Integrated Weed Management in Cropping Systems: Principles, Methods and Experience of Field Trials

36

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Abstract

In recent decades, weeds in field crops have been predominantly controlled by herbicides, at least in developed countries. However, the weak diversity in cropping systems, in combination with the one-sided use of herbicides, has created problems such as herbicide-resistant weeds. This globally increasing threat is further worsened by the continuous loss of registered herbicides. Consequently, there is a considerable need for more integrated weed management (IWM) focusing on preventive weed control. IWM is a complex, long-term approach which involves reducing weed emergence and reproduction. The key element of successful IWM is diverse crop rotation, supported by site-specific primary soil tillage and stubble tillage. However, IWM is not fully accepted by farmers, mainly because its efficacy and costs are hard to predict. Thus, more research and guidance are needed on decision support, weed thresholds and prediction models.

Keywords

Weed control · Competition · Crop rotation · Herbicide resistance · Mechanical control · Soil tillage

36.1 Introduction

In Europe and many other parts of the world, arable weeds are predominantly controlled by herbicides. In the near future, the consumption of herbicides and other pesticides is even expected to increase, especially in developing countries (Gianessi 2013). Different specific herbicides can be applied to all major and many minor crops to make crop production cost-efficient. Because of these clear benefits, field cropping has shifted to more intensive, uniform systems.

However, besides the possible negative impacts on the environment and human health, there is also a high risk for cropping systems when relying mainly on chemical short-term solutions. Employing the same, repeated type of selection pressure using the same control method helps less-sensitive weed species to spread. Furthermore, the number of herbicide-resistant weed species is still increasing and no herbicides with new modes of action have been introduced onto the market. In addition, tougher herbicide registration rules and environmental regulations have resulted in a loss of herbicides, particularly in Europe. The lack of novel herbicide

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chemistries being brought to market, combined with the rapid increase in multiple resistance in weeds, threatens crop production worldwide (Heap 2014).

These factors are currently stimulating integrated weed management (IWM) in terms of new research efforts as well as practical implementation. In addition, the Sustainable Use of Pesticides Directive (2009/128/EC), part of the EU Thematic Strategy for Pesticides, requires Integrated Pest Management (IPM) to be actively promoted. A key objective is to give greater priority to non-chemical methods of plant protection to reduce the impact of pesticides on human health and the environment (Moss 2010).

Furthermore, the debate on sustainability and environmental problems (e.g. Zimdahl 2019), biodiversity and glyphosate as an active substance in herbicides will affect weed and farm management systems in Europe.

36.2 The Principles of Integrated Weed Management (IWM)

Worldwide, there are many versions of IWM, e.g. IPM (Integrated Pest Management), but the basic principles and targets are very similar.

In contrast to the short-term herbicide approach, the IWM system is based on a toolbox of preventive and direct methods of weed control designed to provide the crop with an advantage over weeds. IWM focuses on the weed seed bank rather than weed abundance in the field. The successful combination of applicable methods will not only favour crop competitiveness but also limit weed emergence, growth and seed production. In addition, high diversified preventive and direct control measures reduce selection pressure and avoid serious situations with specific weed species. The following figure shows the weed life cycle and the possible impact points of IWM (Fig. 36.1).

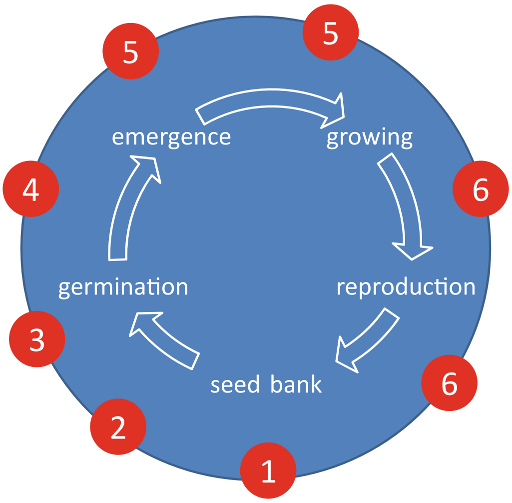

Fig. 36.1 Life cycle of weeds and impact points for control (for details, see the following text)

Depletion of the seed bank and reduction of weed competition can be achieved by

1. increasing seed degradation (soil tillage);
2. increasing fatal germination (soil tillage and false seedbed);
3. decreasing active germination (crop rotation and false seedbed);
4. decreasing initial weed density (false seedbed, delayed sowing and direct control);
5. decreasing weed growth and competition (crop rotation, cultivar choice and direct control);
6. decreasing reproduction (competitive crops and direct control).

