Chapter 1

Introduction

1.1 General Introduction

Since the beginning of agricultural production, pests and diseases have negatively impacted cropping. The presence of unwanted plant species (weeds) inside a crop creates competition, often leading to substantial yield losses (Walker, 1983). Only an effective removal of weeds in the right time window can secure high yield potentials (Welsh *et al.*, 1999). Furthermore, weeds can impede yield and harvest operations. In wheat, the most grown food crop worldwide, weeds can cause up to 18 % - 50 % loss of yield depending on the weed species (Wilson and Wright, 1990; Dierauer and Stöppler-Zimmer, H, 1994; Lemerle *et al.*, 1996; Oerke, 2006). Weeds are also known to be a potential host for crop diseases like insects (Panizzi, 1997), fungal pathogens (Boland and Hall, 1994) and viruses (Christian, 1993), which can negatively affect the yield quality (Heitefuss *et al.*, 2000).
The increasingly rapid growth of the world population, that will need to be fed, is a permanent challenge (Murchie *et al.*, 2009; Calicioglu *et al.*, 2019). Just stabilising current yield levels worldwide will not close the gap between the decline in the agricultural surface and the increasing demand for food production (Martindale and Trewavas, 2008). Proper weed management strategies are one of the key factors to address this problem. While in 1900, in developed countries, around 60 % of the working population was employed in agriculture (Grigg, 1975), today in Europe this workforce declined to just 4 % (International Labour Organization, 2018). In consequence, for any progress in weed management, reduced labour input and enhanced field efficiency, needs to be considered at the same time.

1.2 Weed control methods

Reduction of weed infestations can be achieved with numerous indirect and direct measures. An overview of these strategies is given by Hamill *et al.* (2004). He grouped them in preventive methods, cultural methods, mechanical methods, as well as chemical and biological methods. To reduce the weed infestation, the use of certified weed-seed free crop seeds and clean equipment are the most important preventive method to impede weed seed spread (Walker, 1995). Further on, row spacing and selection of competitive cultivars, as well as an adjusted seed density are methods to reduce the harmful impacts of weeds (Korres and Froud-Williams, 2002; Hamill *et al.*, 2004). A reduction of weed populations can be achieved by diversified crop rotations, with a continues shifting between winter and spring crops, as well as between grass-crops and broad-leaf crops (Young *et al.*, 1994). Such methods can disturb the life cycle of problematic crop-associated weeds by longer periods with bare soil which increase options for mechanical weed control in spring and fall. Furthermore, dense crops prevent certain weeds to emerge and different crops in wider rotations allow the use of diverse herbicidal modes of action (Monaco *et al.*, 2002; Walker, 1995). For such strategies, planting and harvest time needs to be changed (Zoschke and Quadranti, 2002) to prevent major weed emergence within the crop growth period (Anderson, 1994) and to create opportunities to control them at peak emergence. Linked to that are delayed sowing times for certain crops, which may impact the profitability of farms due to a reduced crop yield potential (Monaco *et al.*, 2002). Direct methods against weed infestation in crops are divers too. All sorts of tillage before planting can control established weed populations (Zoschke and Quadranti, 2002). Especially ploughing is an effective measure by burying weed seeds to reduce weed infestation in the following crops or by moving rhizomes of perennial to the top and drying them (Monaco *et al.*, 2002). Whereas other authors report that reduced tillage can lead to an increased occurrence of weed species (Moyer *et al.*, 1994; Tørresen *et al.*, 2003). Some studies showed that tillage during the night can reduce germination stimulation of light-sensitive weed seeds (Melander *et al.*, 2005; Juroszek and Gerhards, 2004). The preparation of a stale seedbed is a method to reduce the soil seed bank of weeds by stimulate weed germination by seedbed preparation and control them afterwards (Rasmussen, 2004).

Post-emergence weed control inside the crop requires methods to secure crop yield potential. Even though it is economically unattractive, the most successful weed control in crops can be achieved by hand pulling of weeds (Monaco *et al.*, 2002; Zimdahl, 2007). Approaches to control weeds less labour intensive are burning weeds with flame machines, destroying them with hot steam (Dierauer and Stöppler-Zimmer, H, 1994; Monaco *et al.*, 2002), kill weeds by flooding (Monaco *et al.*, 2002), with high voltage (Diprose and Benson, 1984), or with laser beams (Mathiassen *et al.*, 2006) or a cover with plastic or organic mulch (Monaco *et al.*, 2002). Biological approaches use living organisms against weed infestation. It is reported as not effective alone and therefore only applied in combination with other methods (Zimdahl, 2007). Today, the most common weed control methods in developed countries are herbicide based or mechanical measures that will be further described in the following sections.

