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An Integrated Weed Management framework: A pan-European perspective

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ABSTRACT

Initiatives to reduce the reliance of agriculture on pesticides, including the European Union (EU) Directive 2009/128/EC on the sustainable use of pesticides (SUD), have yet to lead to widespread implementation of Integrated Pest Management (IPM) principles. Developments in weed management have strongly focused on increasing the efficiency of herbicides or substituting herbicides with other single tactics such as mechanical control. To increase sustainability of agricultural systems in practice, a paradigm shift in weed management is needed: from a single tactic and single growing season approach towards holistic integrated weed management (IWM) considering more than a single cropping season and focusing on management of weed communities, rather than on control of single species. To support this transition, an IWM framework for implementing a system level approach is presented. The framework consists of five pillars: diverse cropping systems, cultivar choice and establishment, field and soil management, direct control and the cross-cutting pillar monitoring and evaluation. IWM is an integral part of integrated pest management (IPM) and adopting IWM will serve as a driver for the development of sustainable agricultural systems of the future.

1. Introduction

Weeds compete with crops for light, water, nutrients and space and farmers therefore need to control weeds to sustain crop yield. The focus of current weed management practices is to reduce the abundance of weed plants to a very low level. Since the discovery of herbicides in the 1950s, they have become the preferred weed control option in conventional agriculture (Kudsk and Streibig, 2003). The current high dependency on herbicides has given rise to environmental concerns and concerns for human health. Herbicide use has been associated with adverse effects on biodiversity (Riemens et al., 2008; Storkey et al., 2012; Strandberg et al., 2017), pollution of water bodies (Kreuger, 1998) and leaching to groundwater (Rosenbom et al., 2015).

An indirect effect of the high reliance on herbicides has also been a simplification of European crop rotations, as the most preferred crops can be grown more frequently with a reduced dependence on break crops to interrupt the life cycle of weeds. This has effectively narrowed the ecological niche for weeds, selecting for fewer but more competitive weed species, which, in turn, increases the reliance on a limited number of herbicide active ingredients effective against the dominant weed species. Besides weed communities becoming less diverse, some weed species adapt to this more intense selection pressure either by evolving resistance or by avoiding exposure to herbicides (e.g. altered weed seedling emergence pattern under changing soil disturbance) (Heap, 2020; Schutte et al., 2013). To reduce the negative environmental impacts of herbicides and to mitigate the increasing prevalence of herbicide resistance, diversification of weed management is needed (Norsworthy et al., 2012; Mortensen et al., 2012). In 2009, the European Union (EU) implemented Directive 2009/128/EC on the sustainable use of pesticides (SUD): a framework to reduce the risk to human health and environment and to promote and implement the use of Integrated Pest Management (IPM). With this directive, member states were required to develop National Action Plans (NAPs) to reduce the risk of pesticides. Since 2014, professional users of pesticides were obliged to apply the eight principles of IPM (https://ec.europa.eu/food/plants/pesticides/sustainable-use-pesticides/integrated-pest-management-ipm_en).
More than ten years later, the practical implementation of the SUD and IPM principles is limited (Traon et al., 2018), the incentives for farmers

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to adopt IPM are weak (European Court of Auditors, 2020) and the dependency of Europe's agriculture on pesticides, and more specifically, herbicides, remains. One impediment to the implementation of IWM is the lack of intuitive tools and frameworks for managing the greater complexity of management compared to using herbicides (where all the relevant information is present on the product label). Hence, there is a need for a new framework to design and implement IWM strategies in practice.

The intention of this paper is to organise the existing knowledge of different tactics and available tools into a generic framework for integrated weed management (IWM), i.e. a systematic integrated approach that can be used by agronomists and weed scientist to design novel weed management strategies appropriate to their specific context.

2. The need for a redesign of weed management strategies

Until now the focus of work on reducing the negative impacts of herbicides has primarily been on increasing the efficiency of herbicides and substituting herbicides primarily by mechanical weed control methods, which are the first two levels in the ESR paradigm (Efficiency, Substitution and Redesign) for transition toward sustainability (MacRae et al., 1990). Redesign has received less attention, but true IWM will require a fundamentally different approach to the management of weeds in cropping systems. Here, we present a novel framework for facilitating a paradigm shift in weed management from efficiency and substitution to redesign. We do not subscribe to a 'zero tolerance policy' or 'take no prisoners' strategy. Instead of aiming at complete eradication, the goal should be to reduce the negative impacts of weeds, while retaining some ecological benefits; two aims that may in fact be mutually reinforcing (Storkey and Neve, 2018). By encouraging the diversification of the system and reducing the reliance on herbicides, our approach also reduces the risk of herbicide resistant weed population revolving. The aim of our new IWM framework is to support the redesign of cropping systems to *manage weed communities* in such a way that the impact of individual weed species will be low and will not adversely affect yield and economic profitability.

Excessive reproduction of the same weed species or groups of weed species (e.g. monocots or perennial species) in the cropping system should be avoided by broadening the available ecological niche allowing for a more diverse weed community. A more functionally diverse weed community is predicted to have a reduced competitive ability in any crop (Adeux et al., 2019). This is a more 'proactive' approach than the 'reactive' approach that targets control of weed species that have become problematic and dominant. Since most weed species have a high phenotypic plasticity, they can adapt to repeated management tactics and escape control measures aimed at their eradication, such as false seedbeds, earlier or later sowing dates and mechanical weeding operations. Adaptation has repeatedly been demonstrated to occur in weed populations in response to herbicide applications. Although hardly any studies have demonstrated the adaptation capacity of weeds to cultural and mechanical operations, it is likely that this also occurs (Vigueira et al., 2013). The lack of evidence is probably due to the complexity of causal relationships throughout the weed life cycle (Darmency, 2019). This adaptability necessitates a diverse management strategy that 'keeps the weeds guessing'. Such a strategy will need to employ all available tools that are now reviewed in the context of a new framework for designing IWM based on five pillars.

3. Five pillars for weed management

Weed community management requires long-term strategies in contrast to management of most insect pests and diseases. In addition, an advanced IWM strategy should affect the population dynamics of weeds at several stages of their life cycle through: 1) Prevention of weed establishment from seeds, rhizomes or tubers; 2) Reduction of the adverse impact of emerged weeds on the crop; and 3) Reduction of replenishment of the seed or vegetative bud bank (Kudsk et al., 2020) (Fig. 1).