A comprehensive review of the principles and practical tools of IWM including preventive methods, crop rotation, crop competitiveness and others has been provided by Buhler (2002). Proposals for integrating physical and cultural methods of weed control were given by Melander et al. (2005).

For legislative purposes, general principles of integrated pest management are listed in Annex III of Directive 2009/128/EC; for the full text, see EU (2009):

1. The prevention and/or suppression of harmful organisms should be achieved or supported among other options especially by crop rotation, use of adequate cultivation techniques (e.g. stale seedbed technique, sowing dates and densities, under-sowing and conservation tillage).

2. Harmful organisms must be monitored by adequate methods and tools, where available.
3. Based on the results of the monitoring, the professional user has to decide whether and when to apply plant protection measures. Robust and scientifically sound threshold values are essential components for decision-making.
4. Sustainable biological, physical and other non-chemical methods must be preferred to chemical methods if they provide satisfactory pest control.
5. The pesticides applied shall be as specific as possible for the target and shall have the least side effects on human health, non-target organisms and the environment.
6. The professional user should keep the use of pesticides and other forms of intervention to levels that are necessary.
7. Where the risk of resistance against a plant protection measure is known and where the level of harmful organisms requires repeated application of pesticides to the crops, available anti-resistance strategies should be applied to maintain the effectiveness of the products.
8. Based on the records on the use of pesticides and on the monitoring of harmful organisms, the professional user should check the success of the applied plant protection measures.

Only four of these eight principles are related to non-chemical methods. The other principles are defining the standards for pesticide applications in compliance with IPM, e.g. IWM. For a clearer view of IWM, we should therefore distinguish between 'true integrated weed management' and 'integrated herbicide management' (Harker and O'Donovan 2013). Integrated herbicide management defines the best herbicide performance in order to avoid herbicide resistance. These are, for example, the application of at least two modes of action or the use of tank mixes. In the following, we focus on 'true IWM'.

36.3 Methods of Integrated Weed Management (IWM)

In contrast to these legal definitions of Integrated Pest Management, there is also more practical guidance. For example, Naylor and Drummond (2002) recommend the following specific actions: *'An IWM strategy is not a set of hard and fast rules but a set of guidelines to follow in the particular and unique circumstances of any particular farm. It addresses the fundamentals of the best practice, and is also concerned with attention to detail; important actions in the development of an IWM strategy are:*

(1) *Ensure correct identification of the weed species which are present.*
(2) *Evaluate the role of crop residue management.*
(3) *Consider the different effects of soil cultivation methods on the weed seed bank and on weed populations.*
(4) *Consider incorporating stale seedbeds before sowing.*
(5) *Choose a more competitive crop variety.*
(6) *Consider mechanical methods of weed management.*
(7) *Use an economic threshold, not a cosmetic one.*
(8) *Map heavy infestations or recurrent infestations to allow for specialised patch treatment.*
(9) *Consider the role of weeds in harbouring beneficial species.*
(10) *Consider weeds as a wildlife resource.'*

Recent European research and administration focus not only on the direct control of weeds but also on the beneficial effects of weeds on the environment, especially on their biodiversity value (Storkey and Westbury 2007; Bückmann et al. 2018). Several studies are available which have analysed the current status of weed diversity and the impact of agronomical conditions (Richner et al. 2015).

36.3.1 Cultural Methods of Weed Control

36.3.1.1 Crop Rotation

Undeniably, diverse crop rotation is the key element for the prevention of weed growth. A crop sequence should optimise the use of resources and also limit the abundance of crop-specific pests and diseases. It is well known that crops need specific cultivation breaks, for example, winter wheat and maize (1 year), oilseed rape (3 years), and potatoes and peas (4 years). Following this simple rule, crops are able to become extremely competitive. Furthermore, alternating spring and winter crops enable the emergence only of those weed species which are adapted to the crop's seasonal timing.

Some crops, such as winter cereals, winter oilseed rape and (especially) forage crops are important for IWM as they are very suitable for suppressing weeds. Furthermore, intercropping can be used to compete with weeds where sowing and growing conditions are favourable. Intercrops such as *Sinapis alba*, *Lolium multiflorum,* or *Secale cereale* require sufficient soil moisture and vegetation time for a dense and competitive crop canopy. Under dry soil conditions, the periods between harvest and sowing of the subsequent crop should be used for subsequent passes of stubble tillage.