1.2.1 Development of weed management

Historically, hand pulling of weeds or manual weed removal with simple tools has been the only means of controlling weed infestation in crops for centuries. The invention of early forms of the plough was important to reduce weed infestation by turning the soil, and thus, burying weed seeds. At the end of the 19th century inorganic chemicals such as Iron-II-sulphur or copper salts marked the begin of chemical weed control (Wegler, 2013; Hamill *et al.*, 2004). Later, the phytotoxic effect of sodium chlorate was discovered and used as a non-selective herbicide (Wegler, 2013). In the 1930s indole-3-acetic acid as well as 2-naphthoxyacetic were discovered during research on plant growth regulators (Monaco *et al.*, 2002). In the 1940s, synthetic herbicides including artificial plant hormones such as 2,4-dichlorophenoxy-acetic acid (2,4-D) (Van Overbeek, 1947) and 2-methyl-4-chlorophenoxyacetic acid (MCPA) were triggers for a wider use of chemical plant protection compounds (Monaco *et al.*, 2002; Oerke, 2006). From this point onwards, the development and usage of modern selective herbicides evolved quickly and became one of the most important methods to reduce weed infestation and to enhance the productivity in crop production (Bastiaans *et al.*, 2008). In 1970 the herbicidal effect of glyphosate was discovered and turned later on to be the most important herbicide worldwide (Duke and Powles, 2008). Today, there are 116 herbicidal active substances approved in the European Union. Half of them will expire at the end of 2020 (European Commission, 2019). Currently, the conventional crop production, which heavily relies on chemical plant protection, is at risk if no new methods are adopted or new herbicidal mode of actions are discovered (Coble and Schroeder, 2016) and successfully registered. In the last decades, there was no introduction of new modes of action and this is unlikely to change soon (Duke, 2012). Nevertheless, the success of herbicide-based weed management is caused by low labour intensity and a high weed control potential which can be achieved in a wide time window under various soil conditions.

1.2.2 Undesired impacts of herbicides and public concerns

Beside many advantages, chemical weeding has also some drawbacks. Even selective herbicides can induce stress to the crop and thus may reduce crop yield and yield quality (Salzman and Renner, 1992). This might be acceptable, as long as the damage is smaller than the yield loss due to weed competition. But there are further critical aspects of herbicides. Soon after their introduction, concerns were expressed about the possible selection of herbicide-resistant weed biotypes. Compared to fungicides and insecticides, the use of herbicides seemed to be less affected by resistance development in weed populations, due to the reduced vitality of resistant weed biotypes (Gressel and Segel, 1978). However, the first resistance case of *Daucus carota* L. (wild carrots) to 2,4-D was reported by Switzer (1957). Nevertheless, most of the resistance issues arose from ineffective usage of herbicides and ignoring best management practices such as herbicide rotation (Massa *et al.*, 2013). The continuous use of the same herbicidal mode of action until it is no longer effective, lead to a rapid increase of resistance cases from 1975 onwards (Chauvel *et al.*, 2012; Shaw, 2016). According to current studies by (Heap, 2019), 23 out of 26 known mode of action have been compromised due to the selection of herbicide-resistant weed biotypes. Even though herbicide application can be a very effective weed control method, there are also ecological costs (Slaughter *et al.*, 2008). E.g. the use of herbicides also influences the species composition of the flora on arable land. Studies by Frieben (1990) have shown the reduced occurrence of endangered species, especially in conventional farming areas, while Rydberg and Milberg (2000) reported in a weed survey in Sweden that endangered or rare species were recorded on organic certified farms. Besides that, undesired contamination of non-target areas with herbicides (Nitschke and Schüssler, 1998; Pietsch *et al.*, 1995) may cause further transportation into the environment. Surface water runoff containing herbicide traces after heavy rainfall, spray drift during the application (Squillace and Thurman, 1992; Monaco *et al.*, 2002; Neumann *et al.*, 2002), volatilization after application (Millet *et al.*, 2016) or accidental losses due to leakage of spraying equipment, wrong handling of products, and mistakes during cleaning and disposal (Neumann *et al.*, 2002) are some of the possible sources. Even metabolites of herbicides can be present for a longer time in the environment (Kolpin *et al.*, 1998). Costs of purifying and monitoring of drinking water, to comply with residue limits of pesticides, was estimated by Waibel *et al.* (1998) as not less than 128 Mio. DM per year in Germany. According to reports from the German Federal Ministry for Food and Agriculture (Bundesministerium für Ernährung und Landwirtschaft (BMEL), 2017) there are often residues beyond thresholds, even though the risk of exceeding the maximum daily uptake was not reached in any case. Increasing concerns about food safety and stricter rules about herbicide residues in the food chain, impacted negatively consumer acceptance of chemical plant protection (Hoban, 1998; Wise and Whalon, 2009). Alarmist reports in mass media on the hazards of pesticides, without highlighting the benefits (Cooper and Dobson, 2007), enhanced the demand to renounce chemical plant protection. Although, herbicides still play a dominant role in weed management strategies, there is a strong need for alternative methods. The discussion about herbicides and the fact that chemical weed control reached certain limits, concerning resistance management, generated research programs to reduce the dependency on herbicides. Further developing of mechanical weeding is playing a major role in this respect (Melander *et al.*, 2005).