Our framework is based on the assumption that multiple tactics need to be combined that affect different life cycle stages (Chikowo et al., 2009; Liebman and Gallandt, 1997). Besides considering the life cycle of weeds, the tactics applied by farmers can be assigned to one of the following five pillars:

1. Diverse cropping system
2. Cultivar choice and establishment
3. Field/soil management
4. Direct control
5. Monitoring and evaluation

Any one tactic can be successful in managing weeds in the short term but may select for species that can adapt to that approach. Therefore, to achieve sustainable weed control in the long term, a combination of tactics is necessary. The tactics listed in Fig. 1 can be assigned to one of the five pillars that, except for pillar 5, also refer to different times in the cropping season. Monitoring and evaluation activities, such as weed scouting, the use of decision support systems (DSS) and high-tech sensing technologies, are cross cutting activities that take place throughout the growing season and during the entire crop rotation. These tools help farmers make informed decisions on what tactics to choose, but they also help to evaluate the success rate of previously applied tactics and strategies. The pillars provide a framework, which can be applied within an individual cropping season, but, more importantly it can be used to facilitate the planning of weed management across the entire cropping system. The tactics are generic but can be selected and combined based on local agro-environmental conditions, the availability of technologies and machinery, the socio-economic system the farmer is part of, and the specific crops and cropping systems on the farm. The framework can be used by agronomists, applied scientists and advisors to aid farmers redesign on farm weed management. The potential contribution of each of these pillars and their associated management options are now discussed.

3.1. Diverse cropping systems –pillar 1

The life cycle of the crop and growing conditions determine the potential crop management operations and the available weed control tactics, both in terms of timing and tools that can be applied. Therefore, diversification of the cropping system allows diversification of the weed management practices that will affect the weed species differently (Liebman et al., 2001). In addition to this, Smith et al. (2010) hypothesised that diverse cropping systems have a higher diversity in soil resource pools and therefore allow for a greater niche differentiation between weeds and the crop (Resource Pool Diversity hypothesis, RPDH). This, in turn, results in a decreased belowground weed-crop competition and hence lower yield losses. In recent years, several studies have tested and partially demonstrated that a higher weed diversity associated with different fertiliser regimes (see Section 3.3 for fertiliser aspects) is related to lower crop yield loss (Cierjacks et al., 2016; Storkey and Neve, 2018). Besides the improved weed control capacity of diversified cropping systems and the decreased competition with the crop, the presence of diversified weed communities can contribute to the provisioning of agroecosystem services such as pollen and nectar supply for wild bees, alternative food sources for beneficial insects, and soil cover to reduce erosion (Blaix et al., 2018). Diverse weed community will offer resources throughout the crop cycle and throughout the year, whereas crops can offer these services only in the short period of mass flowering.

The framework divides weed control tactics based on cropping system diversification into tactics for diversification in time (crop rotations and cover crops) and in space (intercropping, field margin management and landscape arrangement of crops).

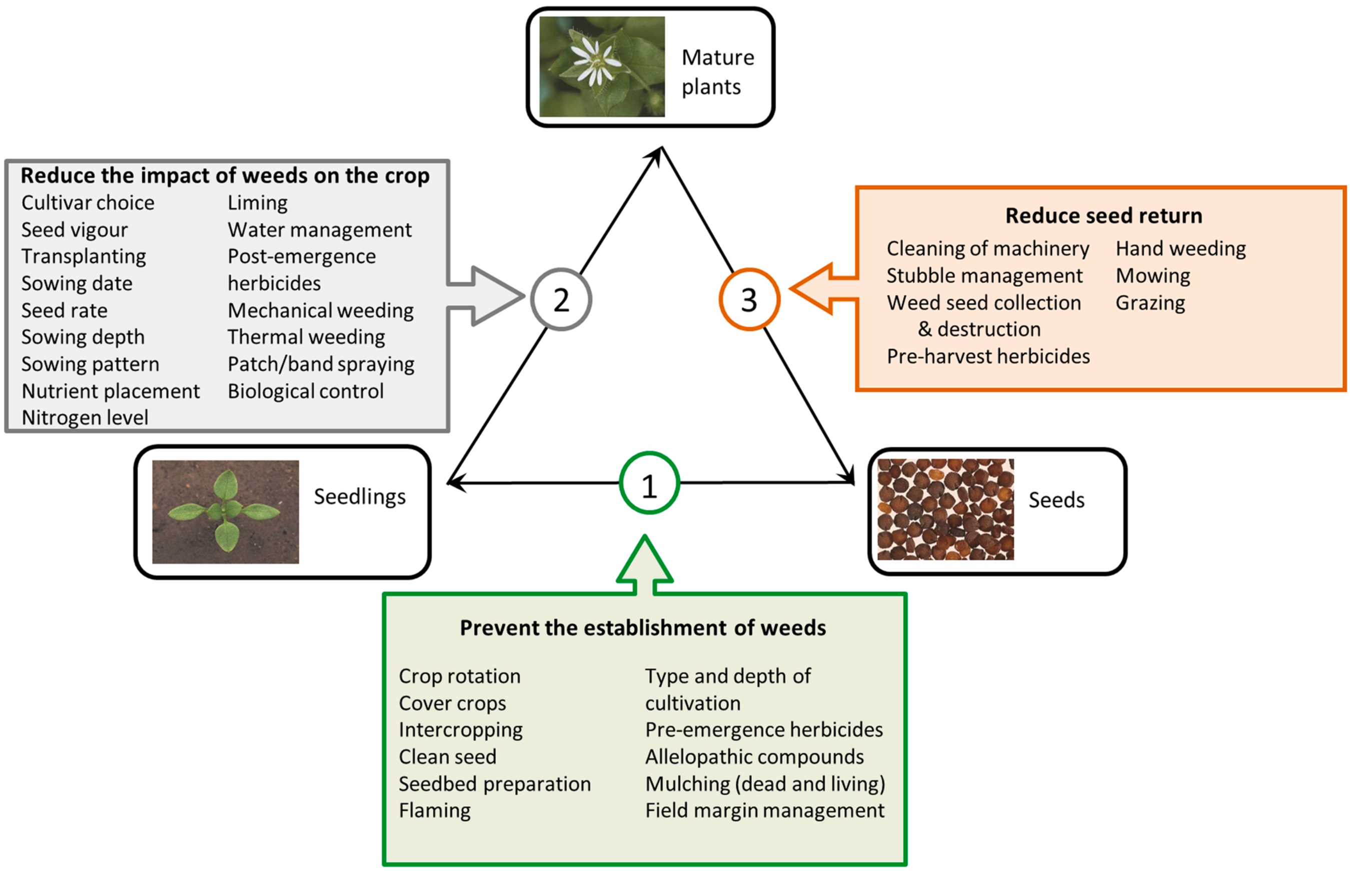

Fig. (1). Weed control tactics are mentioned where they are expected to have maximum effect on weed survival. Weed control tactics affecting weed survival at different stages of their life cycle.
(Adapted from Kudsk and Mathiassen et al., 2020).