The findings of a long-term field trial at JKI Braunschweig, Germany, clearly demonstrate the positive weed control effects of crop rotation (Figs. 36.2 and 36.3). The highest weed infestation was found in crop rotation including only winter crops (winter wheat—winter barley—winter oilseed rape—winter durum). On the other hand, alternating spring and winter crops (maize—winter wheat—sunflower—winter wheat) achieved a significant reduction in weed density after 7 years. In the case of non-inversion tillage, the effects of crop rotation were much stronger compared to inversion tillage. However, several other field studies have pointed out the long-term effect of crop rotation on the weed seed bank, e.g. on weed occurrence in the field.

36.3.1.2 Soil Tillage

Any kind of soil disturbance helps decrease the weed seed bank because it stimulates the degradation of weed seeds and fatal germination. It is also often followed by a higher emergence rate of weeds which can be destroyed by the second soil cultivation (before and while preparing the seedbed for the subsequent crop). This so-called 'false seedbed' or 'stale seedbed' technique can

Fig. 36.2 Long-term field trial for investigation of crop rotation and soil tillage on weed infestation (Braunschweig, Germany, 2015)

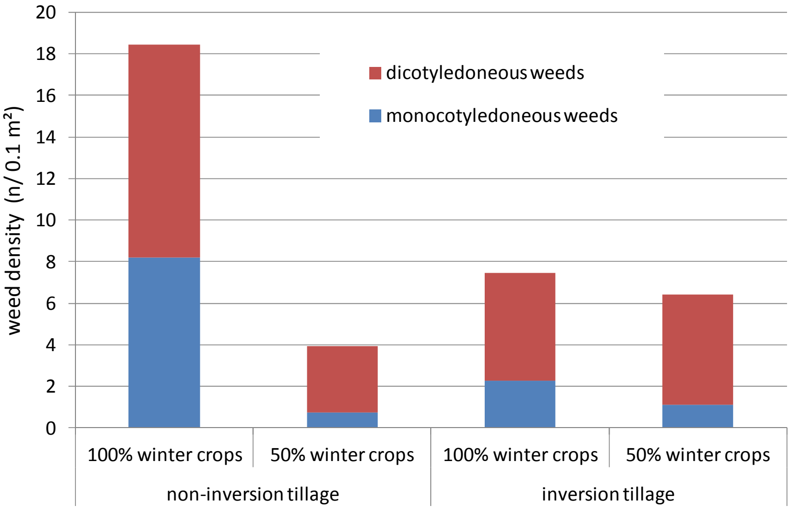

Fig. 36.3 Effect of soil tillage and crop rotation on weed density, 7 years after start of field trial (Braunschweig, Germany, 2015)

significantly reduce the seed bank: after a seedbed has been prepared, the second operation follows 10–14 days after the first one in which emerged weeds are killed mechanically by uprooting or burying.

Inversion tillage is well known for reducing weed growth and dispersal (Brandsæter et al. 2017). Weed seeds are moved to deeper soil layers where they are unable to emerge and remain buried until they decay. For agronomical and environmental reasons, inversion tillage has increasingly been replaced by non-inversion and even minimum tillage. However, practical experiences have shown that perennial weed species such as *Cirsium arvense*, *Elymus repens* or *Sonchus arvensis* are especially hard to control under conditions of reduced soil tillage.

The following results show the effects on grass weeds of combining soil tillage, crop rotation and sowing time (Table 36.1), e.g. herbicide use (Table 36.2). A significant reduction of blackgrass (*Alopecurus myosuroides*) can be achieved by delaying crop sowing (until mid-October), especially combined with inversion tillage. If winter wheat is sown after non-inversion tillage, a delay in crop sowing is essential in order to avoid problems with blackgrass (Table 36.1). The same is true for silky bentgrass (*Apera spica-venti*), which predominantly emerges in the autumn. A crop system with spring crops under inversion tillage will clearly support the efficacy of a herbicide. In other words, cropping systems where winter cereals are continuously grown under non-

Table 36.1 Effects of soil tillage, sowing time and crop on the density of blackgrass (*Alopecurus myosuroides*) (Amann 1991)

Crop	Soil tillage			
	Inversion		Non-inversion	
	Sowing time			
	Early	Late	Early	Late
	Plants/m^2			
Winter oilseed rape	46	27	125	131
Winter wheat	51	9	307	58
Spring barley	53	12	157	66
Maize	9	1	33	6

Table 36.2 Effects of soil tillage, pre-crop and herbicide use on the density of panicles of silky bentgrass (*Apera spica-venti*) in winter wheat (Pallutt 1999)

Pre-crop	Soil tillage			
	Inversion		Non-inversion	
	Herbicide use			
	Without	With	Without	With
	panicles/m^2			
Winter cereals	199	13	703	26
Winter oilseed rape	60	1	58	1
Potatoes/maize	14	0	19	0

inversion tillage herbicides are necessary but less effective compared to more diverse crop and soil management (Table 36.2).