1.2.3 Mechanical weeding

When used in conventional farming, mechanical weeding is mostly combined with herbicide applications. Also, combinations of a mechanical method and a band-spray application is part of agronomic practices in some crops. Since the use of herbicides is not permitted in organic farming systems, mechanical weeding is the main direct control option beside preventive and cultural measures (Rasmussen, 2004). Mechanical methods achieve weeding mostly by uprooting, cutting or covering weeds with soil (Terpstra and Kouwenhoven, 1981). Pullen and Cowell (1997) separated mechanical weeding systems into two main categories: hoeing and harrowing. Harrowing can reduce weed infestation also in the row between the crop plants (Lötjönen and Mikkola, 2000). But successful harrowing of cereals requires treatments at early crop growth stages (Rasmussen and Svenningsen, 1995). One option is to harrow the first time before crop emergence when weed seedlings just germinated. Brandsæter *et al.* (2012) showed

that pre-emergence harrowing lead to a weed density reduction of 26 % and combining of pre- and post-emergence harrowing lead to a weed control success of up to 61 %. If the treatment is done too late only 47 % weed control efficacy was demonstrated (Brandsæter *et al.*, 2012). Inter-row hoeing tools are more effective in controlling especially tap-rooted weeds (Melander *et al.*, 2003). Before the availability of chemical plant protection, hoe-crops such as sugar beets and potatoes were placed in crop rotations in a way to have the possibility to use more aggressive weeding tools like a hoe (Merfield, 2019). Thus, the timing of hoeing treatments is more flexible because weeds can be controlled at later, already well-rooted growth stages (Melander *et al.*, 2003; Tillett, 2005). Another advantage of hoeing compared to harrowing is, that the crop is less mechanically impacted by the tools (Hatcher and Melander, 2003). But depending on the shape of the tools, hoeing can also indirectly reduce intrarow weed infestation by moving soil from the inter-row space into the row, thus covering emerging weeds (Melander *et al.*, 2003). Burying of intrarow weeds works best if the cultivation is performed shallow, in combination with dry soil conditions.
The term hoeing originally was not linked to weeding but was used before the plough was introduced, to describe all type of work to loosen the soil surface. This was performed by hand with simple tools like sticks or handles with right-angled tines at the end. In 1910 E. Hahn (1910) proposed the term of hoe-farming to describe agriculture without ploughing. The invention of the seed drill by Jethro Tull in the 18th century lead to the possibility of inter-row hoeing (Chambers, 1879) on a wider scale. Before that, time weeds were ignored as a potential negative yield impact as they were suppressed by the first mechanical inter-row tillage equipment. Therefore, hoeing is one of the oldest and most common mechanical methods to control weeds in the inter-row space (Griepentrog *et al.*, 2006). But 80 years ago, limitations of direct mechanical approaches lead to a replacement by chemical weeding in developed countries.