3.1.1. Diversification in time

Changing the crop rotation is the main driver of cropping system diversification in time for both arable and horticultural crops. While the intrinsic properties of different crops (e.g. competitive ability) will affect weed communities directly, the main effect of changing a crop rotation will be indirect through changes in the management practices associated with the different crops such as sowing time and pattern, soil cultivation, fertilisation and harvest time. Diversifying crop rotation can also increase the options for mechanical or thermal weed control (if wide row crops are included), and it generally leads to a greater diversity of herbicide modes of action, reducing selection pressure for the evolution of herbicide resistance. Rotating crops changes the growing conditions for weeds between years or even seasons. Weeds that thrive in one crop will be less well adapted to the next crop or selected against by the management practices associated with the cultivation of the crop. The more dissimilar the crops in a rotation are, in terms of planting and harvest dates, crop phenology and structure, nutritional demands, and timing and type of weed management, the less likely it is to find single weed species dominating the weed community (Adeux et al., 2019; Liebman and Staver, 2001). A recent meta-analysis showed that the diversification in planting dates supported weed suppression more than crop diversification in terms of crop species (Weisberger et al., 2019). In terms of controlling most weed species, the most effective change in the crop rotation is the integration of a perennial crop, either as a forage crop (for example lucerne) or as a short-term pasture. Repeated cutting and competition from perennial crop species removes the opportunity for replenishment of the weed seedbank over several years, leading to large decreases in weed abundance in the following annual crop (MacLaren et al., 2019).

A second type of crop diversification in time is the inclusion of a cover crop between two cash crops. In this case, a subsidiary crop, defined as a crop grown for agroecological services (see also https://web5.wzw.tum.de/oscar/wiki/index.php/Subsidiary_crops and the leaflet summarising all crop diversification strategies and their definitions on the IWMPRAISE website https://iwmpraise.eu/publications/), provides soil cover in a period when the soil would otherwise have been bare or covered with the spontaneous vegetation. Cover crops are generally sown to provide ecosystem services such as improved soil fertility, suppression of soil-borne diseases and pests, reduced erosion, leaching and run-off, and improved soil structure, depending on the characteristics of the selected species. In addition, cover crops can benefit weed management by supressing germination in the following cash crop (Schipanski et al., 2014), but this needs to be balanced with the lost opportunity for depleting seed banks using a false/stale seedbed (see section on soil management).

Local conditions will determine the choice of weed management practices. In regions with high precipitation levels around sowing time, false/stale seedbeds may not be feasible while the use of cover crops with allelopathic potential may be a useful addition to other weed control measures. In this case cover crops need to be carefully selected to avoid allelopathic effects on the following cash crop. A review (Koehler-Cole et al., 2020) suggested that the most vulnerable phase for the following cash crop is during germination and early crop growth in laboratory studies, but yield reduction has rarely been reported in field studies. When looking at the weed suppression capacity of cover crops, a review (Osipitan et al., 2019) showed that the strongest effect is expressed during the cover crop cycle and the magnitude of the effect depends on cover crop choice (grasses suppress weeds better than broadleaved species), sowing rate (increased sowing rate provides better weed suppression) and sowing season (higher cover crop biomass and therefore better weed suppression in autumn-sown cover crops than in spring-sown crops). A meta-analysis from Osipitan et al. (2018) shows a significant weed suppression effect in the following cash crop during the first weeks after crop planting. Since this is the period in which the summer crops are most susceptible to competition with weed, any tactic that can decrease competition with weeds in this early growth period is relevant in a successful IWM strategy. For this reason, cover crop green manures or surface mulches would be interesting tactics for tilled and no-till systems respectively. Unfortunately, the meta-analysis does not provide a clear distinction between studies with and without soil tillage after cover crop growth and seeding of the subsequent crop. Limited evidence for cover crop weed suppression in the first weeks during the following cash crops in some years for some cover crop species is provided in Butler et al. (2016) and Campiglia et al. (2014). Curran et al. (1994) instead, found no evidence of increased weed suppression in the following cash crop after incorporation of the cover crop. Overall, there is limited evidence of a clear weed control effect in the first weeks of the following cash crop when comparing tilled arable or horticultural cropping systems with and without the use of cover crops. Cover crop choice and biomass production seem to determine the success of a legacy effect.

3.1.2. Diversification in space

Intercropping is the agronomic practice of growing two or more crops in the same field for at least part of their growing period (Wiley, 1990). Intercropping can involve multiple cash crops, but it can also consist of a cash crop and a subsidiary crop, more commonly referred to as a crop not harvested used as a living mulch. Intercrops can be categorised based on the spatial arrangement in which the crops are planted: row intercropping, strip intercropping, mixed intercropping and relay intercropping (see https://iwmpraise.eu/publications/ for a visual explanation). Living mulches are particularly effective for weed control as they limit the available space for weeds to grow and, in case of intercropping cereals with forage legumes, a positive effect on weed control was also noted post- harvest of the main crop (Amossé et al., 2013). A recent meta-analysis confirmed the potential value of intercropping as a weed management tactic: weed biomass was 58% lower in intercrops than in weaker weed suppressive crops (Gu et al., 2021). Weed suppression was largest in an additive design compared to a replacement design (Gu et al., 2021). Living mulches are increasingly used in orchards and vineyards to control weeds and prevent soil erosion. In these systems, and especially in the dry Mediterranean region, attention needs to be paid to control the living mulch biomass during the dry season to prevent competition for water between the living mulch and the crop (Garcia et al., 2020). Plant species that form a dry biomass in summer should be chosen, or alternatively cutting and mowing or superficial tillage near the crop can be applied to reduce competitiveness of the living mulch.

