light	22–30	25.0	90.4	16.0
(15)	17–19	147–154	*nd*	strong	40–48	50.0	80.4	4.7

* According to Table 2.2; *nd* = data not assessed

2.5.2.2.1 Assessment of input and output variables We used the approach of sensor based mechanical weed control given in Weis et al. (2008): Leaf cover and weed density were assessed using a bispectral camera and the soil density was assessed with a digital sensor (Tedea-Huntleigh's model 615 S-type, Tedea-Huntleigh GmbH., Germany), described below. Weed density was also manually counted to verify the results from digital image analysis. Automated assessment of weed density was carried out in all experiments. A rigid tine mounted on the harrow, perpendicular to soil surface, was used to measure the soil density while harrowing. Horizontal movements of the rigid tine were captured by the digital sensor, and the variation of voltages were calibrated to different force levels measured in Newton (data not shown). The resistance force to the forward movement of the harrow was assessed as the soil density. Soil density could not be measured in all experiments due to technical difficulties, however a good differentiation in soil between winter and spring cereals was identified. The output variable harrowing intensity was constructed from increasingly more aggressive treatments as a result of changing the tine angle into five levels 0 (untreated or none), 1 (lightest), 2 (light), 3 (strong), and 4 (strongest).

2.5.2.2.2 Fuzzy based control system The mathematical foundation for the algorithm to control the harrowing intensity was a fuzzy rule-based inference system, which has three main components: fuzzy sets, rules for inference application, and a defuzzified output (Wong & Hamouda, 2003). A broader description of fuzzy logic is given in Sivanandam et al. (2007), Valente de Oliveira (1995), Yang et al. (2003), Zadeh (1965). The linguistic constructs leaf cover (I_{LC}), weed density (I_{WD}), soil density (I_{SD}), and harrowing intensity (O_{HI}) were transformed into *fuzzy sets* with a continuum degrees of memberships, so called *membership functions* (MF). Three MF were determined for I_{LC} and I_{SD}, and four for I_{WD}, as shown in Figure 2.1. Leaf cover at BBCH 12–14, depicted the *low* MF of I_{LC}; older growth stages, BBCH 15–21 and BBCH 22–31 characterized the *medium* and *high* levels, respectively. At a leaf cover lower than 2%, the crop would not resist being harrowed, but with more than 40% leaf cover, the crop could stand an aggressive harrowing intensity. A high weed competition was assumed with 100 weeds m^{-2} or more, thus

Table 2.4: Fuzzy rule-base to infer the automatic adjustment of the intensity O_{HI} (none, lightest, light, strong, strongest) for site–specific weed harrowing, after three conditions (low, medium, high) of the variables leaf cover (I_{LC}) and soil density (I_{SD}), and four conditions (none, low, medium, high) of the variable weed cover (I_{WC}).

Input variables			Output variable
I_{LC}	I_{SD}	I_{WD}	O_{HI}
low	low	none	none†
medium	low	none	
high	low	none	
low	medium	none	
medium	medium	none	lightest
high	medium	none	
low	high	none	
medium	high	none	
high	high	none	
low	low	low	
medium	low	low	
high	low	low	
low	medium	low	
medium	medium	low	
low	medium	medium	
high	medium	low	light
low	high	low	
medium	high	low	
high	high	low	
low	low	medium	
medium	low	medium	
high	low	medium	
medium	medium	medium	
low	high	medium	
medium	high	medium	
low	low	high	
medium	low	high	
low	medium	high	
low	high	high	
high	medium	medium	strong
high	high	medium	
high	low	high	
medium	medium	high	
medium	high	high	
high	medium	high	strongest
high	high	high	

† The rule: IF (I_{LC} IS low) AND (I_{SD} IS low) AND (I_{WD} IS none) THEN (O_{HI} IS none)

the intensity should be increased to its maximum level. No weed competition was assigned at a density below 15 weeds m^{-2}. For I_{SD}, higher membership degrees than 30 N indicated a highly dense soil, in which weed harrowing would not be favourable due to poor soil workability (Rueda-Ayala et al., 2010).