1.2.4 Impacts and challenges of mechanical weeding

The major drawbacks of mechanical weeding are various and need to be considered for their improvement. Compared to chemical plant protection, the main challenge of mechanical weed control is the dependence on weather and soil conditions for successful treatments (Kurstjens and Kropff, 2001). Only dry weather conditions in the days after the treatment can prevent uprooted weeds to regrow (Van der Van der Schans *et al.* (2006)). Further on, compared to herbicide applications the treatment costs are higher due to more fuel consumption for the power needed to pull tools through the soil. Additionally, inter-row weed hoeing in cereals requires usually wider crop row distances that lead to reduced yield potential (Holliday, 1963). Selectivity, which describes the ratio of weed control efficacy and crop damage, in mechanical weeding is reached by a growth stage difference between crop and weeds (Johnson, 2002). Concerning hoeing, this is reached by the alignment of the tools to the inter-row space and the adjustment of the tools to the soil condition. Only proper guidance of the tools and an adopted aggressiveness enable a highly selective weed control measure. The possible damages to the crop due to hoeing, requires advanced driving skills which may impact other important crop operations if such skills are urgently needed in the same time window (Jabran and Chauhan, 2018). Hand steering a hoe without damaging the crop is difficult to achieve with working speeds of more than 5 km h^{-1} over a longer time period. Also, the weed control efficacy is limited by the untreated area along the crop rows, due to the need for a safety distance between crop and hoe tool. The weeding effect on perennial weed species is not efficient (Lötjönen and Mikkola, 2000) as they can be just reduced but not sustainably eliminated. According to Melander *et al.* (2012) and Brandsæter *et al.* (2017), a sustainable reduction can be only achieved by a combination of more than one measure, where also direct control methods need to be included. That is why high time consumption and reduced levels of weed control limited the acceptance of mechanical weeding as a standalone tool in conventional farming in general (Pullen and Cowell, 1997). Tillett *et al.* (2002) showed that hand steered hoeing compared to spraying is slow. In contrast to chemical weed control, mechanical weeding always creates a physical disturbance on the topsoil layer. In consequence, mechanically weeded fields are prone to erosion, particularly in hilly landscapes and in the presence of light soils (Van Oost *et al.*, 2006). Specifically, inter-row hoeing causes soil loosening and enhances the danger of erosion in case of heavy rain events. When re-compaction behind the hoe tool is applied, uprooted weeds get in close contact to the soil again, rendering the complete treatment useless in terms of weed control. As hoeing mostly needs numerous passes to achieve full weed control, soil compaction is increased and can cause yield reduction in rows close to the driving tracks (Kouwenhoven, 1997). In case hoeing is conducted early in spring, there is a risk for frost damage of the crop (Van der Van der Weide and Bouma (1997)). Other restrictions of inter-row hoeing compared to herbicide spraying is the strong linkage between seeding width, determined by the sowing equipment and the working width of the hoe.

The row width between neighbouring sowing strips varies compared to the row width within a strip (Figure 1.1).

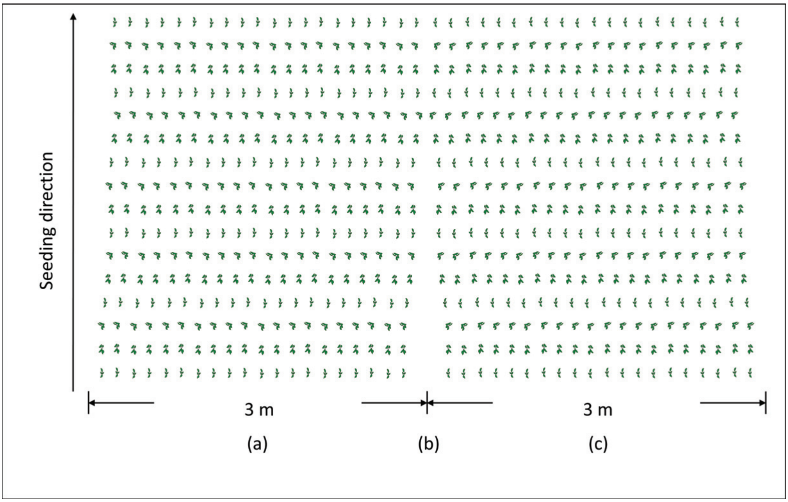

FIGURE 1.1: Typical sowing strip alignment. **(a)** Initial sowing strip, **(b)** Row width deviation of adjacent sowing strips, **(c)** Following sowing strip. (B.Kollenda)

Thus, it is not possible to enlarge the working width of the hoe over more than one seeding strip, due to the spatial deviation of adjacent strips, even if seeding would be performed with Real-time Kinematic (RTK) supported global navigation satellite system (GNSS) guidance. Mechanical weeding and combinations of new possibilities, provided by precision farming technologies, can be a future strategy to address the mentioned issues and to reintroduce it as a major direct measure against weed infestation.

