ABSTRACT: The on-going loss of active ingredients, the total absence of new modes of action, the steady increase in the number of herbicide resistant weed biotypes and the emergence of new weed species is serious challenges to the sustainability of the largely herbicide-based weed management strategies adopted by the vast majority of European farmers. Many farmers have reached a crossroads where weed management strategies need to be redesigned. In June 2014 Directive 2009/128/EU regulating the sustainable use of pesticides in Europe came into force. An important part of the directive is the requirement that all professional users of pesticides from 1 January 2014 were supposed to comply with the general principles of Integrated Pest Management (IPM). Adopting integrated weed management (IWM) often involves major changes in the cropping system as the composition of the weed flora is closely associated with the cropping system. No single alternative control method can replace the use of herbicides and IWM typically involves the application of several control methods in a systematic way and IWM is therefore a more knowledge intensive than the current practice. In recent years more information has become available on the performance of alternative control methods but the information on how to combine these methods into effective IWM practices is still scarce. Furthermore many years access to effective herbicides - a simple to apply and very reliable technology - means that a change in the farmers’ attitude to weed management is also needed for successful implementation of IWM.

Key words: integrated pest management, IPM principles, cultural methods
INTRODUCTION

In June 2011 Directive 2009/128/EC establishing a framework for Community action to achieve the sustainable use of pesticides in the European Union (EU) came into force. For many years the EU have had a common framework for marketing of pesticides stipulating among other things the requirements that pesticides have to fulfill to be registered. With Directive 2009/128/EC the EU for the first time has a regulation focusing on the use of pesticides. The directive requires Member States to launch a number of initiatives to promote sustainable use of pesticides such as training of professional user of pesticides as well as distributors of pesticides and advisors, regular check of the application equipment and provide measures addressing storage facilities for pesticides. The directive also requires that all professional users of pesticides should have adopted the principles of Integrated Pest Management (IPM) by 1. January 2014 and the EU Member States were asked to describe in a National Action Plan how they would endure the implementations of the IPM principles.

European farmers are facing a number of both legislative and biological nature (see next section) and more and more farmers are realizing that a weed management strategy relying upon a single tool, herbicides, is doomed to fail. In this perspective Directive 2009/128/EC with its demand to adopt IPM is very timely.

THE CHALLENGES

In the future European farmers will be facing numerous challenges turning weed management more difficult and knowledge-intensive.

Firstly many active ingredients have been removed from the market in recent years following a review programme of existing pesticides that was done under the conditions of Directive 91/414/EEC. The review programme was initiated in 1992 and finished in 2009. Of the more than 1000 active ingredients registered before Directive 91/414/EEC went into force in 1993 only 26% were approved for re-registration and among the active ingredients lost were also many herbicides. During the same period only around 150 new active ingredients were registered in the EU. In 2011 Directive
91/414/EEC was replaced by Regulation 1107/2009. Along with the regulation came some new initiatives (hazard criteria and comparative assessment) that are expected to make pesticide registration in the EU stricter and thus further reduce the number of herbicide active ingredients.

Secondly herbicide resistance is becoming more and more widespread and is causing increasing problems. In particular non-target site resistance occurring in several grass weed species is causing growing concern due the wide range of modes of action that these weed biotypes are exhibiting resistance to. The increase in the number of resistance cases is coinciding with a total lack of herbicides with new modes of action. The most recent new herbicide mode of action was introduced in the 1980’ies. A recent desk study revealed that natural compounds or compounds derived from natural compounds in contrast to previous expectations has not contributed significantly to the portfolio of new herbicides (Cantrell et al., 2012).

Finally new species partly promoted by the global climatic changes are on the march. The majority of new weed species are confined to non-agricultural areas and aquatic environments but some like *Ambrosia artemisiifolia* have also infested agricultural fields.

