UNIVERSITY OF HOHENHEIM

INSTITUTE FOR PHYTOMEDICINE
DEPARTMENT OF WEED SCIENCE
PROF. DR. R. GERHARDS

"Investigations on Site-Specific Weed Management for a Decision Support System for Patch Spraying"

Dissertation
Submitted in fulfilment of the requirements for the degree
"Doktor der Agrarwissenschaften"
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presented by
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Born: 30. April 1982 in Mühlacker

Ich widme diese Arbeit meiner Familie, insbesondere meiner Tante, meiner Oma, meiner Schwester, meiner Anne, meinem Papa und meinem Onkel, deren tatkräftige Unterstützung mir die nötige Zeit und Ruhe zur Anfertigung dieser Arbeit gegeben haben.

Mit besonderem Dank und in Andenken an meine Mama.

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CHAPTER I

General Introduction

Christoph Gutjahr

1 General Introduction

1.1 Structure of the dissertation

This thesis consists of five papers which discuss several topics and experiments concerning site-specific weed management. The paper "*Precicion farming for weed management: techniques*" and the first part of "*Decision Rules for Site-Specific Weed Management*", which forms part of the book "*Crop Protection – the Challenge and Use of Heterogeneity*", are useful to give an overview on both site-specific weed control techniques and on already existing decision support systems for precision herbicide application (Chapters II and III).

The papers "*Measuring yield effect of weeds and herbicide application in small annual grains and maize using the Precision Experimental Design*" and "*Using precision farming technology to quantify yield effects due to weed competition and herbicide application*" (Chapters IV and V) describe a method of acquiring basic knowledge about the establishment of a decision support system for patch spraying.

In chapter VI, the paper "*Two patch spraying strategies and their potential for herbicide saving*" describes the necessary structure of a patch spraying system to achieve high weed control efficacy and maximized herbicide saving.

The second part of the paper "*Decision Rules for Site-Specific Weed Management*" (Chapter VII) combines the results of the own experiments with the experience which was gained in the previous chapters to propose a possible architecture of a decision support system for online patch spraying. This chapter could be regarded as general discussion and conclusion.

The following papers, which were also published on the topics of this thesis, are not included in the dissertation:

Erarbeitung von Entscheidungsalgorithmen für die teilflächenspezifische Unkrautbekämpfung

Gutjahr, C., Weis, M., Sökefeld, M., Ritter, C., Möhring, J., Piepho, HP. and Gerhards, R., (2008).

Journal of Plant Diseases and Protection, Special Issue XXI, 143-148.

Untersuchung eines automatisierten bildanalytischen Verfahrens zur Erfassung der Unkrautverteilung in landwirtschaftlichen Kulturflächen

Gutjahr, C., Huber, B., Weis, M. and Gerhards, R., (2008).

Bornimer Agrartechnische Berichte, Vol. 62, 76-83

Development of a decision support system for precision weed control in small annual grains and maize

Gutjahr, C., Möhring, J., Weis, M., Sökefeld, M., Piepho, HP. and Gerhards, R., (2009).

Conference of ECPA – EFITA. C Lokhorst, JFM Huijsmans, RPM de Louw (eds.) Wageningen Academic Publishers, 557-565.

1.2 Objectives

The objectives of this study were to derive decision rules for site-specific weed management and to work out a possible architecture of a decision support system for online patch spraying in winter annual grains and maize. The study includes three work packages:

- In the first work package, herbicide savings of site-specific weed control strategies in winter wheat and maize are quantified. The results of this work package would determine the general architecture of the decision support system:
    - Decision support system for single herbicide application to control single weed classes according to their herbicide sensitivity and competitive ability.
    - Decision support system for tank mixture application to control a mixed weed composition.
- In the second work package, an experimental design is established to determine the effects of weed species, soil variability and herbicide application on grain yield in winter wheat and maize separately. Data of these experiments could be used as basic knowledge to establish yield loss functions.
- In the third work package, a decision support system for site-specific weed control is established, which includes yield loss functions and dose-response curves for the most relevant weed species in winter wheat and maize.

CHAPTER II

Precicion farming for weed management: techniques

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Gesunde Pflanzen,
Volume 60; Pages 171 - 181, 2008.