1.3 State of knowledge

Numerous patents were submitted in the first decades of the 20th century describing inventions to mechanically control weeds. These cover simple knives, that were attached to tillage machines (Orr and Radley, 1913), as well as devices for inter-row hoeing close to current systems (Graf Littichau and Liegnitz, 1941). During the mechanisation era, when the tractor was introduced, tillage tools became precise enough to use them also in crop rows (Jabran and Chauhan, 2018). From the 1960s onwards mechanical weed control devices were further developed mainly in support of organic agriculture (Jabran and Chauhan, 2018; Van Der Weide *et al.*, 2008). In cereals, a lot of studies deal with harrowing. Weed control efficacy varies a lot in these reports. A study by Rasmussen (1992) recorded a weed control efficacy of 68.4 % with a spring tine harrow in peas and spring wheat. In oat, Rydberg (1994) measured a weed control success of 57-75 %, whereas Lötjönen and Mikkola (2000) found only 48-56 % and Rueda-Ayala *et al.* (2015) achieved an average of 51 % weed control efficacy in maize. Abundance of several weed species including grass weeds (*Alopecurus myosuroides* H., *Apera spica-venti* L., *Lolium multiflorum* LAM., *Poa annua* L.) and perennial weed species (*Cirsium arvense* L., *Elymus repens* L.) have increased in European cereal production systems during the last decades (Melander *et al.*, 2003). This was mainly due to higher percentages of winter crops in rotations and less intensive soil tillage operations (Massa *et al.*, 2013). Harrowing is less effective to control these type of weeds (Rueda-Ayala *et al.*, 2011). Therefore, hoeing might be a promising mechanical weeding method when higher weed control levels are required. Dierauer and Stöppler-Zimmer, H (1994) recorded 90 % of weeds between the crop rows, were uprooted and 75 % of the weeds within the crop row were covered by soil after two hoeing passes in maize and peas. While the weed control efficacy of uprooted weeds varies from 60 % to more than 90 %, the mortality of buried weeds can be poor depending on the amount of soil that is moved (Kurstjens and Kropff, 2001). Melander *et al.* (2003) recommended higher driving speed in order to move larger amounts of soil. Another strategy was the development of in-row tools to be able to selectively control weeds very close to crop plants or in between plants in the row. Mechanically driven finger weeders were already developed in the 1960s (Buddingh and Buddingh, 1963), and today are available for almost every hoeing equipment for wide-spaced crops (Kirchhoff and Duelks, 2019). A hoe equipped with inter-row sweeps and finger weeders can provide a very effective weed control success in just one run.

In vegetable cropping were plant distances are higher and driving speed is not needed to be fast, also powered tools that automatically hoe around every single crop plants are available (Dedousis *et al.*, 2007; Poulsen, 2018).
The seed row distance in cereals and the potential yield loss was also part of many studies. The recommended row distance varies between 180 and 250 mm (Lötjönen and Mikkola, 2000; Rasmussen, 2004; Melander, 2006). Other studies outline the higher yield potential in cereal crops that can be achieved by seed row distances smaller than 150 mm (Champion *et al.*, 1998; Boström *et al.*, 2012; Benaragama *et al.*, 2016). Lötjönen and Mikkola (2000), Mülle and Heege (1981) and Hakansson (1984) determined a yield loss of 12-15 % in spring barley when row spacing was increased from 125 to 250 mm.
To further enhance the guidance performance the first imaging sensor used for automated steering was introduced in the early '90s. At that time, also the first computer vision guidance systems were invented and tested (Tillett, 1991). Tillett *et al.* (2002); Nørremark *et al.* (2012) combined GNSS and optical sensors guidance to replace the poor performance of manual steering. Melander (2006); Griepentrog *et al.* (2006) showed that hoeing can be done faster and up to 40 mm close to the crop row. Even if the GNSS in combination with a locally provided RTK-correction signal is quite accurate, it does not meet the performance needed to further enhance hoe guidance precision.
For site-specific weed management strategies sophisticated systems also recording in the near-infrared area were used to distinguish between crop and weeds (Gerhards and Christensen, 2003). This is not necessary for a row guidance system where the discrimination is done just for plant material and background (Keicher and Seufert, 2000). Nowadays, using RGB-imaging sensors for precision guidance purposes is a common approach. They are relatively cheap and image processing can be also done online, as the consumption of computing power is low.