The termination of cover crops and living mulches can be done by incorporation into the soil before sowing or planting of the following crop, or the vegetation can be killed and left on the soil surface as a dead mulch depending on the tillage system (Vincent-Caboud et al., 2019). When a dead mulch provides a dense soil cover, it can have a significant weed suppressive effect in the following crop (Abou Chehade et al., 2019). The critical issues in successfully implementing these tactics are related to the difficulty in killing the vegetation, especially if one of the overall aims is to reduce the use of herbicides. The main challenges are the selection of cover crop/living mulch species and varieties that can be successfully killed before planting or sowing of the following crop, either mechanically, through natural senescence or frost. Mechanical interventions using machines such as roller crimpers, sometimes in combination with flaming, may help to killing the vegetation without the use of broad-spectrum herbicides such as glyphosate (Frasconi et al., 2019; Vincent-Caboud et al., 2019).

3.2. Cultivar choice and crop establishment –pillar 2

Two forms of crop-weed interactions can be distinguished: a) competition for physical space or competition for resources such as light, water and nutrients (Bastiaans and Kropff, 2017; Bastiaans and Storkey, 2017) and b) allelopathy where crops and/or weeds produce compounds (allelochemicals) that negatively interfere with weed or crop growth (Bertholdsson, 2005). Altering crop-weed interactions can reduce the negative impact of weeds on the crop and benefit crop yields. Several management tactics at the time of crop establishment can shift the balance of these biotic interactions in favour of the crop and can contribute to an IWM strategy. Choosing the right cultivar can potentially reduce the weed population without additional costs (Andrew et al., 2015) and recently this was confirmed in a study on the problems with weeds in the transition phase to no-till farming (Derrouche et al., 2020).

Selecting weed-suppressive and tolerant crops and cultivars is one way of reducing the need for direct weed control measures. Suppressive crop varieties will reduce the fitness of the weeds, while tolerant varieties will maintain high yield levels under weed pressure but will not necessarily reduce weed pressure and therefore could result in a build-up of the weed population (Hansen et al., 2008). Suppressive varieties should therefore be included in an IWM strategy as they help manage the weed population (Andrew et al., 2015). Crop traits that may be used as a predictor for weed competitive ability have been the focus of many studies. A range of traits have been found to be associated with suppressive cultivars: crop height (Christensen, 1995), early vigour (high early growth rate, expressed as a rapid emergence, early leaf area development, early crop cover) (Hansen et al., 2008, Drews et al., 2009, McDonald et al., 2010), canopy architecture (Andrew et al., 2015), root length, root elongation rate, number of root tips and total root length (Fargione and Tilman, 2006; Stevanato et al., 2011). However, competitive ability cannot be ascribed to a single trait and the importance of traits as an indicator for suppressive ability of a variety can vary between locations and years (Andrew et al., 2015). The option of mixing cultivars with contrasting phenotypes to reduce the available functional space for weeds has also been explored (Pakeman et al., 2020) with some evidence for reduced functional richness of weeds in barley cultivar mixtures. However, there were no significant effects of mixing cultivars on weed biomass. The balance of evidence seems to suggest that the potential for cultivars as a major tool in IWM is currently limited. This may be related to the low genetic diversity among modern, high yielding varieties and it would be beneficial to include suppressive traits in future crop breeding efforts. Nonetheless, a system that ranks cultivars based on their suppressive ability could promote the use of weed suppressive varieties.

Other management tactics, which can alter the crop-weed competitive relationship in favour of the crop, are altering the crop sowing date, crop density (seed rate), sowing pattern, sowing depth and the use of transplanted crops. Delayed sowing in winter cereals is a tactic that is used for managing grass weeds, e.g. *Alopecurus myosuroides* (Moss, 2017*). A. myosuroides* emergence peaks in September / October in the UK, coinciding with the time when most winter wheat is sown, and postponing sowing from September to late October/early November was found to reduce black grass populations on average by 50% (Lutman et al., 2013). Positive effects of postponed sowing on the management of other weeds in winter cereals have also been reported (Melander, 2003; Rasmussen, 2004). However, diversification of the crop rotation in time (Section 3.1.1) by increasing the proportion of spring sown crops in the rotation was found to be even more effective reducing *A. myosuroides* populations by 88% on average (Lutman et al., 2013). If economically feasible, vegetable crops such as onions and cabbage can be transplanted to give the crop a head start compared to the weeds (Weide van der et al., 2008). Increased seeding rates have proved to increase competitiveness of cereals to weeds under low fertiliser inputs conditions (Lemerle et al., 2004), and benefits of increased seeding rate have been observed in combination with wider row spacing and inter-row weeding (Melander et al., 2003; Kolb et al., 2012). Instead of widening the row spaces, Weiner et al. (2001) showed that wheat sown in rows with an inter-row space of 4 cm and a plant to plant distance of 2.5 cm (grid sowing) increased spring wheat yields by 9% and reduced weed biomass with 30%.

3.3. Field and soil management –pillar 3

Weed management tactics in this pillar are primary and secondary tillage (type and depth), dead mulching, water management, nutrient placement, stubble management and liming.

Primary tillage is traditionally performed at depths varying from 15 up to 35 cm (Kouwenhoven et al., 2002; Hakansson et al., 1998). Ploughing, especially mouldboard ploughing, is seen as one of the best ways of managing weed populations mechanically (Kouwenhoven et al., 2002), because it can bury weed seeds at a large depth from which they are unable to germinate and eventually will be decomposed. Optimum effects can be achieved by ploughing depths > 0.20 m (Kouwenhoven et al., 2002; Brandsaeter et al., 2011). Especially in the presence of perennial weeds, primary tillage with a mouldboard, chisel, disc, double layer, eco and powered rotary ploughs can provide a foundation for IWM (Gruber and Claupein, 2009; Hakansson et al., 1998; Brandsaeter et al., 2011). The type of tillage influences the distribution of weed seeds in the soil: seeds are in general more evenly distributed through the soil after treatment with a mouldboard plough and predominantly present in the topsoil layers after non inversion tillage (Scherner et al., 2016; Barberi and Lo Cascio, 2001). The contribution of ploughing (inversion tillage) to weed management varies with the type of crop rotation and weed species (Ruisi et al., 2015). Occasional or rotational ploughing may be an optimum tactic which effect will vary with crop rotation and weed species.