MF for the fuzzy set O_{HI} were defined using the same intensity levels from the data source (Table 2.3), as *none* (i.e. untreated), *light*, *lightest*, *strong* and *strongest*. Intensities which achieved high weed control with low crop soil cover, and yield gain or yield loss due to harrowing not higher than 3% were used. All levels of the fuzzy sets I_{LC}, I_{WD} and I_{SD} were fuzzified into a degree of matching linguistic quantity through an inference mechanism with predefined rules to infer the output O_{HI}. These rules basically consist of two parts: an *IF* 'antecedent proposition' and a *THEN* 'consequent proposition' (Bosma et al., 2010, Mai & Janschek, 2009, Wong & Hamouda, 2003). Thirty six rules (Table 2.4) were created using Boolean relations (Klose & Nuernberger, 1999, Zhou & Gan, 2008). The linguistic output went through *defuzzification*, to be translated into crisp single-valued quantities (numerical data form). Only then data can be used in engineering applications (Marakoglu & Carman, 2010, Sivanandam et al., 2007). The defuzzication method was center of gravity (CoG), which calculates the centroid from the integrated membership function (Nurcahyo et al., 2003).

2.5.2.3 Experimental application of the system

To test the fuzzy inference system, two harrowing experiments (A and B) in winter wheat were conducted. The experiments were located at the Ihinger Hof research station, during the growing period 2009–2010. In experiment A, four harrowing intensity levels served as controls, which were compared to a *fuzzy inferred variable intensity*, resulting in five treatments in total. Each of those four intensities was kept constant along the 80m plot, and the variable intensity was applied along 12 raster-plots, 6m × 6m, within the 80m plot. In experiment B, leaf cover I_{LC}, weed density I_{WD} and soil density I_{SD} were assessed about two weeks before harrowing (Figure 2.2, top). One average value per raster-plot was

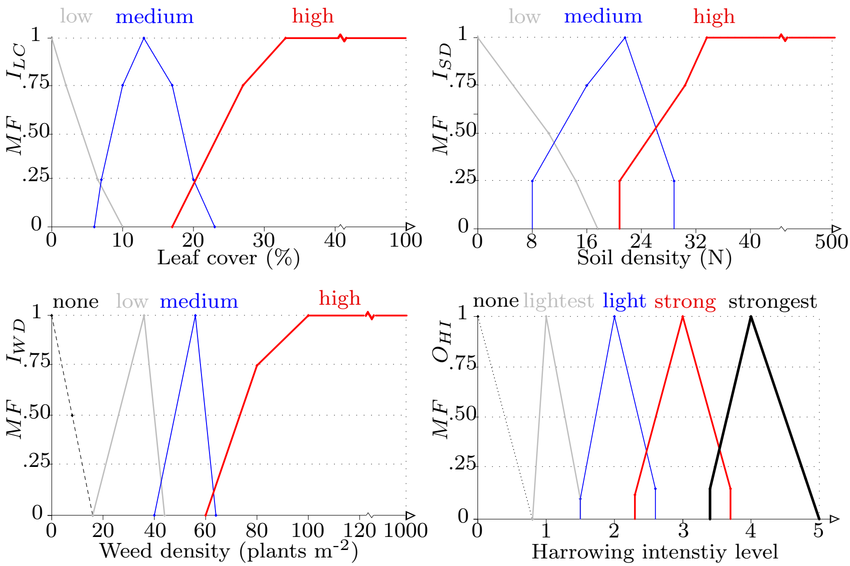

Figure 2.1: Membership functions (MF) of the input variables leaf cover (I_{LC}), weed density (I_{WD}), and soil density (I_{SD}), to generate the output variable harrowing intensity (O_{HI}) by the fuzzy inference model

introduced in the LFIS to derive the intensity levels. The output intensity was introduced in the free geographical information system OpenJUMP (OpenJUMP Pirol Edition, GNU Public License) (FSF, 1980, 1999), to create application maps (Figure 2.2, bottom). Thus, three possibilities of inferring the harrowing intensity were tested along the 12 raster-plots, within the 80m plot: in conformity with the soil density only (s), or the weed density only (w), or a combination of both, soil and weed densities ($soil + weed$). Leaf cover (I_{LC}) was included in all three possibilities as a reference of the crop growth stage. Additionally, one treatment was *not harrowed* (c).