**DIRECTIVE 2009/128/EC AND THE 8 EU IPM PRINCIPLES**

IPM was born with the introduction of the term ‘integrated control’ by Stern et al. (1959). Since then many definitions of IPM have been proposed and back in 2002 Bajan & Kogan (2002) listed 67 different definitions of IPM. The EU also has its own definition of IPM but more importantly Directive 2009/128/EC lays out 8 general IPM principles. In the context of integrated weed management (IWM) the 8 IPM principles can be interpreted as follows:

1. Crop rotation, cultural practices, soil cultivation, hygiene measures etc. should be undertaken to prevent and/or suppress weeds.
2. Diagnostic tools as well as warning/forecasting systems should be used if available.
3. Robust and scientific sound thresholds should be used if available.
4. Non-chemical methods should be preferred to chemical methods if they provide satisfactorily control.

5. Herbicides with least possible side effects on human health and the environment should be used.

6. The use of herbicides should be kept to the level that is necessary e.g. by using reduced doses or reducing the number of treatments.

7. Anti-resistance strategies should be adopted.

8. The success of the weed management strategy should be assessed based on the spray records and monitoring of the occurrence of weeds in the fields.

The eight principles follow the crop growth cycle focussing firstly on prevention (‘prevention is better than cure’), then on identification and quantification of the weeds, control measures highlighting the use of non-chemical methods, proper use of herbicides and finally assessment of the strategy with the view of assessing the results and correcting the strategy for the coming growth season if required.

**THE FRAMEWORK OF IWM**

In contrast to the majority of the most important diseases and pests the weed flora is more influenced by crop rotation, crop type and management practices than by a specific crop in the crop rotation. Winter annual weeds, for example, are primarily associated with cropping systems consisting of winter annual crops while perennial weeds are more dominant in perennial crops. Due to the close association between weed flora and the cropping system IWM has to consider the cropping system and IWM is therefore more closely related to the broader Integrated Crop Management (ICM) than integrated management of diseases and pests. Another feature distinguishing weed management from disease and pest management is that the target in most cases is a community of species that vary in their relative abundance, economic impact on the crop, susceptibility to weed control measures and environmental benefits.
A framework for IWM needs to consider the whole life cycle of weeds and to be sustainable is should achieve at least one but preferable more of the following goals:

1. Minimise weed establishment in the crop from the soil seed bank or subterranean vegetative organs.
2. Minimise competition for light, nutrients and water by removing the weeds or by manipulating the weed flora or the crop to reduce the competitive ability of the weed flora.
3. Minimise the return of seeds to the soil seed bank or subterranean vegetative organs to the organ bank.

Farmers have a number of IWM tools available to reach the goals (see Figure 1). Although the number of IWM tools are many most of them are not as effective or reliable as herbicides (Lutman et al., 2013), i.e. they cannot be considered stand-alone methods but have to be combined with other methods to provide a sustainable IWM strategy. There is no ‘silver bullet’ than can replace herbicides and IWM has therefore been referred to as “many little hammers’ (Liebman & Gallant, 1997). This makes IWM different from integrated disease and pest management where more effective tools such as resistant cultivars are often available. Additionally, some non-chemical weed management options incur a higher cost than herbicides that needs to be balanced against the potential long term benefits, such as a reduced risk of selecting herbicide resistant biotypes, of more sustainable IWM strategies.

IWM TOOLS

It is not the purpose of this review to discuss in detail all the IWM tools listed in Figure 1 but just to provide some examples. Direct non-chemical weed control methods such as inter-row cultivation are not included as they are covered by Melander (2014) (this volume).
Soil cultivation and crop establishment is pivotal in reducing the recruitment of weed seeds from the soil seed bank. Delayed sowing of particularly winter crops combined with a false seed bed and higher crop density are effective tools to reduce weed numbers in narrow-row crops such as small grain cereals and oilseed rape (e.g. Melander, 1995; Kolb et al., 2012) but can be associated with yield losses (delayed sowing) and increased costs (higher crop density). Higher temperature requirements for germination and for some weed species loss of germinability due to secondary seed dormancy are most likely the causes of reduced weed germination. Lutman et al. (2013) reviewed the literature on cultural control of blackgrass (*Alopecurus myosuroides*) in winter wheat in the UK and found that, on average, delayed sowing provided 30% of the weed. Higher crop densities are routinely recommended in spring cereals in Western Canada to suppress weed and reduce herbicide use (Blackshaw et al., 2008).

