Chapter 1

General Introduction

Weed control in crop production systems is not only a major challenge in plant cultivation but also an ever-expanding discipline in farming practice and science. An effective weed control in arable farming is needed to ensure yield stability and product quality (Cousens, 1985). Chemical weed control provides enormous cost-effectiveness but at the same time it has effectuated new problems, which may jeopardise the long-term operating efficiency (Kudsk and Streibig, 2003). The major drawbacks are on the associated environmental impacts and the selection of herbicide-resistant weeds (Heap, 2019; Kudsk and Streibig, 2003). In order to respond to the growing awareness of these problems, chemical weed control strategies are increasingly being adapted to the variable conditions of the fields (Gerhards and Oebel, 2006; López-Lozano *et al.*, 2010; Lindblom *et al.*, 2017; Fernandez-Quintanilla *et al.*, 2018; Lambert *et al.*, 2018). Nevertheless, effective weed control remains the primary objective to maintain stable crop yields (Cousens, 1985).

To perpetuate high production standards and concurrently enabling sustainable cropping systems, weed research focuses on the development of sound ecological and environmentally acceptable weed control practises. In order to adopt traditional weed control measures and develop new weed control strategies intensive observations of the crop and weed responses and accompanying effects are required. For the evaluation of the investigated measures, sensor systems are suitable tools to collect precise and quantifiable data (Peteinatos *et al.*, 2014, 2016). Unmanned aerial vehicle (UAV) mounted sensors open up new perspectives on plant populations, which are not comparable with ground-based data collection (Torres-Sánchez *et al.*, 2013). In the further combination of the UAVs with hyperspectral sensors, crop parameters can thus be recorded that cannot be seen with the unaided eye or that would require an unmanageable amount of work for human auditors. The combination of these sensors with existing technology enables site-specific weed control, using real-time kinematic global navigation satellite system (RTK-GNSS) controlled sprayers (Gerhards and Oebel, 2006; Mesas-Carrascosa *et al.*, 2016), but also expert system based decision support for crop production systems (Mortensen and Coble, 1991; Lindblom *et al.*, 2017). Beside site-specific weed management techniques, sensors were also used for the detection of herbicide-resistant weeds (Baker, 2008; Reddy *et al.*, 2014) and crop stress evaluation (Zhou *et al.*, 2016; Peteinatos *et al.*, 2016).

The state of the art of sensor technology for weed mapping is reviewed in Fernandez-Quintanilla *et al.* (2018). The more specific UAV-based aerial hyper-spectral and red-green-blue (RGB) digital imagery for weed mapping has been demonstrated by Rasmussen *et al.* (2013) and Peña *et al.* (2013), but also in recent studies by Lambert *et al.* (2018) and de Castro *et al.* (2018). Although, considerable limitations in the ground sampling distance (GSD), compared to ground based approaches, UAVs are the preferable tool for site-specific weed management (Fernandez-Quintanilla *et al.*, 2018). The large number of research projects on the UAV weed detection for site-specific weed control shows not only the great potential, but also a wide variety of approaches. While many studies prefer the higher resolution RGB sensors (Rasmussen *et al.*, 2013), others argue for a combination of RGB and multispectral cameras (Peña *et al.*, 2013). Since multispectral cameras enable a more simple differentiation between vegetation and non-vegetation (e.g. soil, plant residues) pixels, they are often used as sensors for weed mapping despite their lower resolution compared to a RGB sensor. In addition to the vegetation detection, multispectral images also provide information about plant vitality (Zarco-Tejada *et al.*, 2013).

The use of aerial and ground based multi- or hyperspectral sensors for the vegetation stress assessments is based on the plant reflectance (Thenkabail *et al.*, 2018b). Various external and internal factors on the plant, may change its reflection of the incident light. These can be caused by genetic variability (Reddy *et al.*, 2014), but also by the deprivation of water or nutrients, by toxic substances or by temperature and daylight (Peteinatos *et al.*, 2016). Therefore, plant reflection depends not only on the cell tissue contents, but also on the efficiency of the photosystem and the associated changes of the absorbed light (Thenkabail *et al.*, 2018a). The stress origin often remains unclear if multiple factors affecting the plant vitality, as its manifestations in plant reflection overlap. This can be overcome in field experiments if assessments of a stressing factor can be compared to a untreated control variant. Therefore, these sensors could be employed for the evaluation of crop and weed responses to e.g. herbicide treatments.

