1 General Introduction

According to the latest UN estimates, the human population is projected to grow to 9.7 billion people in 2050 and 10.9 in 2100. This corresponds to an increase of 26 % and 42 % compared to 2019, respectively (United Nations, 2019). Alexandratos and Bruinsma (2012) calculated a 60 % higher demand of agricultural products in 2050 as indicated in the interim report "World Agriculture: towards 2030/2050" of the FAO (FAO, 2006). It is therefore essential to enhance agricultural production. Due to modern machinery, competitive and high-yielding cultivars, fertilizers, irrigation systems and pesticides, the agricultural industry attempts to fulfill the growing demand. However, the progressive sealing of land is opposed to the increasing demand and abiotic factors can cause high yield losses. Additionally, the biotic factors weeds, pests and diseases permanently endanger crop yield (Oerke and Dehne, 2004). In a global point of view, weeds generate the highest biotic yield losses of 34 % by competing with the crop for relevant growth parameters such as space, water, nutrients and light (Oerke, 2006). The time of occurrence and the infestation level of weeds determine the potential damage considerably. Further, weeds also impede harvest, can reduce the product quality and might serve as hosts for pests and diseases (Zwerger and Ammon, 2002).

The competition by weeds can be reduced or even eliminated due to integrated weed management (IWM) strategies, using preventive, cultural, biological, mechanical and chemical weed control measures. Preventive and cultural measures aim to avoid and suppress the occurrence of weeds in a field and support the competitiveness of the crop towards weeds (Swanton and Weise, 1991; Mortensen et al., 1995; Buhler, 2002). Traditionally wide crop rotations were used to maintain soil fertility and to control weeds and pests. However, as a result of the development of pesticides and synthetic fertilizers, most crop rotations have been simplified and narrowed (Leighty, 1938; Froud-Williams, 1988). The mechanical weed control focuses on physical measures, disrupting weed germination and destroying plant tissue. Typical mechanical measures include the cultivation of the crop as well as pre- and post- cultivating tillage but also mowing, cutting and hand weeding (Swanton and Weise, 1991; Buhler, 2002; Rueda-Ayala et al., 2010). Nevertheless, chemical treatments achieve the highest weed control efficacies. Due to the application of selective herbicides, control efficacies of up to 99.99 % can be achieved (Foster et al., 1993). Further, herbicides are easy to use, relatively cheap and have a high area output. From a global perspective, the use of herbicides is the most common and efficient weed control strategy, which has replaced almost all other weed control strategies in conventional cropping systems since they were developed (Heap, 2014). Alternative IWM strategies have been less pursued due to the high control efficacy of herbicides and as a consequence weed pressure and infestations increased unnoticeably.

Through intensive and continuous use of herbicides, a high selection pressure was exerted over a long period. This resulted in a selection of herbicide resistant weed biotypes (Powles and Yu, 2010). Ryan (1970) reported the first well-documented case of herbicide resistance of a triazine-resistant common groundsel *Senecio vulgaris* L. (Asterales: *Asteraceae*) in 1968. To date, about 50 years later, 502 cases in 258 species (150 dicotyledonous and 108 monocotyledonous) were documented worldwide, which prove a propagation of herbicide resistance (Heap, 2019). Herbicide resistance is defined as a naturally occurring and inherent ability of a weed biotype within a weed population, to survive a herbicide application at a rate normally lethal to the wild type and reproduce itself (Powles and Preston, 1995; Heap, 2005). There are different mechanisms known in plants leading to herbicide resistance, that can be divided into target-site (TSR) and nontarget-site resistance (NTSR). TSR mechanisms comprise structural changes of target enzymes which stop the herbicide molecule from efficiently binding to the site of action. Further TSR mechanisms are an overexpression of the target site, when the plants synthesize the target protein in larger amounts, or if structural changes in the promotor region of the gene occur (Devine and Shukla, 2000; Gaines et al., 2010). NTSR mechanisms, include the ability of weeds to reduce the herbicide concentration reaching the target enzyme, for example by enhanced metabolism or sequestration of the herbicide molecules into the cell wall or vacuole (Délye, 2013; Délye et al., 2013; Yu and Powles, 2014). Theoretically, resistances evolve towards one active ingredient (AI), however as a result of cross-pollination resistances to different chemical families within one mode of action (MOA) and different MOA can accumulate in one biotype. These types of resistances are considered as cross – and multiple – resistances, respectively (Powles and Preston, 1995; Werck-Reichhart et al., 2000; De Prado and Franco, 2004). The term multiple resistance is also used when more than one mechanism of resistance is present in one biotype (Jutsum and Graham, 1995).