2 Precicion farming for weed management: techniques

Abstract – Site-specific weed control techniques have gained interest in the precision farming community over the last years. Weed control on a subfield level requires measuring the varying density of weeds within a field. Decision models aid in the selection and adjustment of the treatments depending on the weed infestation. The weed control can be done either with herbicides or with mechanically. 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 applicable to a wide spectrum of crops.

Site-specific techniques for the detection and management of weeds are presented. A system for the discrimination of different weed species and crops from images is described, which generates weed maps automatically. In On Farm Research experimental setups models for the yield effect of weeds were developed and applied. Economic weed thresholds are derived and used for a herbicide application with a patch sprayer.

Keywords: site-specific weed control, weed mapping, chemical control, mechanical control, expert systems for weed control.

CHAPTER III

Decision Rules for Site-Specific Weed Management

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Precision Crop Protection,

(eds. E. Oerke, G. Menz, R. Gerhards, R. Sikora)

Pages 223 - 232, 2010.

3 Decision Rules for Site-Specific Weed Management

Abstract – For Precision weed management decision rules are needed that take into account temporal and spatial variability of weed populations and weed-crop interactions. In the following chapter different decision rules for online and offline site-specific herbicide application are described. Those decision rules use crop-weed competition models, dose-response functions, weed population models and cost functions to calculate the best intensity of weed control for each location within a field. It is shown that herbicide input and weed control costs can be significantly reduced when farmers use those models in combination with modern sensor and application technologies.

CHAPTER IV

Measuring yield effect of weeds and herbicide application in small annual grains and maize using the Precision Experimental Design

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Conference of ECPA - EFITA, 2009

(eds C Lokhorst, JFM Huijsmans, RPM de Louw)

Wageningen Academic Publishers. Pages: **557-565**.

4 Measuring yield effect of weeds and herbicide application in small annual grains and maize using the Precision Experimental Design

Abstract - The heterogeneous distribution of weeds in agricultural fields allows for site-specific weed management resulting in significant savings of herbicides and economic and ecological benefits. In the department of weed science at the University of Hohenheim, a bi-spectral camera system has been developed to identify weed species and map weed distributions in arable fields. This sensor system will be used for real-time applications of herbicides in combination with a decision algorithm for patch spraying. This algorithm decides about location and intensity of weed control based on economic weed thresholds. Seven field trials in wheat, barley and maize were conducted in 2007, 2008 and 2009 to study the impact of weeds and herbicides on grain yield. A Precision Experimental Design in combination with a linear mixed model with anisotropic spatial correlation structure has been developed to explain the yield variability within a field. In this model, the effects of weed competition, soil variability and herbicides on grain yield can be quantified separately. Weed species in the seven field experiments were distributed heterogeneously within the fields with high variation in density and species composition. It was possible to measure yield effects of single weed species and also yield effect of herbicide applications. Results show, that in areas without weeds or with low weed density, the herbicide application tended to have a negative yield effect. Using a GPS controlled patch sprayer with three separated hydraulic circuits site-specific herbicide application technique was realized, resulting in herbicide savings of up to 90 %. The results of these experiments are used to create a decision support system for online site-specific herbicide application.

Keywords: patch spraying, experimental design, decision rules, herbicide application.

CHAPTER V

Using precision farming technology to quantify yield effects due to weed competition and herbicide application