In both experiments, the soil was rolled on strips-plots by one, two, or three passes after sowing. Each strip was 24 m long separated by a 4 m buffer-border to facilitate the rolling operations. The aim was to artificially generate three soil density levels along each experimental plot, thus enabling harrowing according to three known soil densities. A strip-plot design with four replication blocks was applied; the harrowing intensity was arranged in the whole plot and the rolling treatments in the strip-plot. Each strip-plot was 24 m long separated by a 4 m buffer-border to facilitate the rolling operations, giving a total plot length of 80 m. The variable intensity in experiment A, as well as those in experiment B, were applied off-line with the prototype for automatic adjustment of the harrow (Figure 2.3). The soil sensor (a) sends the soil density data to the computing unit (b), which controls the actuator (c) to vary the harrowing intensity to a light (c_1), a strong (c_2) or the strongest (c_3) level, according to the measured variability. The crop and weed density were included through predefined maps, which was possible because the system has a precise positioning system RTK-DGPS (Trimble ® 5800 Limited GPS System 2001) (d). The fuzzy output variable O_{HI} was transmitted to the computing unit, which sends the signals to the motors to automatically adjust the tine angle.

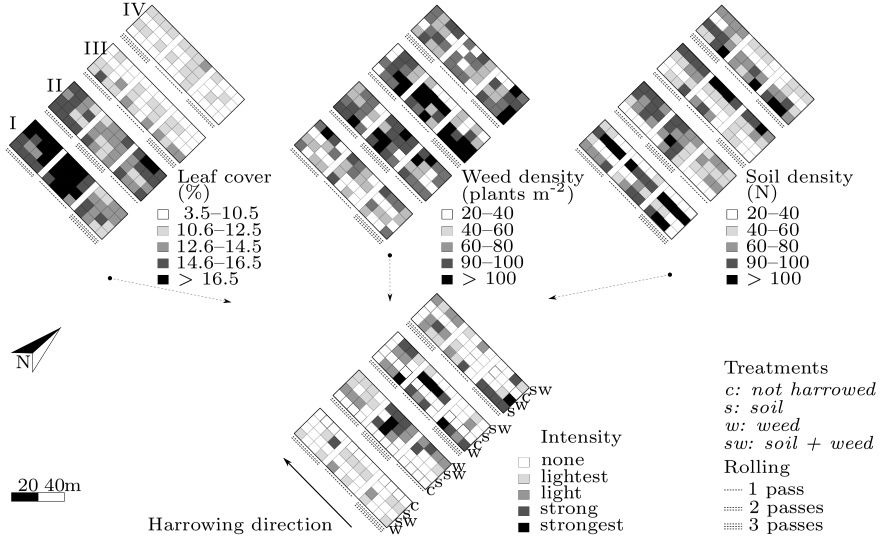

Figure 2.2: Experimental setup to the LFIS application (Experiment *B*). Inputs were obtained for leaf cover I_{LC} (topright), weed density I_{WD} (top) and soil density I_{SD} (topleft) assessed before harrowing to infer the output harrowing intensity and create the application map (bottom). I–IV repetition blocks.

Figure 2.3: Prototype of the automatically controlled flexible-tine harrow, modified after Rueda-Ayala et al. (2010). (a) Soil sensor; (b) computing unit; (c) motor; (c_1) light intensity; (c_2) strong intensity; (c_3) strongest intensity; (d) RTK-DGPS

Two timings of harrowing were used for both experiments, at BBCH 24 and 28, because at the first timing the soil crust after the winter made soil loosening very difficult, thus not enough soil cover was produced to control weeds effectively. For both timings the harrowing intensity was the same, except at BBCH 24 one pass with the harrow at a driving speed of 8 km h^{-1}, and at BBCH 28 two passes at 10 km h^{-1}. Bispectral cameras and manual counting were used to assess leaf cover and weed density reduction immediately after harrowing. At crop maturity, yield was assessed with an automatic yield mapping system, that uses a gravimetric measuring system in the combine harvester (New Holland Agriculture). Statistical data analysis was done with PROC MIXED in SAS (SAS version 9.1, SAS Institute Inc, NU Cary, 2004). F-tests were applied through a mixed model with a significance level of 0.05 to test factor effects on weed density reduction and yield. An exponential spatial covariance structure was accounted for the raster-plots, nested within the rolled strips with the function type=sp(exp). The Tukey's

Studentized Range Honest Significant Difference test (Tukey HSD) was applied to compare effects of harrowing intensities and rolling passes on weed density reduction.