Blackgrass, *Alopecurus myosuroides* Huds. (Poales: *Poaceae*), is a grass weed mainly germinating in autumn and promoted by growing winter annual crops (Naylor, 1972a; Moss, 1985). It is favored by crop rotations with high proportions of winter annual crops, early sowing dates of winter cereals and reduced tillage practices (Moss, 1985; 1987a; Hurle, 1993; Melander, 1995; Gerhards et al., 2013; Lutman et al., 2013). Due to non-persistent seeds, high growth rates and cross-pollination *A. myosuroides* is a prone species for a fast resistance development (Mortimer et al., 1992; De Prado and Franco, 2004). Cross- and multiple-resistant populations are reported throughout Europe and *A. myosuroides* is stated to be one of the most important weed species (Moss et al., 2007; Heap, 2019). In addition to the increasing resistance development, a further challenge is that the number of AIs that are available to control *A. myosuroides* is declining because several AIs lose their permission in the course of the re-registration process (Drobny, 2016).

1.1 Objectives

The aim of this study was to investigate reliable management methods to control *A. myosuroides* effectively. Different IWM strategies were tested. Thereby preventive, cultural, mechanical and chemical weed control methods were conducted and combined. Effect on crop yield, *A. myosuroides* abundance, herbicide control efficacies and the resistance development were investigated. Further, the costs of the IWM strategies were analyzed and the impact of the contribution margins of the measures were evaluated.

1.2 Structure of the dissertation

The thesis is presented as a cumulative dissertation and consists of three scientific papers. One paper is published. Two papers are submitted and currently under review.

The first paper titled "Suppressing *Alopecurus myosuroides* Huds. in Rotations of Winter-Annual and Spring Crops" is published in the MDPI open access Journal "Agriculture". It describes the impact of preventive, cultural and chemical IWM strategies on *A. myosuroides* abundance, herbicide efficacy and crop yield.

The second paper titled "A long-term study of different crop rotations and herbicide strategies: Effects on *Alopecurus myosuroides Huds.* abundance and resistance development" is submitted to ELSEVIER Journal "Crop Protection". It investigates the effect of preventive, cultural and chemical IWM strategies on crop yield, herbicide efficacy and *A. myosuroides* abundance as well as resistance development.

The third paper titled "A long-term study of crop rotations, herbicide strategies and tillage practices: Effects on *Alopecurus myosuroides* Huds. abundance and contribution margins of the cropping systems" is submitted to ELSEVIER Journal "Crop Protection". It illustrates the effect of preventive, cultural, chemical and mechanical IWM strategies on *A. myosuroides* abundance, herbicide efficacy and crop yield. Further, variable costs and contribution margins were investigated to evaluate the IWM strategies.

The format and citation style of the papers, which are presented in this thesis have been formatted uniformly.

Chapter II

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Suppressing *Alopecurus myosuroides* Huds. in Rotations of Winter-Annual and Spring Crops

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2 Suppressing *Alopecurus myosuroides* Huds. in Rotations of Winter-Annual and Spring Crops

2.1 Abstract

Alopecurus myosuroides Huds. has become one of the most abundant grass weeds in Europe. High percentages of winter-annual crops in the rotation, earlier sowing of winter wheat and non-inversion tillage favor *A. myosuroides*. Additionally, many populations in Europe have developed resistance to acetyl-CoA carboxylase (ACCase), acetolactate synthase (ALS) and photosynthetic (PSII) inhibitors. Hence, yield losses due to *A. myosuroides* have increased. On-farm studies have been carried out in Southern Germany over five years to investigate abundance, control efficacies and crop yield losses due to *A. myosuroides*. Three crop rotations were established with varying proportions of winter- and summer-annual crops. The crop rotations had a share of 0, 25 and 50% of summer-annual crops. Within each crop rotation, three herbicide strategies were tested. In contrast to classical herbicidal mixtures and sequences, the aim of one of the herbicide strategies was to keep selection pressure as low as possible by using each mode of action (MOA) only once during the five years. *A. myosuroides* population was susceptible to all herbicide at the beginning of the experiment. Initial average density was 14 plants m^{-2}. In the rotation with only winter-annual crops, density increased to 5347 ears m^{-2} in the untreated control plots. Densities were lower in the rotations with 25% and even lower with 50% summer-annual crops. Control efficacies against *A. myosuroides* in the herbicide strategy using only MOAs of the HRAC-groups B and A, according to the Herbicide Resistance Action Committee (HRAC) classification on MOA, dropped after five years compared to the strategy of changing MOA in every year. Nevertheless, the results demonstrate the need for combining preventive and direct weed-management strategies to suppress *A. myosuroides* and maintain high weed-control efficacies of the herbicides.