Secondary tillage operations are shallower and are used to prepare the seed bed and incorporate amendments such as fertilisers. When these operations are performed close to seeding, they will control any emerged weed seedling, but at the same time stimulate new weed seeds to germinate causing new flushes of weed seedlings during early crop growth. Repeated shallow tillage operations in combination with the elimination of the emerging seedlings can reduce weed densities (De Cauwer et al., 2019; Riemens et al., 2007). Emerging seedlings are commonly killed using non-selective herbicides but, if the objective is to reduce herbicide use, control of the emerging weed seedlings can also be achieved with superficial cultivation or with non-mechanical tools (e.g. flame weeding) to prevent new flushes of weed seedling germination and emergence (De Cauwer et al., 2019). When mechanical weeding tools are used, tillage should be more superficial than the first operation to avoid germination of new flushes of weed seeds (Lamour and Lotz, 2007).

Tillage affects the composition and functional attributes of the weed community in a field. Weed communities under conventional tillage tend to have a lower abundance of perennial species, a higher density of annual species (Melander et al., 2013) and a lower diversity (Armengot et al., 2016) than weed communities under reduced or no tillage. Hence, varying tillage type, timing and depth during the crop rotation may be used to regulate weed community density and composition and provide a foundation for IWM. However, the use of soil tillage as a basis for IWM and a way to reduce the dependency on herbicides may conflict with other goals such as increasing soil carbon sequestration, improving soil fertility or reducing fuel use. If these considerations are decisive for weed management, other tactics from this or other pillars will become increasingly important for IWM.

Plants compete for the resources they share (e.g. water and nutrients) during different stages of their life cycle (Holst et al., 2007). The response of weed species to changes in soil water level and nutrient availability is often different from the response of the crop plants (e.g. *Chenopodium album* and *Polygonum lapathifolium* in maize) (Krahmer, 2016). This knowledge can be used to optimise the growing conditions for the crop, while rendering them less suitable for the main weed species in the crop through the targeting of resources in time and space. Soil moisture is, next to temperature, one of the major environmental drivers controlling weed seed germination and seedling emergence in field crops (Chauhan, 2012). In other words: the strategic management of nutrients (fertilisation) and water (irrigation) can be a tool in managing weeds in both conventional and reduced tillage systems.

Several studies have addressed the interactions between fertilisation strategies and weed competition (Fracchiolla et al., 2018; Blackshaw et al., 2002; Cheimona et al., 2016). Many weed species may be more effective in taking up high levels of soil nitrogen than the crop reflecting the dominant ruderal strategy of weeds that is adapted to capture nutrients quickly in a short time frame (rapid growth and short life span). In a study of the response of 21 weed species, wheat and oil-seed rape (*Brassica napus* L.) to nitrogen fertilisation, wheat was among the least responsive species (Blackshaw et al., 2003). Hence inorganic fertiliser use can sometimes reduce crop yield if weeds benefit more than the crop and the use of inorganic fertilisers may have led to dominance of nitrophilous weed species in many European cropping systems (Storkey et al., 2021).

Timing of weed management tactics such as tillage operations, false/stale seedbed operations, chemical, mechanical and physical weed control applications also need to be optimised with respect to the main environmental conditions affecting weed communities such as soil moisture and temperature (Scherner et al., 2017). For example, secondary tillage to stimulate weed germination in a false/stale seedbed will be ineffective if conditions to break seed dormancy are not met (e.g. temperature, light) and conditions are not suitable for germination (e.g. sufficient soil moisture, temperature, light).

Weed suppression by dead mulching is a tactic that can replace or supplement tillage operations for weed management and is an option in zero till systems. A range of dead mulches can be used: cover crop residues (see Section 3.1.1), polyethylene (PE), organic based mulches such as rice and barley straw, and hay, absinth wormwood plants, black biodegradable plastic, paper (Haapala et al., 2014), spruce bark and cocoa husk mulches (Warnick et al., 2006). The efficacy of these mulches depends on their penetrability, resilience to weather conditions and thickness (Warnick et al., 2006). Most weed seeds germinate and emerge from the top 2.5 cm of the soil (Chancellor, 1964) while crop seeds are generally larger and are sown at a greater depth. Mulching can, therefore, inhibit weed emergence by creating a physical layer that is too deep for weed seeds to penetrate. The depth, from which seeds are able to emerge, varies with seed size; the larger the seeds, the deeper the depth from which a seed is still able to emerge. A practical example of dead mulch use, is sowing of carrots and onions under a layer of compost (2–6 cm deep) that reduces weed emergence by 69–85% (Achten et al., 2005). There is, however, a risk of inhibiting crop establishment through the same process and selectivity of the approach depends on appropriate management of the physical barrier.

Post-harvest treatments affect the weed population dynamics in a field. Mowing the stubbles or shallow post-harvest tillage prevents further weed growth, weed seed development and vegetative propagation in the soil (Melander et al., 2013). Multiple passes during this period can reduce perennial weed growth significantly. Again, there is a trade-off as stubble treatments may lead to increased survival of annual weed seeds after burial (Jensen, 2009, 2010). Key is to find the right combination between weed composition, the size of the weed seed bank, number of weeds and seed production in the stubble and the timing and type of the treatment to contribute to IWM with stubble treatment.

3.4. Direct control – pillar 4

Direct weed control tools are required when indirect measures applied to suppress weed establishment are insufficient to prevent crop yield losses and/or a build-up of a weed population that potentially can cause problems in the succeeding crops. Different types of direct control tools are available to farmers, such as chemical herbicides, microbial herbicides, mechanical tools, thermal equipment and electro weeders, and these can be further sub-divided based on their scale of operation (whole field, inter-row, intra-row, patch, and individual plants).

Herbicides are the mainstay of direct control of annual weeds and broadcast application of either pre- or post-emergence has been the preferred method of application from the mid-20th century until now. Perennial weeds are primarily controlled by glyphosate applied pre-sowing, pre-harvest or in the stubble (post-harvest). The number of herbicides available to farmers in the EU has decreased and the use of some of the herbicides still available has been restricted, in terms of e.g., lower doses or a limited application window. This, in combination with the fact that no new herbicide sites of action have been marketed since the 1980s (Duke, 2012), and none are expected in the foreseeable future, have spurred interest in alternative direct control methods (Kudsk and Mathiassen, 2020; Lamichhane et al., 2016). However, it is unlikely that the reduced availability of active ingredients and stricter legislation in itself will be sufficient to initiate a shift from chemical herbicides to alternative methods. Rather, it has been the rapid evolution of resistance to herbicides that has catalysed the development and uptake of non-chemical approaches (Hawkins et al., 2019). Should the ongoing controversy regarding the effects of glyphosate on human health and the environment lead to a ban on glyphosate, the options available to farmers for control of perennial weeds will be severely restricted (Kudsk and Mathiassen, 2020). Band spraying in the crop rows, e.g., in combination with inter-row cultivation, is one way of overcoming dose reductions. If no selective herbicides are available, inter-row application of non-selective herbicides may pose an alternative in combination with mechanical tools capable of intra-row weeding. Site-specific herbicide application/precision spraying also offers an opportunity for further reductions in herbicide use (Martin et al., 2016), but these technologies are still under development and has only recently become commercially available, e.g. the Blue River See & Spray Technology and Machine Learning (www.bluerivertecnology.com).