2.5.3 Results and Discussion

2.5.3.1 Reliability of the fuzzy inference system for automatic control of intensity

The relationships between crop soil cover (%) and weed control (%), and the yield response studied during our previous experimental period 2007–2009, were the reference to delimit our input and output variables for the decision system. Our most relevant findings were that leaf cover ranged between 2 to 20%, being lower at early crop growth stages. Weed densities varied across experimental fields from 40 to about 250 plants m^{-2} and soil density varied from 9 to 19 N in spring cereals and from 23 N (autumn) to 153 N (end of winter) in winter cereals. Generally for winter cereals, harrowing in autumn generates high degrees of crop soil cover because the soil is still loose, but in early spring the soil may become highly compacted forming a crust that increases the soil density (Rasmussen & Nørremark, 2006). The intensity levels taken from this previous experimental period, attained 80% weed control with a range of 16–30% crop soil cover. In cases of high weed competition and denser soils, over 45% crop soil cover was necessary, challenging the maximum recommended of about 25% crop soil cover to achieve 80% weed control (Rasmussen et al., 2010, Rueda-Ayala et al., 2011). Those ranges of crop soil cover resulted in 3–45% yield gain in case of high weed competition, and in cases of poor weed competition, the yield losses effect due to harrowing were lower than 1% (Rueda-Ayala et al., 2011).

Previous attempts to adjust the harrow automatically have shown that it is not easy to define a standard intensity for every field, because it depends on the crop growth stage, weeds and soil conditions (Dierauer & Stöppler-Zimmer, 1994, Engelke, 2001). Søgaard (1998) could automatically control the intensity of a flexible tine harrow, considering essentially the working depth as the deciding variable to characterize the harrowing intensity. This means that crop growth stage and weed abundance were not considered in his system. Engelke (2001) had a more complete approach by taking into account the soil density, soil structure, the crop- and weed growth stage at the time of harrowing and the site-specific weed distribution. However, both studies did not take into account neither selectivity, nor crop resistance and recovery to crop soil cover, which is the main cause of crop damage as a result of harrowing in cereals (Jensen et al., 2004). The system proposed in the present study, is advantageous owing to two main reasons. Firstly, it integrates substantial elements for successful weed harrowing namely the relationship between crop soil cover and weed control, and the contributions to yield when controlling weeds by harrowing, e.g. as suggested by Weis et al. (2008), and Rasmussen et al. (2010). Secondly, those substantial elements and relationships were objectively assessed (leaf cover, weed density, soil density) and accurately analysed with robust scientific methods, given in Rasmussen et al. (2008, 2009), Rueda-Ayala et al. (2011).

2.5.3.2 Fuzzy inference system and experimental application

Data assessed before harrowing are displayed Figure 2.2 (top), served as input to characterize the harrowing intensity (bottom). The maps at the top of Figure 2.2 correspond from left to right to leaf cover (%), weed density (plants m^{-2}) and soil density (N), respectively. About one half of the experimental field had a lower leaf cover than 14%, which refers to the first true leaf crop growth stage (Figure 2.2, topleft). The other half was also nearly at one- or two leaves stage, however the crop seemed more dense thus covering more field area. Weed density seemed to have occupied the area with a lower leaf cover because that are showed a denser weed abundance of about 40 to more than 100 plants m^{-2} (Figure 2.2, top-center). The dominant weed species in both experiments were: *Veronica persica* Poir., *Stellaria media* (L.) Vill./Cyr., and *Lamium purpureum* L., accounting for 70% of the weed infestation, and *Viola arvensis*, *Matricaria inodora* L. and other species, the missing 30%. Soil density was heterogeneously distributed throughout the field and showed no clear spatial patterns, as it varied from 20 to nearly 100 N, at each 6

× 6 raster plot (Figure 2.2, topright).