The potential of sensors for herbicide sensitivity assessments by multi- or hyperspectral plant information (Reddy *et al.*, 2014; Lee *et al.*, 2014; Matzrafi *et al.*, 2017) or chlorophyll fluorometry (Kaiser *et al.*, 2013; Wang *et al.*, 2016) has already been demonstrated. The herbicide stress quantification using spectral data derived from imaging sensors or spectrometers can be assessed as other plant stress through changes in the plant reflectance values. The chlorophyll fluorometry is assessing the maximum quantum yield of the photosystem II, which can draw conclusion on the herbicide sensitivity of the investigated plant (Baker, 2008). By the evaluation of these parameters, information on the herbicide sensitivity or resistance can be derived, before visible symptoms of a herbicide injury occur (Reddy *et al.*, 2014; Kaiser *et al.*, 2013; Wang *et al.*, 2016). The focus of these studies was set on the investigation of possible parameters indicating a herbicide-resistance using chlorophyll fluorometry (Kaiser *et al.*, 2013), while Reddy *et al.* (2014) already trained a classifier on hyperspectral plant reflection of genetically homogeneous and heterogeneous weeds under artificial light conditions.

In order to extend the use of sensors for practical applications in plant protection, several aspects have to be overcome. The implementation of UAV weed mapping for site-specific weed control could drastically reduce the total amount of herbicide use if restrictions on data volume and ground sampling distance could be reduced. This would accelerate the computation time for the calculation herbicide application maps and therefore enable site-specific herbicide applications. A wider use of multispectral UAV imagery and ground-based hyperspectral plant information could significantly improve the quality of field experiment results if the auditor dependant visual estimates are supplemented by sensor derived datasets. The same applies to sensors used for herbicide-resistance detection in weeds. Here, portable field sensors would allow in-field sampling. A subsequent sensor data classification of a potential herbicide-resistant weed using pre-trained classifiers would enable direct in-season weed control of herbicide-resistant weeds prior to seed ripening.

1.1 Objectives

The further development of UAV and ground-based sensor information technologies for agricultural use cases to reduce the chemical burden to farmland, evaluate crop responses after following herbicide treatments and decision-support systems for herbicide-resistance management were investigated in this work, driven by the following objectives:

- the development and validation of site-specific herbicide applications, based on aerial imagery derived weed prescription maps
- the examination of hyperspectral aerial imagery to determine crop vitality in field trials to assist and expand the assessment of weed control strategies
- the examination of ground-based hyperspectral and chloropyll fluorometry sensor data to enable in-field and in-season detection of herbicide-resistant plants using classifiers.

1.2 Structure of the Dissertation

This dissertation is organised into 3 chapters covering the development, application and evaluation of UAVs and sensors for use in the management of weed control strategies. Chapter 1 provides an 'General Introduction' to the field of research and the specific research work of this dissertation, as well as the Structure of the Dissertation.

In chapter 2 the four individual research articles of this work are presented. The articles are arranged according to the course of weed control measures. Prior to the measure, the weed infestation on the area to be treated is mapped and a following site-specific herbicide application is presented in section 2.1. Subsequently, the effects of the treatment are evaluated regarding crop vitality and yield performance, which is described in the research article of section 2.2. Finally, it remains to be investigated whether there are resistant individuals among the possibly surviving weeds, which indicate the emergence of a herbicide-resistant population. Two systems to identify these individuals are presented in sections 2.3 and 2.4.

Finally a critical overview summarises the individual research articles in chapter 3. This 'General Discussion' provides additional insights, which exceed the contents discussed in the main articles.

Apart from the journal articles, contributions to national and international scientific conferences were part of this thesis. This work was supplementary to the studies presented and therefore not included in the current thesis:

- Menegat, A., Sievernich, B., Linn, A., Mink, R. and Gerhards R. Development of a standardised test system for detection of resistance against pre-emergence herbicides in *Proceedings 7th International Weed Science Congress*. "Weed science and management to feed the planet", Prague, Czech Republic, 2016. ISBN: 978-80-213-2648-4
- Mink, R. and Gerhards, R. Bewertung der Biomasseproduktion und Bodenbedeckung verschiedener Zwischenfrüchte durch UAV-Bildanalyse *in Programm Deutsche Phytomedizinische Gesellschaft Arbeitskreis-Herbologie*, Nicht-Chemische bzw. Präzisions-Unkraut-Bekämpfungsverfahren. Bingen, 2017
- Dutta, A., Gitahi, J., Ghimire, P., Mink, R., Peteinatos, G., Engels, J.-J., Hahn, M. and Gerhards, R.: Weed Detection in Close-range Imagery of Agricultural Fields using Neural Networks *in Beiträge Photogrammetrie-Fernerkundung-Geoinformatik-Kartographie-2018*. München, Germany, 2018. ISSN: 0942-2870
- Mink, R., Dutta, A., Peteinatos, G., Sökefeld, M., Engels, J.-J., Mozer, A., Mayr, W., Hahn, M. and Gerhards, R. Assessment of black-grass (*Alopecurus myosuroides* Huds.) densities using airborne imagery *in Book of Abstracts of the 18th European Weed Research Society Symposium*. Ljubljana, Slovenia, 2018. ISBN: 9789616998215.
- Linn, A., Mink, R., Peteinatos, G. and Gerhards, R. Herbicide efficacy estimation of ALS-inhibitors in *Stellaria media* L. and *Papaver rhoeas* L. *in Book of Abstracts of the 18th European Weed Research Society Symposium* Ljubljana, Slovenia, 2018. ISBN: 9789616998215.
- Mink, R., Linn, A., Gerhards, R. and Peteinatos, G. Classification of Herbicide Resistant *Papaver rhoeas* L. and *Stellaria media* L. Using Spectral Data *in Book of abstracts of the European Conference on Agricultural Engineering AgEng2018*. Wageningen, the Netherlands 2018. https://doi.org/10.18174/471678.

- Peteinatos, G. Mink, R., Linn, A. and Gerhards, R. Separating between herbicide sensitive and resistant *Papaver rhoeas* L. and *Stellaria media* L. Vill. plants, *in Sustainable Integrated Weed Management and Herbicide Tolerant Varieties*. American Farm School, Workshop, Thessaloniki, Greece, 2019.

Chapter 2

Research Articles

2.1 1st Study: Multi-Temporal Site-Specific Weed Control of *Cirsium arvense* (L.) Scop. and *Rumex crispus* L. in Maize and Sugar Beet Using Unmanned Aerial Vehicle Based Mapping

Article
Published in Agriculture 2018, 8(5), 65;
Received: 23 March 2018 / Accepted: 25 April 2018 / Published: 29 April 2018
https://doi.org/10.3390/agriculture8050065

Multi-Temporal Site-Specific Weed Control of *Cirsium arvense* (L.) Scop. and *Rumex crispus* L. in Maize and Sugar Beet Using Unmanned Aerial Vehicle Based Mapping

by Robin Mink[1], Avishek Dutta[2], Gerassimos G. Peteinatos[1], Markus Sökefeld[1], Johannes Joachim Engels[2], Michael Hahn[2] and Roland Gerhards[1]

1 Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany
2 Faculty Geomatics, Computer Science and Mathematics, University of Applied Sciences Stuttgart, 70174 Stuttgart, Germany

Abstract

Sensor-based weed mapping in arable fields is a key element for site-specific herbicide management strategies. In this study, we investigated the generation of application maps based on Unmanned Aerial Vehicle imagery and present a site-specific herbicide application using those maps. Field trials for site-specific herbicide applications and multi-temporal image flights were carried out in maize (*Zea mays* L.) and sugar beet (*Beta vulgaris* L.) in southern Germany. Real-time kinematic Global Positioning System precision planting information provided the input for determining plant rows in the geocoded aerial images. Vegetation indices combined with generated plant height data were used to detect the patches containing creeping thistle (*Cirsium arvense* (L.) Scop.) and curled dock (*Rumex crispus* L.). The computed weed maps showed the presence or absence of the aforementioned weeds on the fields, clustered to $9\ m \times 9\ m$ grid cells. The precision of the correct classification varied from 96 % in maize to 80 % in the last sugar beet treatment. The computational underestimation of manual mapped *C. arvense* and *R. cripus* patches varied from 1 % to 10 % respectively. Overall, the developed algorithm performed well, identifying tall perennial weeds for the computation of large-scale herbicide application maps.