Mechanical weeding using harrows, inter-row cultivators or mowers are well-known methods that were widely used in farming before herbicides took over and remain the most common alternative to herbicide use for direct weed control. In recent years, inter-row cultivation techniques have developed significantly, and today machine-vision techniques can distinguish crop plants from soil and weed plants by a combination of light reflectance and recognition of crop row pattern (Fennimore et al., 2016). This allows for weed control very close to the crop row and with some inter-row weeders also for control of intra-row weeds (Fennimore et al., 2016; Kennedy et al., 2020). A next step will be to replace tractor-mounted inter-row weeders by autonomous machines (McCool et al., 2018). Currently, advanced inter-row cultivators are primarily being developed for high-value crops but, considering the progress made in inter-row cultivation in recent years, an obvious question is whether crops traditionally sown on narrow rows should be sown on wider rows to allow inter-row cultivation. This approach should consider possible trade-offs with optimum sowing arrangement (see section 4.3).

Other non-chemical methods are available to farmers. Thermal weed control by flaming, hot water/foam and steam has been extensively studied but performance is variable and thermal methods are expensive and require energy inputs that are 100–1000-fold higher compared to the energy requirement of tillage treatments (Coleman et al., 2019). Electrocution of weeds is currently receiving a lot of attention (Eberius, 2017). The method needs further development before it can be considered a viable direct control measure (Korres et al., 2018), but some of the preliminary results are promising (Koch et al., 2020). In contrast, microbiological control of weeds has had limited success and is mainly used against invasive environmental weed species (Watson, 2018). Currently, no microbiological products against weeds in agriculture are authorised in the EU.

Harvest weed seed technologies, where weed seeds are collected and destroyed during harvest, have received a lot of attention in recent years. Originally developed in Australia, the technology is now being studied in other parts of the world (Walsh et al., 2018). Efficacy depends on the percentage of seeds retained on the weed plants at the time of harvest, and this varies among weed species and years (Bitarafan and Andreasen, 2020). Harvest weed seed control reduces seed return to the soil seed bank but not the adverse impact on crop yield. Similarly, cutting seed heads that grow above the crop canopy can be an effective tool as well (Tavaziva et al., 2019).

Interestingly, increasing problems with herbicide resistant plants have necessitated the 'rediscovery' of the most ancient weed control method, hand weeding, as a method to minimise the build-up of populations of resistant weed biotypes (Inman et al., 2017).

3.5. Monitoring and evaluation- pillar 5

In contrast to a chemical herbicide-based weed control strategy, IWM involves a combination of options, each of which have been shown to deliver results that can be inconsistent and context specific. During the season and across years, evaluation and monitoring are essential for the farmer to establish the optimal weed management strategy and react to the efficiency of the applied tactics. A range of methods and support tools are currently available, and technology is developing quickly to enable IWM, including site-specific management on different levels. The farmer can use the history of the field to make a preliminary weed management strategy before weed emergence. Many farmers know their fields and the level of weed infestation, including the most common and troublesome weed species. However, not all farmers use this knowledge in an active and structured manner. Some farmers have weed maps stored on paper, while others use a digitalised field management system, where observations on a number of different factors can be managed. During the season when the weed population is visible, the farmer can use scouting plans, either on their own or in combination with a decision support system, to adjust the strategy to the actual weed situation. In general, manual scouting is not carried out systematically and there is limited literature available for manual scouting methods. Scouting strategies are important and influence the efficiency, which has been shown in peanut fields (Robinson et al., 2007). Manual scouting is, however, highly time consuming and requires knowledge of weed species in very early developmental stages. This can be a barrier for patch spraying and extensive use of decision support systems (DSS). Machine vision combined with image analyses through machine learning can take over the scouting task and several initiatives are under development with either airborne remote sensing or ground-based observations (Behmann et al., 2015). One important advance would be to develop ways of systematically capturing data on weed abundance and distribution so that the relative success of weed management strategies over time can be assessed at the field or farm level (Hicks et al., 2018).

Once a weed map is created, a direct control programme can be planned manually, or the information can be transferred to a DSS for further automation. Systems available are highly diverse in their approach and aim. Whereas some early DSS evaluated the need for weed control, others aimed at optimising the choice of herbicide, dose rate, timing and spraying equipment (Gonzalez-Diaz et al., 2020). Several new systems have been introduced, and some DSS are more focused on guiding the farmer than on producing a list of specific solutions (Sønderskov et al., 2020; Lacoste and Powles, 2016, Gonzalez-Andujar et al., 2009). Currently no DSS for farmers and advisors offers holistic solutions considering crop rotation, mechanical and chemical weed control, let alone all the tools depicted in Fig. 2. One future aim could be to adapt detailed research models to more user-friendly systems, which require a limited number of input parameters and the production of easy to understand outputs (Colas et al., 2020; Lacoste and Powles, 2016). Very few DSS are available for weed control in perennial crops and orchards, but DSS for IPM in apple and olive orchards have been developed

Fig. 2. Framework for the planning and design of holistic IWM strategies that require combinations of individual management tools appropriately selected from each of the five pillars of IWM: Diverse cropping systems, cultivar choice and establishment, field and soil management, direct control and the cross-cutting pillar monitoring and evaluation. This framework allocates all the options identified in Fig. 1 to one of the five pillars. It is unlikely that any one system will use all approaches, but the framework invites farmers and advisors to 'mix and match' based on the local environmental, agronomic and socioeconomic context and encourages a diversity of practices that target different stages of the weed life cycle.

and tested in Spain for identification of common diseases, insects and weeds (Gonzalez-Andujar, 2009; Mondino and Gonzalez-Andujar, 2019).