Keywords: mode of action (MOA); preventive weed control; herbicide resistance management; crop rotation; herbicide rotation

2.2 Introduction

Crop rotations can be very effective at controlling weeds in Integrated Weed Management (IWM) (Swanton and Murphy, 1996). However, crop diversity has decreased by 50–70% in European cropping systems within the past 50 years. This is due to the use of synthetic fertilizers and pesticides (Walker and Buchanan, 1982). Production of spring cereals, potatoes, fiber crops and legumes has decreased, whereas production of winter cereals, oilseed rape and corn has increased. Winter wheat, winter barley and winter oilseed rape are dominant in moderate and humid areas with often 75–100% winter-annual crops in the rotations (Gerhards et al., 2013). Winter cereals realizes higher yield output than spring cereals and achieve higher contribution margins (OECD, 2018). The combination of cost reduction due to a minimized cultivation and a herbicide-related system used as described by Power and Follet (1987), made the system sustainable.

Alopecurus myosuroides Huds. is a winter-annual weed predominantly germinating in autumn (Naylor, 1972a). It prefers heavy, loamy, and waterlogged soils. In Western Europe, *A. myosuroides* has become very abundant in winter wheat and winter oilseed rape, particularly in early sown winter cereals after reduced tillage practices (Moss, 1987a; Melander, 1995; Lutman et al., 2013). *A. myosuroides* produces about 100 seeds per ear with a lifetime of up to 10 years (Moss, 1987a). It is a very competitive grass weed in winter wheat with 100 plants m^{-2} resulting in crop yield losses of approximately 20% (Moss, 1987b; Blair et al., 1999; Moss, 2017). Infestation rates of 500 plants m^{-2} cause yield losses of up to 50% (Moss, 1987b; Blair et al., 1999; Lutman et al., 2013; Moss, 2017).

Due to continuous applications of herbicides with the same modes of action (MOA), there has been a selection for herbicide-resistant weed populations (Powles and

Yu, 2010). Because of widespread evolved resistances, a lot of *A. myosuroides* populations have survived standard herbicide applications. Therefore, *A. myosuroides* has become the most problematic weed species in Europe (Moss, 2017). Populations with evolved resistance to herbicides have been documented in almost all European countries. Resistances to ACCase-, ALS- and PS2- inhibitors are widespread in Germany (Drobny et al., 2006). Several *A. myosuroides* populations showed cross- and multiple-resistances (De Prado and Franco, 2004). Nevertheless, farmers prefer cultivating winter wheat because it provides higher contribution margins than spring cereals (Gerhards et al., 2016). They usually start resistance management once the problem has become very evident.

There are studies that highlight the influence of spring barley on *A. myosuroides* densities (Blair, 1999; Lutman et al., 2013; Freckleton et al., 2018). Furthermore, recent studies have investigated the effect of herbicide mixtures and sequences, which are intended to prevent resistance development by using different MOA (Hicks et al., 2018). In our five-year study, we demonstrate the long-term effect on *A. myosuroides* densities by summer-annual crops, and the influence of different proportions of summer-annual crops in the crop rotation. Furthermore, we show the combination and interaction between different herbicide strategies. Additionally, we deviate from typical herbicide mixtures and sequences by setting the focus on minimal selection pressure, and not on the herbicide efficacy of *A. myosuroides* as usual.

We tested, (1) how much summer-annual crops in a rotation can reduce *A. myosuroides* densities compared to typical winter-annual cropping systems under conditions in Southern Germany. For this purpose, three different crop rotations were carried out, which differed in their proportion of summer-annual crops (0, 25 and 50%). The second hypothesis was (2), that using every herbicide MOA only once over the five-