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Weed Research, 2012

Volume 52, Issue 1, Pages 6-15,

5 Using precision farming technology to quantify yield effects due to weed competition and herbicide application

Abstract - Field experiments using Precision Farming technology and Geographic Information System, following a so-called Precision Experimental Design, were conducted in winter wheat maize and winter barley and compared with two randomized plot experiments in maize to quantify yield effects due to weed competition and weed control. Fields were divided into cells and weed densities for all weed species, soil conductivity and grain yield were measured in each cell. Untreated plots and herbicide treatments against grass-weeds or broad-leaved weeds were included in all three experiments. *Chenopodium album* L., *Polygonum* ssp. and *Echinochloa crus-galli* (L.) Pal. Beauv. were the dominating weed species in maize. *Stellaria media* (L.) Vill., *Veronica hederifolia* L., *Matricaria chamomilla* L., *Alopecurus myosuroides* Huds. and *Galium aparine* L. were the most abundant weed species in the winter barley and winter wheat fields. All species were distributed heterogeneously within the fields with densities ranging from 0 to more than 200 plants m^{-2}. In the Precision Experimental Design, it was found that grass-weed competition and herbicide application had a significant effect on grain yield using a linear mixed model with spatial correlation structure to determine the effects of groups of weed species, soil variability and herbicide application on grain yield separately. When a conventional plot experiment was set up in the same field, no statistically significant grain yield difference between the treatments was found. The results highlight the benefits of Precision Experimental Design for studying weed-crop competition. Data can be used to calculate yield loss functions for groups of weed species and to create a decision support system for site-specific weed control.

Key words: crop-weed competition, economic weed thresholds, mixed linear models, Geographic Information System, weed distribution, Precision Farming.

CHAPTER VI

Evaluation of two patch spraying systems in winter wheat and maize

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Weed Research, 2012
Volume 52, Issue 6, Pages 510-519,

6 Evaluation of two patch spraying systems in winter wheat and maize

Abstract - Altogether 15 field experiments were conducted in winter wheat and maize to analyse the spatial distribution of weed species and patch spraying systems. Fields were divided into cells and weed densities for all weed species were measured in each cell. Weed species were then grouped into annual monocotyledonous weed species, annual dicotyledonous weeds and *Galium aparine* L. for the winter wheat fields and in the maize fields weed species were grouped into annual monocotyledonous weeds, annual dicotyledonous weeds and perennial weeds. The most abundant weed species in winter-wheat were *Stellaria media* (L.) Vill., *Veronica hederifolia* L., *Matricaria chamomilla* L., Alopecurus myosuroides Huds. and *Galium aparine* L.. In the maize fields, the dominating weed species were *Chenopodium album* L, *Polygonum* ssp., *Echinochloa crus-galli* L. and *Convolvulus arvensis* L.. Weed control thresholds were set for each group of weed species and application of different herbicides were simulated at locations where the weed control threshold was exceeded. All three weed species groups were distributed heterogeneously within the fields with densities ranging from 0 to more than 1700 plants m^{-2}. The spatial distribution was different for all three groups of weed species. Therefore, three separate application maps were created and loaded on the board computer of the sprayer. Site-specific weed control was simulated with a GPS-controlled multiple-tank sprayer, containing three separate spray lines for each of the three application maps. This allowed varying the herbicide mixture on-the-go depending on the spatial distribution of the weed species groups. In winter wheat herbicide average savings of 70% were possible with the multiple-tank sprayer compared to a uniform herbicide application. Site-specific weed control using a GPS-controlled single tank sprayer, only 37% herbicide savings were possible. In maize herbicide use could be reduced by 47% with the multiple tank sprayer and 6% with the conventional single tank sprayer. The results demonstrate the need for sensor- and application technologies for patch spraying. The economical and ecologic benefits of site-specific weed management with a multiple tank sprayer are discussed.

Keywords: Application technologies, tank mixtures, economic weed thresholds, Geographic Information System, weed distribution, Precision Farming.

CHAPTER VII

General Discussion

Decision Rules for Site-Specific Weed Management

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Precision Crop Protection,

(eds. E. Oerke, G. Menz, R. Gerhards, R. Sikora)

Pages, 233 - 239, 2010.

7 General Discussion

Abstract – For Precision weed management decision rules are needed that take into account temporal and spatial variability of weed populations and weed-crop interactions. In the following chapter different decision rules for online and offline site-specific herbicide application are described. Those decision rules use crop-weed competition models, dose-response functions, weed population models and cost functions to calculate the best intensity of weed control for each location within a field. It is shown that herbicide input and weed control costs can be significantly reduced when farmers use those models in combination with modern sensor and application technologies.