Evaluation of the applied tactics and the overall strategy is important to ensure efficient management strategies. The information on successful control and failures are equally valuable for future weed management. Farm management systems can help the farmer to keep track of the management, e.g. the Dutch FarmMaps system (https://akkerweb.eu/en-gb/) or the Danish CropManager system (https://cropmanager.dk/#/?cmredirect=https:%2 F%2 Fcropmanager.dk%2 F&currentLanguage=%22en%22). These systems allow farmers to collect all field-relevant information in one online system, including not only weed history but e.g., also graduated fertilisation and sowing maps.

In general, DSS work well for specific key pest, weeds or diseases. For entire communities or multiple pests, the number of parameters required, and the potential interactions become too complex to be able to make straightforward predictions. Instead of building DSS that predict or accurately describe system behaviour under different weed management scenarios, future DSS should guide farmers during the development of their IWM strategy based on the framework presented in Section 3.1.

4. Case study

The idea behind the IWM framework was used to design the IWM strategy for an arable cropping system experiment in the Netherlands, which was established in 2018. An eight-year rotation based on the IWM principles is compared with a conventional four-year rotation, where weed management is based on direct control with herbicides. The crops in the four-year rotation are potato, seed onion, sugar beet and spring wheat, all common crops in an arable rotation on clay soil in the Netherlands. Weed control is predominantly chemical. These crops were also included in the eight-year IWM rotation, but to increase crop diversification (pillar 1), the rotation was extended with winter cover crops (pillar 1, improving soil structure and soil coverage to prevent emergence and establishment of species such as *Stellaria media*), carrot (good mechanical weed control options, pillar 4), cabbage (late sowing date, pillar 2); possibilities for stale seedbed treatments, pillar 3) and an additional potato crop (for economic viability of the system, potatoes are an important cash crop in the Netherlands). Cultivars (pillar 2) with early soil coverage were chosen to improve competition for light (e.g. sugarbeet and cover crop varieties) and sowing pattern (pillar 2) was adjusted to enable mechanical weeding (cereal crops, onions) and seed rate (pillar 2) was increased (cereal crop and cover crops) to improve crop competition. With the diversification of the crop rotation through these additional crops, crop management is more variable during the growing season and growing conditions more variable for weed species (see also above 3.1.1). In both rotations the soil was ploughed, however, in the IWM rotation the main soil treatment was followed by stale seedbed treatment (pillar 3). Targeted control tactics (pillar 4) included in the IWM rotation were mechanical weeding (harrowing, hoeing, finger weeders), thermal weeding (flame weeding and electroweeding), mowing and herbicides, which were applied site specific in patches or with band spraying, depending on the weed density and crop. In the IWM rotation weeds were monitored visually (counts) to determine densities and the need for control (pillar 5), based on the growth stage of the weeds and soil conditions the most suitable weed control methods was chosen. Monitoring was not used in the conventional system to determine the need and type for direct control. Preliminary results indicate that weed management based on the IWM principles provided sufficient weed control with a significant reduction of herbicide dependence Table 1.

As well as being a demonstration of the principles of the redesign of weed management strategies and a platform for quantifying the agronomic and economic trade-offs, this experimental case study is also an example of the need for a new generation of cropping system experiments that integrate tactics over long time scales.

5. Concluding discussion

The European Union Framework Directive 2009/128/EC (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2009.309.01.0071.01. ENG&toc=OJ%3AL%3A2009%3A309%3AFULL) on the sustainable use of pesticides requires the application of eight IPM principles by all professional pesticide users: prevention and suppression, monitoring, decision making, non-chemical methods, pesticide selection, reduced pesticide use, anti-resistance strategies and evaluation. However, the implementation of the SUD is currently limited by the lack of effective tools for managing the increased complexity of IWM systems. Here, we convert the linear IPM principle approach to a more practical holistic approach. The scheme depicted in Fig. 2 is an attempt to make application of the holistic approach more manageable to farmers.

Table 1
Tools and tactics used in the IWM strategy from the five IWM framework pillars and the conventional reference weed management system for an arable cropping system on clay soil in the Netherlands.

Pillar of IWM framework	Tactic	IWM rotation	Conventional reference
Diverse cropping system	Length of rotation (years)	8 (potato, cabbage, carrot, cereal (spring wheat), grass/clover, sugarbeet, onion)	4 (potato, sugarbeet, onion, spring wheat)
	Cover crops	Yes	No
Cultivar choice and establishment	Cultivar choice	Yes, early soil coverage	No
	Sowing date adjustment	Yes, delayed	No
	Sowing pattern altered	Yes	No
	Seed rate altered	Yes	No
Field/Soil management	Seed bed preparation	Yes	No
Direct control	Pre emergence herbicides	Yes	Yes
	Post emergence herbicides	Yes	Yes
	Mowing	Yes	No
	Hand weeding	Yes	Yes
	Patch/Band spraying	Yes	No
	Mechanical weeding	Yes, harrow, hoe, finger weeding	Yes, hoeing
	Thermal weeding	Yes	No
Monitoring & Evaluation	Scouting	Yes	No
	DSS	Yes	No
	Sensing technology	Yes	No

5.1. Barriers to IWM uptake by farmers

Use of the five pillar holistic approach for weed management by farmers will contribute to the management of weed populations and reduce the farmers' dependency on herbicides. Some broad categories for barriers of IWM uptake can be outlined based on farmers' perceptions and experiences with IPM implementation 1) increased risk 2) lower cost-effectiveness 3) increased complexity and time consumption 4) constraints in access to markets, e.g. new crops 5) investment in new technology 6) limited evidence of efficiency 7) trade-offs with other parts of the system (e.g. soil erosion after mechanical treatment) 8) lack of framework for knowledge exchange and peer-to-peer learning among farmers 9) individual values and perception of farmers 10) insufficient support through policy instruments (Lefebvre et al., 2015; Hillock and Cooper, 2012; Liebman et al., 2016; Moss, 2019). Increased risk, increased complexity, time consumption, investments in new technologies and physical effects all relate to practical experience, knowledge transfer and financial constraints.