The five O_{HI} levels: *none*, *light*, *lightest*, *strong* and *strongest* (Figure 2.2, bottom) were experimentally applied in Experiments A (*varied*) and B. Harrowing along the whole plot (80m) with a constant intensity requires continuous operation of the vehicle and therefore full use of fuel, as in experiment A. From this study, we could realize that varying the intensity might reduce the treated area, offering fuel saving possibilities. According to ÖKL (2012), about 3.5 L ha^{-1} of fuel are needed for harrowing. In Figure 2.2 (bottom), it can be seen that at least a 50% of the treated plots did not require harrowing. The highest potential to reduce fuel consumption was when the harrowing intensity is characterized on soil and weed variation, simultaneously. Harrowing based on weed density only or soil density only determined more area to be treated. However, the testing experiments revealed that weed density is the most influential input to take decisions about the harrowing intensity, because the soil density was relatively homogeneous across the field.

In general for both experiments, weed density was effectively reduced due to harrowing. In experiment A, a tendency that varying the intensity according to the measured variability of soil and weeds increased weed reduction ($P = 0.09$). F-test in the mixed model and Tukey (HSD) ranking showed that weed density was reduced in comparison with the untreated plots in experiment A, $P < 0.001$ and in experiment B, $P < 0.0001$ (Table 2.5). In experiment A, contrasts between the varied intensity throughout the whole plot against the individual fixed intensities suggested that a higher weed density reduction might be achieved ($P = 0.009$) when the intensity is not kept constant along the cultivated plot. Similarly, Søgaard (1998) found that changing the tine angle of the harrow along the whole plot, reduced the variations in working depth, thus soil cover and weed control would be uniform. In experiment B, although varying the harrowing intensity reduced effectively weed density compared with the untreated control ($P < 0.001$), there was no difference in the way of varying the intensity, i.e. according to either soil- or weed occurrence or a combination of both assessments ($P = 0.42$). Soil density was not influenced by the 1 to 3 passes with the roller, thus the desired high, medium and low levels of compaction could not be achieved. Therefore, soil density assessed before harrowing was almost constant across the whole experimental area (Table 2.5; Figure 2.2, topright.).

Table 2.5: Effects of harrowing treatments on leaf cover, weed density and crop yield in experiments A and B.

Treatment*		Responses after harrowing		
intensity (code)	rolling (passes)	Leaf cover ^{ns} (%)	Weed density† (plants m^{-2})	Crop yield ^{ns} (t ha^{-1})
Experiment A				
	1	28.7	18.0 *b*	5.9
0	2	27.7	27.2 *b*	6.4
	3	25.9	22.3 *b*	5.9
	1	23.2	14.3 *a*	6.4
1	2	21.9	12.7 *a*	6.3
	3	20.7	8.7 *a*	6.6
	1	22.7	11.8 *a*	6.8
2	2	23.5	13.9 *a*	6.1
	3	22.5	8.1 *a*	6.4
	1	21.3	7.1 *a*	6.5
3	2	22.1	9.0 *a*	6.4
	3	22.6	8.8 *a*	6.8
	1	24.2	9.5 *a*	6.6
varied	2	23.0	7.8 *a*	6.7
	3	24.5	8.4 *a*	6.7
Experiment B				
	1	30.8	26 *B*	5.7
not harrowed	2	28.0	28.5 *B*	6.7
	3	26.0	23.1 *B*	6.2
	1	23.0	8.1 *A*	6.6
soil	2	24.3	8.4 *A*	6.8
	3	23.4	4.1 *A*	7.0
	1	23.6	4.2 *A*	6.3
weed	2	25.4	6.3 *A*	6.9
	3	23.9	5.2 *A*	6.8
	1	24.3	7.8 *A*	6.9
soil + weed	2	23.5	6.1 *A*	6.8
	3	23.3	4.7 *A*	6.4

* Intensity code as in Figure 2.2

^{ns} non-significant effects

† Tukey (HSD) ranking at $\alpha = 0.05$, small letters for experiment A and capital letters for experiment B

In theory, increasing harrowing intensities results in higher weed control at the risk of raising crop damage due to soil cover (Cirujeda et al., 2003, Rasmussen et al., 2009). The crop harrowed at both, BBCH 24 and 28, showed a good anchorage to the soil, hence a higher resistance to being covered by soil. According to Kurstjens & Perdok (2000), when harrowing at advanced crop growth stages, crop plants resist more being covered by soil. Nevertheless, in our experiments leaf cover tended to decrease by increasing harrowing intensities ($P = 0.05$), but to stay unaltered with the variable intensity ($P = 0.59$). Consequently, the crop damage due to crop soil cover as an effect of harrowing was diminished after adjusting the intensity to the variable field conditions, as also found for winter wheat by Engelke (2001).