Figure 1. Tools available to farmers to reduce weed establishment, competition with the crop and return of seeds/vegetative organs.
Growing competitive cultivars can also reduce weed growth (e.g. Hansen et al., 2008) and increasing the spatial uniformity of the crop may increase the competitiveness of the crop (e.g. even distribution rather than in narrow rows) (e.g. Olsen et al., 2012). Alternatively the row distance can be increased to allow for inter-row cultivation. In many crops this will be associated with a yield penalty but e.g. in winter oilseed row distance can be increased without yield penalties.

Cover/mulch crops, in particular the ones showing allelopathic properties such as Brassicas and rye, can also contribute to a reduced weed density but may also have an adverse impact on the crop (e.g. Haramoto & Gallant, 2005a; 2005b). The allelopathic potential of Brassicas have been attributed to their content of glucosinolates (Haramoto & Gallant, 2004) while the effect of rye is assumed to be due primarily to their content of benzoazinoids (Schulz et al., 2013). While Brassicas should be incorporated to minimise the loss of the volatile glucosinolate metabolites which are the allopatic compounds rye can either be left on the soil surface or incorporated in the soil. The most promising results have been found when rye killed chemically or mechanically is left on soil surface (e.g. Creamer et al., 1996; Bottenberg et al., 1997). Reduced weed growth by a rye residue on the soil surface need not to be due to allelopathy but could also simply be caused by the presence of the plant residues on the soil surface e.g. reducing light intensity at the soil surface. Recently Teasdale et al. (2012) found that suppression of weeds grown in soil samples collected under a rye residue was very short compared to the season long suppression observed in the field suggesting that allelopathy alone cannot explain the observed effects of rye cover crops.

Nutrient placement can favour the growth of crop at the expense of the weed (the ‘feed your crop - starve your weed’ concept) (e.g. Rasmussen, 2002).

Correct stubble management are important for reducing the return of seeds to the soil seed bank partly because it can have a direct effect on seed survival and seed dormancy but also because it can influence seed predation (e.g. Baraibar et al., 2009). Seed collection or seed destruction, as it is practiced in Australia, can also have a pronounced effect on seed return (Walsh et al., 2012).
CONCLUSIONS

The higher level of complexity of IWM compared to chemical weed control, the fact that IWM may require fundamental changes to the cropping system and most importantly the high level of control provided by the herbicides until recently may explains why IWM has not received the same attention as integrated management of other pests. As pointed out by Swanton & Wiese (1991) IWM relies on essential information and focuses on crop health rather than weed control, i.e. IWM is more knowledge-intensive than chemical weed control and thus requires a higher level understanding of the biological processes taking place in the field which may also have hampered the adoption of IWM.

Another factor limiting the adoption of IWM is the perceived higher risk of failure of IWM than of chemical control among farmers and the lack of obvious short-term benefits in terms of better control or reduced costs. The risk of failure can be contained by developing truly IWM strategies that combines several of IWM tools listed in Figure 1. The agronomic benefits of IWM are often long-term and thus difficult to comprehend comparing pros and cons. Thus proving the long-term benefits of IWM is pivotal and this is essentially a task for research institutes. Unfortunately weed scientist have not devoted much attention to IWM as highlighted recently by Harker & O’Donovan (2013) who found that from 1995 to 2012 the number of papers on ‘weed control’ outnumbered the number of papers on ‘integrated weed management’ by 14 to 1.

In contrast to agronomic benefits environmental benefits of IWM may be more immediate but farmers are rarely rewarded financially for this and therefore there is little economic incentive for them to adopt IWM. This is also reflected in the current EU policies where IPM has been made mandatory and is not a part of the Common Agricultural Policy (CAP) although IWM could undoubtedly contribute to the so-called ‘greening’ of the CAP.
REFERENCES

BAJWA, W.I.; KOGAN M. Compendium of IPM Definitions (CID) - What is IPM and how is it defined in the Worldwide Literature? Integrated Plant Protection Center (IPPC), Oregon State University, Corvallis, Publication Number 998, 2002 (http://www.ipmnet.org/ipmdefinitions/index.pdf)