Besides the spread of annual grass weeds, perennial weed species are also identified as an increasing problem in Europe. The most serious perennial weed species, especially in the north of Europe, are *Cirsium* spp., *Elytriga repens* (syn. *Elymus repens, Agropyron repens)* and *Sonchus arvensis* (Salonen et al. 2011).

It is widely assumed that the spread of these species is mainly a result of climate change, reduced tillage systems and increasing restrictions regarding the application of herbicides. As demonstrated above, more diverse crop rotation is important, especially under systems with reduced soil tillage. In principal, this is true for both annual and perennial weeds. Spring soil tillage followed by growing spring crops has been found to be an effective means of controlling *Cirsium arvense* and *Sonchus arvense*. Soil tillage in spring and autumn controls *Elytriga repens* in the same way (Brandsætter et al. 2017). There are similar studies indicating that deep inversion soil tillage and stubble tillage are the best non-chemical methods of controlling *Elytriga repens*, *Convolvulus arvensis* and other perennial weed species. Some of these studies pointed out that the timing and accuracy of the applied measures are important, rather than the type of machinery. Although most of these investigations were conducted many years ago, the findings and conclusions are still relevant for practical implementation today. However, the range of devices used for soil tillage has been considerably improved in terms of equipment diversity, working width, area capacity and depth control. Thus, today there are a lot of options for good, site-specific stubble mulching and seedbed preparation, which also reduces weed growth and the weed seed bank.

36.3.1.3 Crop Competitiveness and Cultivar Choice

Almost all agronomic measures such as soil tillage, fertilising and sowing are aimed at a high yield combined with a competitive crop stand. However, in terms of IWM, some methods are of major importance, e.g. the choice of competitive cultivar: Investigations on winter wheat and other cereals have shown that cultivars differ significantly in their ability to compete with weeds. The studies have demonstrated a strong correlation between light interception through the crop stand and weed suppression. Competitive cultivars can

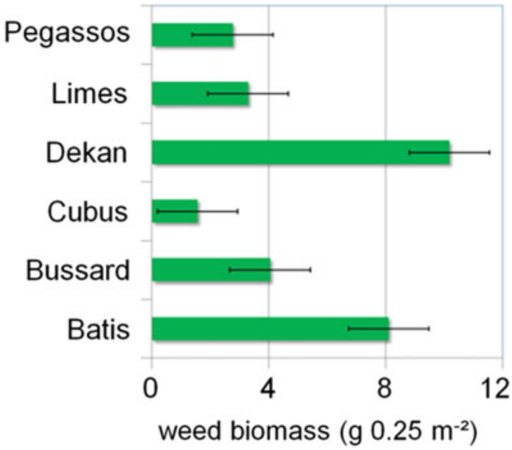

Fig. 36.4 Effect of different winter wheat cultivars on weed biomass before crop harvest (mean values and standard deviation, six field trials, Braunschweig, 2005–2007)

be characterised by morphological attributes such as planophile leaf angle, large leaf size and fast growth during the juvenile growing period. As shown in Fig. 36.4, highly competitive wheat cultivars (such as cv. *Cubus*) are able to suppress weeds to a level of 20% beneath weak competitors (such as cv. *Dekan* and *Batis*). The range of weed suppression depends on the spectrum available on the market, which might differ between countries and years. Cultivar-specific weed suppression has also been identified for many other crops and other cereals (Andrew et al. 2015), oilseed rape (Beckie et al. 2008), rice (Dass et al. 2017) and peas (Gronle and Böhm 2014).

Field crops vary widely in their ability to compete with weeds. Besides the suppression of weeds, cultivars also differ in their ability to tolerate weeds. Field studies in Germany have shown cultivar-specific yield losses caused by weeds (Verschwele 2014). Although we found highly weed-suppressing wheat cultivars (cv. *Cubus* and *Limes*) which also react with low yield loss, there was no correlation between the traits of weed suppression and weed tolerance (Fig. 36.5). It is not yet clear which specific characteristics might be responsible for a low yield reduction caused by weeds.

The same studies indicate that yield effects caused by herbicides also differ significantly between winter wheat cultivars. The yield increase brought about by herbicides ranged from 7 to 18% for the eight tested cultivars. These findings are promising in terms of improving integrated weed management by selecting competitive cultivars. However, as there is a lack of information on the cultivar-specific trait of weed suppression, this method is not systematically applied by farmers. In a few European countries, the specific trait of ‘competitiveness’ is published yearly in official national cultivar lists so that farmers can consider it when making their choice of cultivars.