The aim of site-specific harrowing is to avoid yield losses, due to wrongly applied treatments, and to secure homogeneous results on the whole field level. This means, reducing unnecessary passes with the harrow, or increase the intensity in highly weed infested of denser soil areas. Varying the intensity in this study tended to reduce leaf cover ($P = 0.07$) and slightly improve crop yield ($P = 0.13$), as seen in Table 2.5. This increment in crop yield was non-significant, thus we could not calculate an optimal intensity in any of both experiments. It seemed that weed competition was very low, because the untreated plots showed similar crop yields as the harrowed ones.

In conclusion, we could acquire valuable information through experiments and combine it in this study with expert knowledge to formulate simple rules and create a system to automatically control the harrow intensity. This fuzzy inference system to control the intensity was fairly well adapted to the variability in soil conditions, and crop- and weeds in the field. However, its application did not result in significantly better weed control and crop yield increment, mainly because of the lack of weed competition. Further validation of the LFIS is required, and experiments should include fields with variable soil types and competitive weed distribution, to make visible the weed control effect when varying the intensity. Differing soil textures would be more accurate to improve the fuzzy decision algorithm for site-specific harrowing, rather than artificially creating variable compaction levels with the roller. A future perspective is that a real-time intensity adjustment should be achievable. The system could include cameras attached in the front and at the rear or sides of the harrow. Then, additional feedback information about the remaining weed competition on the harrowed area might be a new input to the model that would indicate the necessity of cultivating a second or more passes.

3 General discussion and conclusion

3.1 General Discussion

In this study, different levels of harrowing intensity were tested in spring and summer cereals. Through analyses of selectivity, crop resistance, crop tolerance, crop recovery and contributions to crop yield gain, a optimal level was determined. This optimal intensity was added to a fuzzy inference system, together with measurements of crop- and weed coverage, soil resistance and weed abundance, in order to generate the algorithm for adjusting accordingly the tine angle and therefore the harrowing intensity. This system aims to perform a site-specific weed management, reducing the variability in weed control on the whole field area, however it still requires further development to move from the off-line-map-based application to a real-time harrowing system.

In conventional farming, it is well known that herbicides play a major roll on weed control, reducing human labor and multiplying crop yields, specially in intensive farming (Andújar, 2010). Since continuous use of herbicides keeps raising problems of herbicide resistant weed species and environmental problems or threats to human health, it is necessary to improve the non-chemical possibilities of controlling weeds, such as mechanical weed control. Mechanical weeding resistant populations are not probable to occur, and in case they were, it would take much longer time to appear, because mechanical weeding is non-selective for determined weed species. However, the crop plants would simultaneously evolve with weed species, developing both tolerance to cultivation. Some other constraints may be added to those mentioned before, such as situations where weeds escape control within the weed management system. For instance, herbicide resistant populations that prevail, other difficult-to-control weed species (i.e. perennial weeds), or fields where due to environmental laws, herbicide usage is forbidden (e.g. in vegetable production). alternative weeding strategies may include mechanical tools. Similarly, weed seeds may also slip away from weed control operations and even in some cases, weed seedlings may benefit by low herbicide dosages, known as the hormesis effect (Belz et al., 2011).

Nowadays, either in conventional or organic farming, weed management should be a balanced approach by including many different measurements to successfully reduce weed pressure. The combination of different methods has the advantage that the weed suppression measures can be used throughout the whole growing period and also in larger scales. Therefore, an integrated weed management (IWM) is a reasonable approach to be applied Swanton et al. (2008). An IWM is par of an integrated pest management, which is defined by the European research network ENDURE[1], as:

> IPM is a sustainable approach to managing pest by combining biological, cultural and chemical tools in a way that minimises economic, environmental and health risks.

Soil preparation (tillage), according to depth and soil type has a great influence on vertical weed distribution. Reduced tillage and no-tillage practices leave weed seeds close to the surface, where they can be predated. However, a more uniform emergence may occur and therefore a rotational tillage can be considered, and weed harrowing may enter into the management plan. Additionally, the classical techniques for weed suppression, such as crop rotation and reintroduction of cover crops, may also be combined with mechanical weeding techniques.