Summary

Zusammenfassung

Christoph Gutjahr

Summary

Weeds mostly occur in aggregated patches of varying size or in stripes along the direction of cultivation. However, the spatial distribution of weeds has often been ignored in weed management decisions, and weed control methods are usually applied homogeneously across fields. During the past five years, powerful sensor technologies have been developed which are capable of classifying weed species in digital images based on shape features and which allow assessing weed seedling distributions automatically in arable crops. Classification algorithms have been computed based on shape features to differentiate between the most abundant weed species in winter wheat, winter barley, maize and sugar beet. The average accuracy of classification ranged from 80 to 95 % for each crop. Those cameras were used in combination with GPS and GIS-technologies to create weed distribution maps or they can be mounted in front of a sprayer to detect and spray weed patches in real-time.

It has been shown in previous studies that patch spraying, based on weed distribution maps and simple decision rules for herbicide application significantly reduces the amount of herbicides needed. Therefore, site-specific weed management practices have economic and ecological benefits by reducing the amount of herbicides applied. It has further been shown that populations of *Galium aparine* and *Alopecurus myosuroides* did not significantly change in location and size when site-specific weed control methods were applied over a period of 8 years. However, precise decision rules for site-specific weed management are still lacking. Current economic weed thresholds are still based on average density estimates, resulting in incorrect predictions of the yield losses due to weed competition. So far, decision rules for patch spraying have only been developed for Danish wheat production system (Christensen et al., 2003).

The objectives of this study were to derive and verify decision rules for site-specific weed management in winter annuals grains and maize. This study includes three work packages:

In the first work package, weed species were grouped into three classes based on their competitive ability and sensitivity to herbicides. The first group contained annual grasses, the second group annual dicotyledons and the third group perennial weed species. Weed distribution maps were created for all groups of weed species in winter wheat, winter barley, maize and sugar beets. It was then analysed at which locations in the field weed

control measures were warranted and which herbicides and combinations of herbicides were required. Weed control measures were realized with a multiple tank sprayer and spatial and temporal stability of weed patches was assessed in the following year.
In the second work package, a so-called Precision Experimental Design using Precision Farming technologies and Geographic Information System, was applied in maize, winter barley and winter wheat to determine the effects of each weed species group, soil variability and herbicide application on grain yield separately. Data of these experiments were used to calculate yield loss functions for individual weed species.
In the third work package, the structure of a decision support system for site-specific weed control was created including yield loss function and dose-response curves for the most relevant weed species in winter wheat and maize.

The results of the three work package can be summarized as followed:
Chenopodium album L., *Matricaria chamomilla* L., *Convolulus arvensis* L. and *Echinochloa crus-galli* (L.) Pal. Beauv. were the dominating weed species in maize. *Stellaria media* (L.) Vill., *Veronica hederifolia* L., *Alopecurus myosuroides* Huds. and *Galium aparine* L. were the most abundant weed species in the winter barley and winter wheat fields. All species and weed classes were distributed heterogeneously within the fields with densities ranging from 0 to more than 200 plants m^{-2}. Patch spraying resulted in 30-40% herbicide saving when a tank mixtures of all herbicides needed was applied. Savings of 77% were achieved when a three tank sprayer was used to apply each herbicide at different locations.

For the Precision Experimental Design, a linear mixed model with spatial correlation structure has been modified and fitted to the data. It was found that competition of *E. crus-galli* resulted in significant yield losses of 0.027 t ha^{-1} plant m^{-2} in maize and *G. aparine* in 0.034 t ha^{-1} plant m^{-2} yield loss in winter wheat. However, herbicides against grasses and annual dicotyledons also reduced grain yield by approximately 0.3 t ha^{-1}, which again underlines the necessity to save herbicides at location where no or only few weed species are present.
“HPS Online” describes a possible structure of a decision support system for patch spraying. The combination of yield loss functions for the most abundant weed species/group of species with dose response curves for the most relevant herbicides to

control these species allowed determining the most economic weed control strategy at each location in the field. It is recommended to include weather conditions or historical data of the fields, if available, such as maps of perennial weed species to optimize weed control decisions.

In conclusion of the results, precision weed management offers a great potential for herbicide savings in arable crops. It requires the combination of automatic sensor technology for weed detection, a decision support system for weed control and application technology to vary the herbicide mixture in real-time.