36.3.1.4 Sowing Pattern and Sowing Time

Weed suppression can be improved by higher seed densities and spatial uniformity. For example, early investigations have indicated that narrow row spacing in maize has a clear effect on

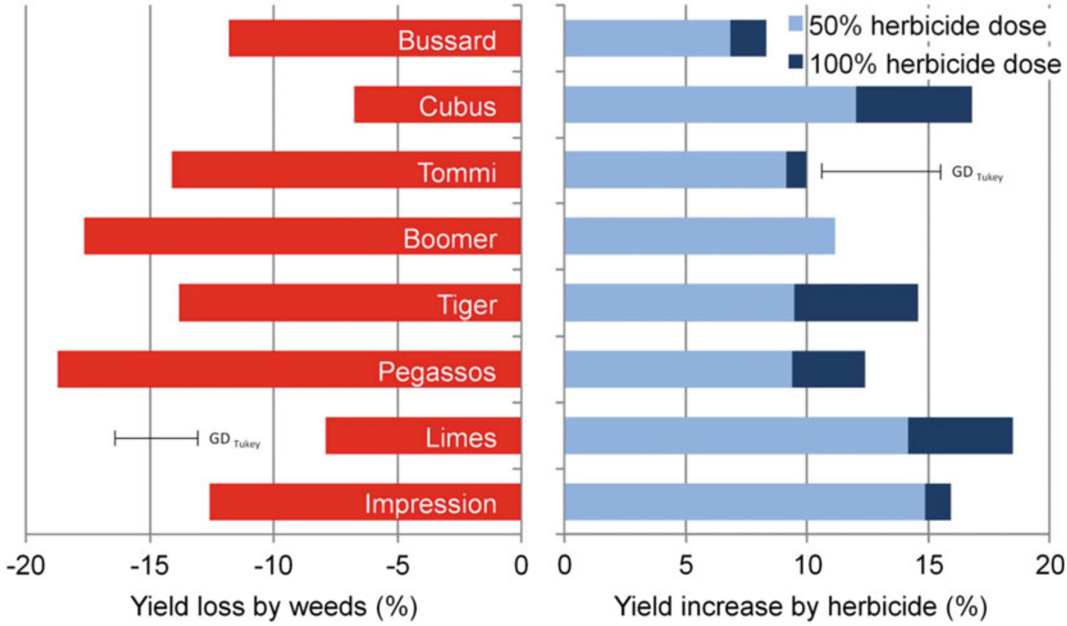

Fig. 36.5 Yield loss by weeds and herbicide effects in different winter wheat cultivars (three trials, Braunschweig, Germany, 2008–2010)

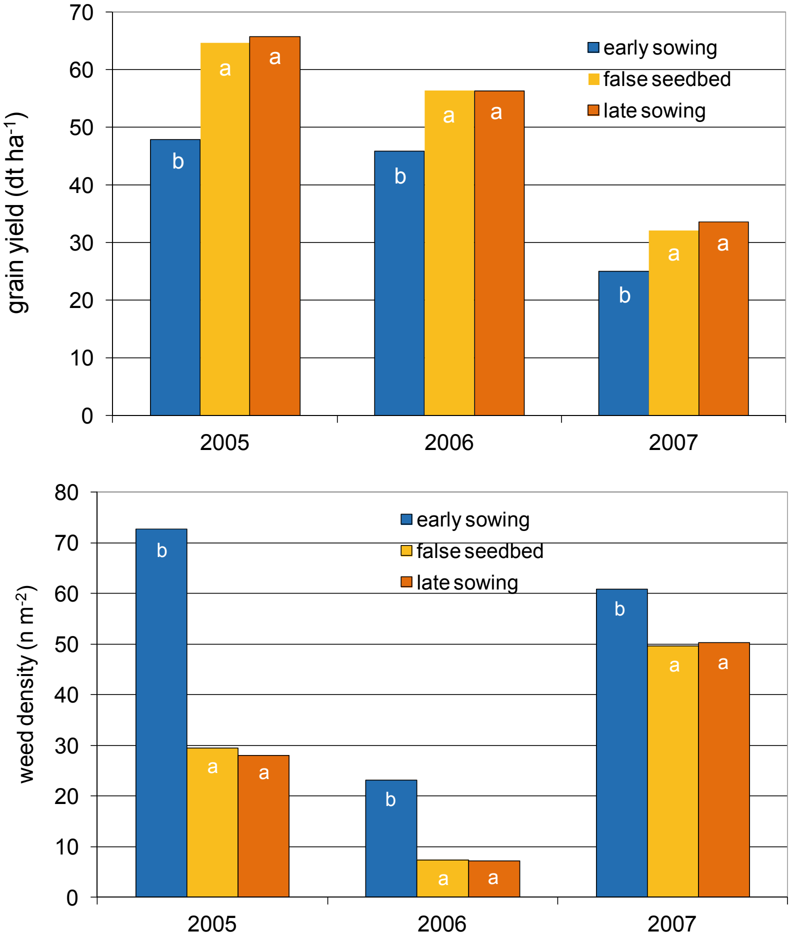

Fig. 36.6 Effect of sowing method on grain yield of winter wheat and weed density (six trials, Braunschweig, Germany, 2005–2007)