Considering the previous statements, it is feasible to include weed harrowing into the alternative strategies of weed control in cereals and

[1] ENDURE ® diversifiying crop protection, `http://www.endure-network.eu/about_ipm/endure_s_definition_of_ipm`, accessed on September, 1$^{st.}$, 2011.

legumes. In situations where herbicides are not permitted, weed harrowing can be a reliable tool for direct weed control, as long as the important parameters such as selectivity, crop resistance, crop tolerance and crop recovery are considered (Rasmussen, 1990, Rasmussen et al., 2008, 2009). Consequently, if there is a balance between weed control and crop damage as a result of harrowing, weed control by harrowing may be highly successful and furthermore, it may be comparable to that efficacy of herbicides, as shown in (Rueda-Ayala et al., 2011). Weed seed production may be reduced by pre- and post-emergence harrowing in a long-term view, as an effect of disturbed weed growth and development, which gives the crop and advantage at every cropping season (Lundkvist, 2009).

In this study it was also intended to find the optimal harrowing intensity in cereals, as shown in section 2.5. Since harrowing intensity was based on percentage of soil that covers crop and weed plants, the way of obtaining the desired crop soil cover percentage is irrelevant, i.e. by varying the tine angle, or increasing the driving speed or the number of passes in the same day of cultivation. Therefore, the levels of intensity selected as optimal in Rueda-Ayala et al. (2012) might be transferable to other fields, if the desired level of 20 to 40% crop soil cover is achieved. However, during the years, those intensity levels may be varied to reduce the required soil cover by integrating weed harrowing within a more complete plan for integrated weed management, mainly including crop rotation and crop diversification across the cultivated field.

Timmons (1970) and Evans (2010) made a detailed description of the history of mechanical tools for weed control. Cultivating the soil with mechanical tools is almost as old as agriculture itself, over 10,000 years ago. By the year 500 B.C., dragging a tree limb with short stub of branches as teeth was a way of harrowing. About 600 years later, the harrow had been improved in a 'A-shaped' wooden triangular crotch with wooden teeth, pulled by slaves or animal power. To the present date, the basic principles of a harrow remain, and weed research has been focused on gaining knowledge to apply weed harrowing in a more precise way, in order to maximise weed control and minimise crop damage (Rasmussen, 1991). Therefore, in this study it was intended to satisfy the need for decision support systems aiming to a site-specific weed control in a fully automated tool. However, side-effects of weed harrowing, such as loosening of the soil, improvement of soil aeration and increased N-mineralization, although mentioned in this thesis, they require further research.

Evans (2010) mentioned the need to address limitations in the development of current tools for mechanical weeding, such as high purchase and maintenance costs; limited efficacy; excessive soil disturbance and narrow applicability across a range of soil types, soil moisture conditions, and weed growth stages. In this study, it has been attempted to address these limitations. Weed control efficacy of mechanical tools can be improved when the expert knowledge is developed considering the aforementioned key parameters to successful weed control with the least possible crop damage. The system described in the present study can deal with the excessive soil disturbance, because it aims to adjust the treatment aggressiveness according to the site-specific variability, and therefore areas without weed competition for instance, will not be treated. Applicability of weed harrowing on different soil types can be broaden when harrowing treatments are combined with hoeing by increasing row width, without associated crop damage (Rasmussen & Svenningsen, 1995). Similarly, under high soil moisture conditions the field may be treated inter-row with brushes and when drying conditions are available, weed harrowing could be used as a supplementary control strategy.