Keywords: digital elevation model; excessive green red vegetation index; patch spraying; site-specific weed control; UAV weed detection; weed mapping

2.1.1 Introduction

One of the major milestones in weed remote sensing technology research has been the implementation of Unmanned Aerial Vehicles (UAVs) as sensor carriers. Rasmussen *et al.* (2013) presented an estimation of plant soil cover from small and inexpensive aircraft systems evaluating the efficacy of mechanical weed harrowing in barley (*Hordeum vulgare* L.) and chemical weed control in oilseed rape (*Brassica napus* L. subsp. *napus*). Early season site-specific weed management in sunflowers based on UAV imagery is described in Torres-Sánchez *et al.* (2013). Both authors conclude that UAVs are useful to map weed pressure for site-specific weed management. Several UAV imaging sensors (e.g., Red, Green and Blue (RGB) and multispectral cameras), spatial resolutions and data analysis algorithms (e.g., Object-Based Image Analysis (OBIA)) are discussed in the literature (Rasmussen *et al.*, 2013; Torres-Sánchez *et al.*, 2013; Borra-Serrano *et al.*, 2015; Pérez-Ortiz *et al.*, 2016; Hung *et al.*, 2014; López-Granados *et al.*, 2016b,a; de Castro *et al.*, 2018; Fernandez-Quintanilla *et al.*, 2018).

Airborne imagery enables vegetation detection using vegetation indices, as reviewed in Salamí *et al.* (2014). Based on the Structure from Motion technique, 3D Models and Digital Elevation Models (DEM) can be created out of UAV imagery (Salamí *et al.*, 2014; Turner *et al.*, 2012). Combining this information can provide biomass estimations on barley (Tilly *et al.*, 2015) or yield predictions in maize, when combined with multispectral images (Geipel *et al.*, 2014). Further, weed identification has been performed by analysing vegetation height differences in a maize field using ground-based ultrasonic sensors (Andújar *et al.*, 2011a).

Christensen *et al.* (2014) discussed the complexity of various weed detection procedures, along with the generally low economic weed threshold levels (e.g. < 5 weeds m^{-2} or < 0.1 % weed cover). The authors remarked that the field area to be treated with herbicide highly depends on the used economic weed thresholds as also presented in Hamouz *et al.* (2018), Keller *et al.* (2014) and Longchamps *et al.* (2014). The information about local weed infestations becomes even more important in less competitive crops (e.g. sugar beet) or perennial weeds with a development stage dependent herbicide compatibility. Thus, high-resolution weed detection and multi-temporal mapping can play a major role in weed management.

Considering these possibilities and the well-known heterogeneous nature of weeds (Marshall, 1988; Johnson *et al.*, 1995), site-specific herbicide applications as reported by Gerhards *et al.* (2002) and Gerhards and Oebel (2006), should already be state of the art in today's farming practise. Yet, only a few site-specific herbicide application techniques have been commercially used (Christensen *et al.*, 2009). Fewer systems support the use of UAV weed mapping based on application maps.

It is crucial to fuse information from the different sensor systems and computing capabilities, used in modern precision farming, to crosslink all gathered field data for weed classification. Nevertheless, weed differentiation systems working in multiple crops by combining comprehensive field information have so far not been described in literature.

Consequently, the hypothesis was that the UAV mapping of herbicide-relevant weeds like creeping thistle (*Cirsium arvense* (L.) Scop.) can be accomplished by combining multiple sensor-based sources of precision farming information. Information on vegetation coverage and height derived from UAV imagery was connected to crop planting information (e.g. geo-coordinates of crop row locations and row space). By concatenating these data inputs, we propose a new methodology for improving the UAV weed mapping in arable fields. It is of particular interest to separate perennials like *C. arvense* and curly dock (*Rumex crispus* L.) from the rest of the fields' vegetation cover.

The objectives of the present study were (a) the development of an algorithm for the computation of herbicide application maps based on UAV weed mapping, (b) the subsequent use of these maps for weed spot spraying. (c) Realise the above objectives in row crops like maize at the three-leaf stage and in sugar beet between the cotyledon stage and the five-leaf stage. The computed application maps were transferred to a multiple tank spot sprayer for the site-specific treatment of *C. arvense* and *R. crispus*. This additional herbicide treatment was then applied along with a uniform herbicide application against annual grasses and broadleaf weed species.

2.1.2 Materials and Methods

Trial Sites and Precision Sowing

For the current study, four experiments were chosen at the Ihinger Hof research station (48.74°N, 8.93°E; 478 m a.s.l.) of the Hohenheim University, in southwest Germany during 2016 and 2017. The average 30-year annual temperature and precipitation are 8.4 °C and 738 mm. The fields were rotated within the two years of this study and they differed in their slope as shown in Table 2.1. The soil types differed from terra fusca, brown soil and pseudogley.