crop yield and weed suppression (Teasdale 1998). Furthermore, a higher seed density improves the crop's competitiveness, as does the sowing design. In contrast to row sowing (which is commoner), more uniform grid sowing can result in a higher maize grain yield and reduced weed growth. Thus, weed infestation is significantly affected by seed density, maize variety and sowing pattern, but strong interactions between the variety and sowing pattern were found by Marin and Weiner (2014). However, these promising findings have not yet been widely implemented in agricultural practice.

In general, weed emergence rates decline later in the season because of unfavourable growing conditions (temperature and day length). Thus, delayed crop sowing in autumn can be used as an IWM tool by giving the crop advantages over the weeds. For Maritime European conditions, seeding later than mid-October is dedicated to reducing initial weed infestations in winter wheat (see also combined effects with soil tillage in Sect. A.1).

The so-called 'false seedbed' technique can also be used to reduce weed infestation. This means that the soil is already cultivated 10–20 days before crop sowing. Consequently, emerged weeds are destroyed by the seedbed preparation. A 3-year set of field experiments has demonstrated that the false seedbed technique can reduce the seed bank, but the weed density in the crop is the same as with late sowing (Fig. 36.6) (Verschwele 2009). For spring crops, delayed sowing cannot always be recommended

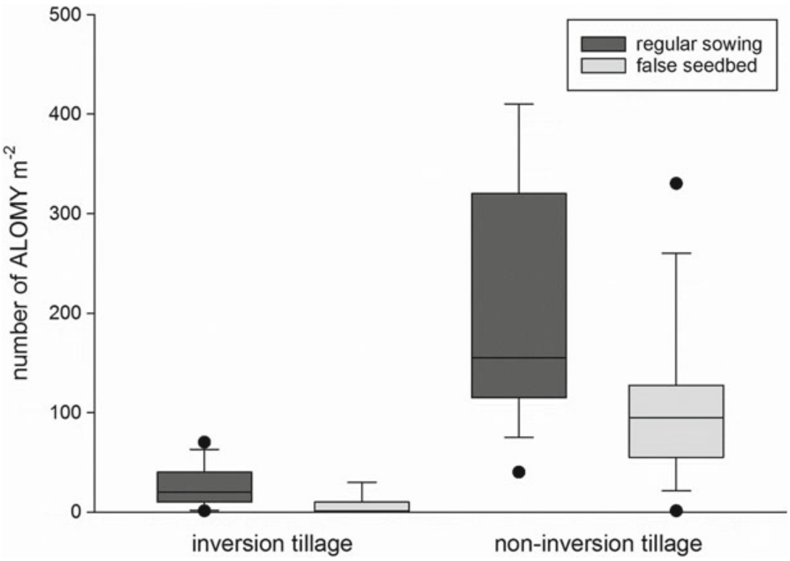

Fig. 36.7 Number of blackgrass (ALOMY) plants m^{-2} in spring in winter barley for different seedbed preparation methods (Wellhausen et al. 2018)

because the loss of vegetation time might reduce the crop yield.

Other field studies (Rasmussen 2004) which also tested different row distances and control methods (mechanical, chemical) showed similar findings. At low weed levels, mechanical weed control caused a yield decrease compared with untreated or herbicide-treated fields. At intermediate weed levels, there were no differences, whereas at high weed levels, mechanical weed control and herbicide treatment caused a yield increase compared with untreated fields. False seedbeds were shown to contribute to a decrease in the soil seed reserve.

As shown in Fig. 36.6, delayed autumn drilling affects weeds differently depending on the conditions in any given year. Since weather and soil conditions are mostly difficult to predict, the impact on weeds and grain yield differs widely. Further field studies (Fig. 36.7) have demonstrated that the false seedbed technique enables blackgrass to be controlled very well if combined with inversion tillage (Wellhausen et al. 2018).