It could be argued that the prototype for automatic site-specific harrowing presented in this work may have had high purchase and maintenance costs, because it used electric motors for adjusting the tine angle and a precise real time kinematic – differential global positioning system (RTK–DGPS). However, new developments in the fabrication of old tools such as the spring tine harrow, provide alternatives to reduce purchase costs. In this sense, the company Einböck GmbH & CoKG has developed the *AEROSTAR*[2] tined weeder, which has a hydraulic tine adjustment to facilitate varying the treatment aggressiveness according to the variability. The decision algorithm to adjust the harrowing intensity from this study, could perfectly fit this developed tool to reduce purchase

[2] AEROSTAR Tined Weeder, `http://www.einboeck.at/index.php?option=com_docman&task=cat_view&gid=101&Itemid=136&lang=en`, accessed on June $2^{nd.}$, 2011

costs and achieve high weed control with neglectible crop damage. Initially, the farmer's practical knowledge on their fields of weed distribution and abundance will provide the required parameters of weed coverage; also the digital soil resistance sensor is of easy access and acceptable cost. Nevertheless, automation technology for accurate positioning (e.g. RTK–DGPS) and precise parameter assessments (i.e. image based plant recognition) are still required for applying a precision weed management strategy (Griepentrog et al., 2010, Slaughter et al., 2008, Weis et al., 2008).

Development of weed management systems is being directed towards autonomous robotic weeding, and although there is high uncertainty about weed control efficacy, even the worst case technology has been found to be profitable, e.g. for growing vegetables and sugar beet (Griepentrog et al., 2010, Sørensen et al., 2005). However, it is important to determine whether robotic weeding is the right way to follow for mechanical weed management. From the three basic components that an agricultural robot should incorporate –a sensor system, a decision-making system and variable rate application technology– the sensor technology for weed discrimination is the most critic and complicated, especially due to the complexity of weed detection, large number of species and varying appearance (Slaughter et al., 2008, Weis, 2010). Even the already commercialized video camera sensor technology *Robocrop* cannot discriminate between crop and weeds, but only crop plants in the row (e.g. cotton and vegetables) (Taylor, 2004); the user should know data of the planting pattern, such as row and plant distance, in order to favour the recognition accuracy Wrest Park History Contributors (2009). For the purposes of mechanical weeding this technology seemed sufficient, thus it has been used in a fully automated application technology for inter- and intra-row weeding, known as the *Robocrop InRow*[3]. Nevertheless, some crop plants might not be recognized being also cultivated by the machine as weeds, and therefore the component decision-making system becomes the most important when robots are to be used for weed control.

Expert knowledge is essential for decision making technology in robotic

[3]Garford Farm Machinery Ltd., Brochure. Available online at: `http://www.garford.com/Brochure%20Robocrop%20InRow%20A3.pdf`, accessed on August 8th, 2011

weeding, and it must still be produced through robust experimentation and reliable predictive models and parameter estimates, as mentioned in Rueda-Ayala et al. (2011), otherwise, even the most sophisticated robot would perform wrongly. The present work has paid much attention to the decision making system, considering the aforementioned parameters for successful weed harrowing, specially the crop-weed selectivity and the yield gains as a result of controlling weeds by harrowing. These concepts offer a broader field applicability to different soil types and the experimental approach may be easily reproduced, provided objective assessment of characteristics of the crop, weeds and soil (Rueda-Ayala et al., 2012). Previous studies, demonstrated that automatic weed harrowing is possible, but they were either missing information on weed distribution and soil conditions or the intensity levels were not adapted to reliable parameter estimates (Engelke, 2001, Søgaard, 1998).

In conclusion, once accurate and robust methods for automatic and real-time weed discrimination are developed, the future of robotic weeding seems promising to become highly successful in industrialized countries Griepentrog et al. (2010), Slaughter et al. (2008). However, mechanical weed control must be of easier and cheaper access for the farmers, so it can compete with herbicides. Therefore, it might be much more important to learn to correctly use the existing tools –including old ones, i. e. as in Evans (2010)–, as the alternative for farmers who cannot buy those autonomous weeding robots. Direct weeding tools might be developed towards farmer's benefit, maintaining of course the sustainability principle. That is why, combining existing tools as the Bezzerides-cultivator for in-row and intra-row weed control in Schweizer et al. (1992), would have a higher adoption rate than latest-technology implements. Furthermore, although measures such as primary tillage, strip-tillage, stubble-tillage combined with harrowing and hoeing and other soil cultivating tools that may intensively disturb the soil, increasing the problems of soil erosion or N mineralization (e.g. against in reduced or no-tillage systems), physical weeding technologies are necessary and must be included into the weed management strategy, specially due to the rising problems with herbicides. Thus, mulching, crop rotation, multi-cropping, green manuring, are additional measures to be used in combination with mechanical weeding tools, in order to lessen these problems.

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