Zusammenfassung

Unkräuter treten meist in Nestern unterschiedlicher Größe oder in Streifen entsprechend der Bearbeitungsrichtung des Feldes auf. Bei der Planung und Durchführung der Unkrautkontrollmaßnahmen werden die räumliche Verteilung sowie unterschiedliche Bestandesdichten der Unkräuter meist ignoriert und die Kontrollmaßnahmen einheitlich und ganzflächig durchgeführt. Während der letzten fünf Jahre wurden effektive Sensorsysteme entwickelt, die in der Lage sind, Unkrautarten in Digitalbildern zu klassifizieren. Dies ermöglicht eine automatische Erfassung der Unkrautverteilung innerhalb eines Kulturpflanzenbestandes. Klassifikationsalgorithmen, die auf Formparametern basieren wurden errechnet, so daß die wichtigsten und häufigsten Unkräuter und Ungräser in Winterweizen, Wintergerste, Mais und Zuckerrüben voneinander unterschieden werden können. Die durchschnittliche Genauigkeit der Klassifikation lag bei jeder Kulturpflanze zwischen 80 – und 95 %. Solche Sensorsysteme wurden in Kombination mit GPS und GIS- Techniken genutzt, um Unkrautverteilungskarten zu erstellen. Werden sie vor ein Spritzgestänge montiert, würden sie sich eignen, um Unkrautnester in Echtzeit zu erkennen und zu bekämpfen.

Vorangegangene Studien haben gezeigt, dass eine teilflächenspezifische Herbizidapplikation mit einfachen Entscheidungsregeln zu einer signifikanten Reduktion des Herbizidaufwandes geführt hat und somit einen ökonomischen sowie ökologischen Nutzen mit sich bringt. Außerdem konnte gezeigt werden, dass Populationen von *Galium aparine* und *Alopecurus myosuroides* bei einer teilflächenspezifischen Bekämpfung über einen Zeitraum von acht Jahren räumlich stabil geblieben sind. Präzise und angepasste Entscheidungsregeln für die teilflächenspezifische Herbizidapplikation gibt es bisher jedoch noch nicht. Die aktuellen ökonomischen Bekämpfungsschwellen für die Unkrautkontrolle basieren auf Schätzungswerten für die durchschnittliche Unkrautdichte eines Schalges, was häufig zu einer falschen Einschätzung des tatsächlich durch das Unkraut verursachten Ertragsverlustes führt. Bis zum heutigen Zeitpunkt wurden nur für dänische Weizenproduktionssysteme Entscheidungsregeln für die teilflächenspezifische Herbizidapplikation entwickelt (Christensen et al., 2003).

Die Aufgabenstellung dieser Arbeit war es, Entscheidungsregeln für die teilflächenspezifische Herbizidapplikation in Wintergetreide und Mais zu entwickeln. Die Arbeit setzt sich aus drei Hauptarbeitsschritten zusammen:

Im ersten Arbeitsschritt wurden Unkräuter entsprechend ihrer Sensitivität gegenüber Herbiziden und Konkurrenzkraft in drei Klassen unterteilt. Die erste Klasse setzte sich aus einjährigen Ungräsern, die zweite aus einjährigen Unkräutern und die dritte Klasse aus perennierenden Unkrautarten zusammen. Für alle Unkrautklassen wurden in Winterweizen und Mais Unkrautverteilungskarten erstellt. Dann wurde ermittelt, an welchen Teilflächen Unkrautkontrollmaßnahmen erforderlich sind und welche Einzelwirkstoffe oder Herbizidmischungen für deren Bekämpfung benötigt werden. Die Herbizidapplikation wurde mit der Rau Cerberus Dreikammerspritze durchgeführt. Die zeitliche und räumliche Stabilität der Unkrautnester wurde in den Folgejahren anhand von Bonituren bestimmt.

Im zweiten Arbeitsschritt erfolgte die Entwicklung des so genannten Precision Experimental Designs, mit dem durch den Einsatz von Precision Farming Techniken und Geoinformationssystemen in Mais, Wintergerste und Winterweizen Versuche durchgeführt wurden. Das Ziel war es, Ertragseffekte von Unkrautklassen, Bodenvariabilität und Herbizidapplikation getrennt voneinander darzustellen. Ergebnisse dieser Versuche wurden dann benutzt, um Ertragsverlustfunktionen für die einzelnen Unkrautklassen zu bestimmen.