36.3.1.5 Overall Effects of Cultural Methods

In principle, the different indirect methods mentioned above can be used in combination in order to suppress weed growth and reduce weed seed production. However, there are only a few studies available where more than two methods have been tested. A meta-analysis of more than 50 field studies has shown that spring cropping and ploughing are most effective—at least for controlling the most serious weed species in United Kingdom blackgrass (*Alopecurus myosuroides*) (see Table 36.3) (Lutman et al. 2013).

Table 36.3 Control effects (%) of different cultural weed control methods in winter cereals (Lutman et al. 2013)

Method	Mean effect (%)	Range (%)
Ploughing	69	−82 to 96
Delayed sowing	31	−71 to 97
Higher seed rates	26	7–63
More competitive cultivars	22	8–45
Spring cropping	88	78–96

Although these data reflect the general situation, farmers have to consider their specific conditions and especially the level of blackgrass in the field. For example, delayed sowing (here from mid-September to mid-October) may be more risky in some regions with heavy soils and higher rainfall in autumn. The range of competitiveness among cultivars is also different in the European countries, and competitive cultivars are also expected to provide high yields and quality.

36.3.2 Mechanical Weed Control

In recent decades, mechanical weeding has been replaced with the broadcast application of herbicides in conventional cropping systems. However, recently hoeing and harrowing equipment have significantly been improved by technical innovations such as GPS technology. Additionally, online digital image analysis is able to detect crop rows or even single crop plants; this nowadays works not only with RGB technology but also with ultrasonic or laser sensors.

For example, the steering of hoeing equipment is supported by camera devices and positioning using GPS and RTK signals. This results both in a higher driving speed and higher accuracy: modern hoeing tools are able to work up to 2 cm close to the crop row. Thus, automated weeding results in higher efficacy and area treatment. Today a wide range of different machines are offered on the market (Fig. 36.8).

Field studies in Germany conducted in grain maize over 4 years have demonstrated that even regular interrow hoeing in combination with herbicide band application resulted in similar crop yields and weed infestation compared to broadcast herbicide application (Table 36.4).

Similar field studies on integrated weed management in maize have been conducted in Italy, Germany and Slovenia. These results showed that the IWM tools tested in the different countries (1) provided sufficient weed control without any significant differences in yields, (2) greatly reduced maize reliance on herbicides and (3) were economically sustainable as no significant differences in gross margin were observed in any country compared to conventional herbicide broadcast application (Vasileiadis et al. 2015).

Mechanical weed control in cereals is mostly done by harrowing due to the narrow row distances of 10–13 cm. However, under conditions

Fig. 36.8 Camera-steered hoeing machine in faba beans *(Vicia faba)*

Table 36.4 Weed and yield effects of herbicide broadcast application and herbicide band application combined with interrow hoeing in maize (eight trials, Germany, 2011–2014)

	Herbicide broadcast application	Herbicide band application + interrow hoeing
Weed control efficacy (%)	90	83
Treatment frequency index (TFI)	1.9	0.8
Maize grain yield (t/ha)	12.4	12.2
Weed density (plants/m^2)	13	24

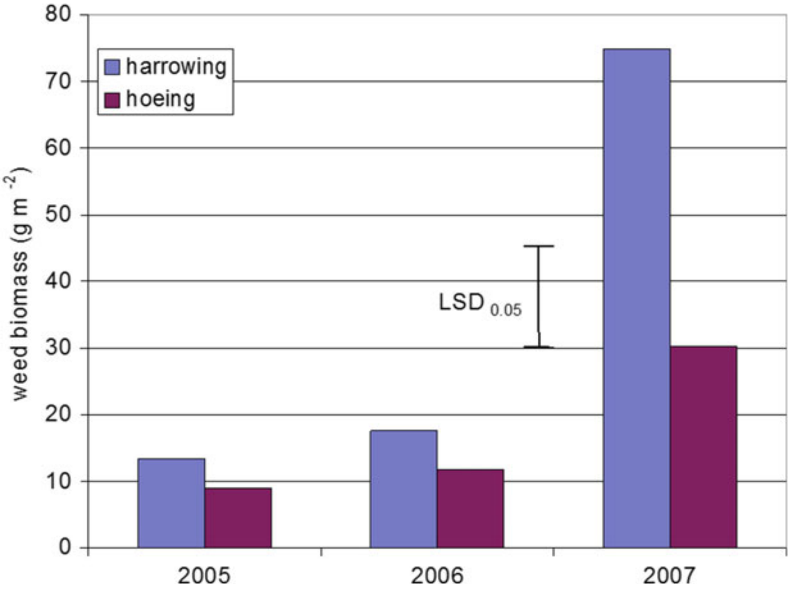

Fig. 36.9 Effect on residual weed biomass after harrowing and hoeing in winter wheat (six trials, Braunschweig, Germany, 2005–2007)