Im dritten Arbeitsschritt wurde die Grundstruktur eines Entscheidungssystems für eine teilflächenspezifische Herbizidapplikation entwickelt. Dieses System beinhaltet Ertragsverlustfunktionen sowie Dosis – Wirkungs – Kurven für die wichtigsten Unkrautklassen in Wintergetreide und Mais.

Die Ergebnisse dieser drei Arbeitsschritte können wie folgt zusammengefasst werden:
Chenopodium album L., *Matricaria chamomilla* L., *Convolulus arvensis* L. und *Echinochloa crus-galli* (L.) Pal. Beauv. waren die dominierenden Unkräuter in Mais. *Stellaria media* (L.) Vill., *Veronica hederifolia* L., *Galium aparine* L. und *Alopecurus myosuroides* Huds. waren in Wintergerste und Winterweizen die am häufigsten vorgekommenen Unkräuter. Alle Unkrautarten und Unkrautklassen waren innerhalb der Flächen heterogen verteilt und traten in einer Dichte zwischen null bis über 200 Pflanzen m^{-2} auf. Die teilflächenspezifische Herbizidapplikation einer Tankmischung führte in Weizen zu einer durchschnittlichen Herbizideinsparung von 37 %. Anhand der mit der Dreikammerspritze durchgeführten teilflächenspezifischen Applikation von Einzelwirkstoffen konnten Herbizideinsparungen von durchschnittlich 70% erzielt werden.

Für die Auswertung der im „Precisoin Experimental Design“ ermittelten Daten wurde ein gemischt lineares Modell mit räumlicher Korrelationsstruktur abgeändert und an die Daten angepasst. Es konnte gezeigt werden, dass die von *E. crus-galli* in Mais verursachte Konkurrenz zu einem signifikanten Ertragsverlust von 0.027 t ha^{-1} und Pflanze m^{-2} geführt hat. In Weizen verursachte eine einzelne *G. aparine*- Pflanze m^{-2} einen Ertragsverlust von 0.034 t ha^{-1}. Jedoch auch die Herbizide zur Kontrolle von Ungräsern und Unkräutern führten tendenziell zu einer Ertragsreduktion von etwa 0.3 t ha^{-1}. Dies unterstreicht die Notwendigkeit, an Teilflächen mit geringem Unkraut- bzw. Ungrasbesatz, die Herbizidapplikation zu reduzieren oder einzustellen.
„HPS Online“ zeigt eine mögliche Grundstruktur für ein Entscheidungssystem zur teilflächenspezifischen Herbizidapplikation im online Verfahren. Die Kombination von Ertragsverlustfunktionen der am häufigsten vorkommenden Unkräuter bzw. Unkrautklassen mit Dosis – Wirkungs – Kurven der wichtigsten Herbizide für deren Kontrolle, ermöglicht es, die für die jeweilige Teilfläche ökonomisch optimierte Unkrautkontrollstrategie zu bestimmen. Um die Applikationsentscheidung zu optimieren ist vorgesehen, sofern verfügbar, historische Informationen zur Unkrautverteilung wie zum Beispiel Verteilungskarten perennierender Unkrautarten sowie aktuelle Witterungsbedingungen in das Entscheidungssystem miteinzubeziehen.

Zusammenfassend betrachtet, bietet die teilflächenspezifische Unkrautkontrolle ein großes Potenzial für Herbizideinsparungen in landwirtschaftliche Kulturpflanzenbeständen. Sie erfordert die Kombination eines automatischen Sensorsystems zur Unkrauterkennung mit einem Entscheidungssystem zur Unkrautkontrolle sowie einer Applikationstechnik zur Variierung der applizierten Herbizidmischung in Echtzeit.

Curriculum Vitae

Personal Data

Name	Christoph Gutjahr
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Erklärung

Hiermit erkläre ich, dass ich diese Dissertation selbständig angefertigt habe, nur die angegebenen Quellen und Hilfsmittel benutzt und wörtlich oder inhaltlich übernommene Stellen als solche gekennzeichnet habe. Die Arbeit wurde entsprechend der Promotionsordnung der Universität Hohenheim, § 8.2.2 angefertigt.

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Christoph Gutjahr