with high competition by weeds, hoeing might also be an option. This requires crop row distances of 25 cm or more if the equipment currently available on the market is used. Recent research efforts with camera-steered hoeing machines focus on smaller row distances for mechanical weed control in cereals, peas or faba beans. If the weed level is low (<50 plants/m^2) and if there are no problematic species such as *Galium aparine, Matricaria* spp. or *Chenopodium* spp., we expect similar sufficient control effects by harrowing and hoeing. On the other hand, according to field studies in winter wheat, the efficacy of harrowing was not sufficient compared to hoeing in 2 out of 6 trials (Fig. 36.9). This was mainly affected by high initial weed densities and crusted soil surfaces.

36.3.3 Other Integrated Control Methods

Besides cultural and mechanical weed control, other research on non-chemical weed control methods has been carried out in Europe. For example, flaming, hot water and other thermal measures have been technically improved but so far these are only applied to some minor crops such as carrots and onions. Electrical control methods have shown potential for killing weeds (Vigneault and Benoît 2001) and are currently supplied by some manufactures for non-selective weed control and desiccation in crops, as well as for uses in non-cropping areas.

Allelopathic effects have been investigated in many plant species. Crops such as sunflower and rye are able to actively inhibit the emergence, growth and reproduction of weeds by releasing biochemicals. Although this biological phenomenon has often been demonstrated in the glasshouse, it is difficult to use allelopathic plants in practice, under field conditions. The same is true for any methods of biological weed control. So far, the classical biological control strategy against weeds has not been applied in Europe (Naylor 2002).

36.4 Practical Relevance and Future

In practice, IWM often falls under Good Agricultural Practice. For example, the choice of a crop and a cultivar which are best adapted to the site will automatically result in high weed suppression by the crop. This is in line with the farmer's interest in achieving a high crop yield and quality. In many situations, the farmer has to weigh up the effects on the weeds and the crop. During those complex decision-making processes, long-term negative effects on weeds are normally underestimated, especially because they cannot be exactly predicted. In unfavourable cases, more efforts at IWM by the farmer do not automatically result in a lower herbicide input. The economic effects of IWM are also hard to predict since they cannot be calculated as a net return per year. These are clear obstacles for better acceptance of IWM: It is not (yet) possible to evaluate what effect the complex IWM toolbox has in controlling weeds.

In general, the barriers identified as preventing greater acceptance of IWM are a perception of a higher risk to management, a lack of economic incentive, and a lack of support from the crop-protection industry. In order to overcome these barriers, more research and guidance are needed on decision-making support, weed thresholds and prediction models (Swanton et al. 2008).

Farmers often consider IWM when they already have serious problems with one or more specific weed species. However, at that stage it is often too late for preventive control methods to be successful. Therefore, it is absolutely necessary to provide farmers with adequate guidance and support in the field. Public or private advisory organisations should support farmers with the effective and early implementation of IWM.

Due to the increasing limitations for herbicide options in field crops, we can expect IWM to be applied more broadly, at least for some easy-to-use and inexpensive tools. Much progress has been made in developing alternative weed management techniques and integrating those techniques into real IWM systems (Harker and O'Donovan 2013). Recent technical innovations such as digital weed recognition and devices for automated weeding will also improve IWM in the future (Young and Pierce 2014).

Finally, Zimdahl (2013) gave a more personal outlook on future weed research and weed management:

> Integrated control will no longer be able to limit its focus to weeds and weed control. To be successful, the focus should be the total vegetation complex or better, habitat management rather than weed control in a year in a crop. Perhaps it is most correct to say that industrialization will change the scale of concern. Sustainable integrated weed management systems must extend concern to environmental quality and future generations. These are large-scale concerns. Small-scale concerns such as how to control weeds in a crop in a year have dominated and future agricultural systems require change. Environmental concerns demand large-scale thought. Small-scale thought suffices for individual concerns. Large thoughts are needed for large systems. Everything needs to be integrated to have a complete crop management system. It won't be easy to do, but it is necessary.

36.5 Conclusions

1. In recent decades, cropping systems have been developed with low diversity—based on the permanent and one-sided use of pesticides.
2. Herbicide resistance will be the strongest agronomic spur for IWM in the near future. This trend will be followed by a continuous loss of registered herbicides.
3. Technical innovations such as automated mechanical weeding can support the broader practical implementation of IWM.

4. Sustainable crop production requires highly diverse preventive and direct crop protection tools.
5. Farmers have to understand weed management as a complex long-term strategy.
6. Although the principles and guidance for integrated weed management are scientifically accepted, they are poorly implemented in practice.

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