There is a learning curve for farmers, who want to implement alternative tactics and strategies. Many farmers mainly rely on their own experiences or that of neighbouring farmers (Jabbour et al., 2014). A study among UK farmers argued that the degree of IPM adoption is path dependent and that farmers are more likely to implement new IPM tactics, when they have already started using some other tactics in the past (Sharma et al., 2011). A recent study amongst arable farmers in the UK and Ireland found that 100% of the farmers implemented some IPM tactics. However, only 6% of the farmers had adopted more than 85% of the possible IPM tactics (Creissen et al., 2019) highlighting the opportunity to encourage the implementation of 'suites of tactics'. Full-time young farmers, or farmers with limited experience, are more likely to adopt IPM tactics (Sharma et al., 2011). This indicates that experienced farmers rely on their own experience and as they mainly have relied on pesticides, they stick to this strategy, because the risk appears high and they seek for an economic return for every crop, rather than assessing their success based on the long-term economic return of the entire cropping system. A farmer may have many concerns and will need to acquire new skills before an effective IWM strategy can be implemented on the farm. Especially, in the transition phase from a herbicide dependent strategy to an efficient IWM strategy based on advice from, or participatory collaboration, with other stakeholders, agronomic, socio-economic and knowledge barriers need to be overcome. This transition phase may also involve short to medium term increases in costs, and reduced profitability, which might require support from governments for additional investments or compensation for (temporarily) lost income.

From a scientific perspective, the many faceted aspects of barriers for IWM implementation calls for transdisciplinary research to address both the fundamental ecological mechanisms, the practical management strategies and the socio-economical aspects (Neve et al., 2016; Jordan et al., 2016). It is important to address the perception of low cost-benefit and increased risk, which requires providing evidence of long-term strategies, which maintain productivity and hence profitability and for governments to establish the framework to support this development (e.g. Adeux et al., 2019; Boussemart et al., 2013). Increased knowledge exchange and research efforts on IWM technologies are essential to show that it is possible to change the management system to the benefit of both the environment and human health (Colas et al., 2020; Lefebvre et al., 2015; Lechenet et al., 2017). This will also involve engagement with agronomists, plant pathologists and entomologists, who are developing recommendations for Integrated Pest Management (IPM), that may complement or conflict with some of the IWM approaches discussed above. For example, reduced tillage is generally perceived to be beneficial for natural enemies of crop pests but may lead to an increased weed pressure. Activities focussed on increasing familiarity of farmers and advisors with IWM tactics will contribute to an increased level of IWM adoption, since levels of familiarity with and adoption of IPM are correlated (Creissen et al., 2021).

One of the pillars of the IWM framework is monitoring and evaluation. The use of DSS can be viewed as a tool to mitigate the barriers for IWM implementation, but also a barrier in itself. DSS can be a way to communicate and exchange knowledge with farmers and advisors, and at the same time, the technological approach can be intimidating for some farmers or too time consuming. The developing technology in robotics and machine learning can be expected to decrease the time requirements to do proper scouting and monitoring, which is a major concern in a more tailor made weed control scheme. Some of the barriers for increased use of DSS are the same as for IPM in general, e.g. risk aversion, limited trust in technology or insufficient guidance availability. There is also a strong influence of the individual farmer's values and perceptions, which can be considered general for IWM as well as for the adoption of DSS. A Danish study on uptake of DSS showed that farmers could be grouped into three main categories: system-oriented, experienced-based and advisory-contracting (Jorgensen et al., 2007). The first group of farmers rely on many different sources of knowledge and they use this new knowledge in planning. They have a longer perspective than the other groups of farmers, and the economic evaluations include future multiplication of pests. The experienced-based farmers also seek new knowledge from a variety of sources, but only implement this new knowledge if it agrees with the personal experience of the farmer. The third group of advisory-contracting farmers typically run mixed farms and leave the decisions related to plant protection to an advisor (Jorgensen et al., 2007). Another study on end-users of DSS concluded that there are two types of situations, which call for different types of DSS: 1) guidance to improve an existing system or 2) full redesign of a system when reaching a dead-end, e.g. wide-spread herbicide resistance (Colas et al., 2020).

A cause for optimism lies in the increased adoption of precision agriculture and in the site-specific application of inorganic fertilisers. European farmers can now map their fields for soil properties, such as texture and available phosphorus, and adapt their management accordingly. A similar approach, making weed maps a standard tool for planning management strategies, should be encouraged for crop protection and offers great potential for reducing herbicide use. However, the potential of site specific measures will be higher if the other pillars of IWM are adopted.

Another barrier for uptake of IPM is that the concept of IPM can be difficult to communicate, as the interpretation of the term varies. It can be perceived as an extension of good agricultural practices with a focus on reduced reliance on pesticides, while others perceive IPM as a complex, long-term planning process for the whole farm. If single IPM tools are described, such as crop rotation or timing of crop establishment, many farmers can claim that they already consider this in their management decisions, but without naming it IPM. In order to move on and increase implementation in Europe, a more holistic and conscious interpretation is necessary. Commonly adopted good agricultural practices are part of an IWM strategy, but a more elaborate strategy must be implemented to actually comply with the requirement for IPM implementation and achieve long lasting reductions in pesticide reliance. The framework we present here can potentially be used as a simple guidance to transfer complex knowledge on IWM to farmers, or potentially even be used in gamification.

5.2. Regional approach

Typical rural landscapes in Europe are highly diverse due to the regional differences in drivers of land use typology and land use change. Regional differences in agro-environmental, political and socio-economic conditions have resulted in heterogeneous land use patterns and a wide variety of cultural landscapes (Jepsen et al., 2005). Although agricultural production is under pressure from physical and socio-economic challenges all over Europe, the responses of farmers in terms of land management changes depend on farmer typology and geographical region (Kristensen et al., 2016). Farmers in all regions will need to find new value chains and markets in order to value their products. In regions with limited agro-pedoclimatic restrictions to intensive agricultural production this will be easier compared to regions with sub-optimal conditions for agricultural production. If European agricultural policies are to benefit all farmers in Europe, the future of EUs Common Agricultural Policy (CAP) should provide guidelines for a common, sustainable European production system that values the diversity of farming scenarios within Europe. This approach is also reflected in the IWM framework that offers a long list of tactics that can be combined in a wide variety of IWM strategies based on the local constraints and drivers. Regions with highly specialised cropping systems may need to explore crop diversification. A survey among 946 farms in France showed that a reduced pesticide use had a neutral effect on productivity and profitability for the majority of farms, but it also showed that farmers with high value crops, e.g. sugar beets or potatoes, had a higher productivity and profitability following high pesticide inputs (Lechenet et al., 2017). The potential for pesticide reduction was, however, associated with crop rotation, yield potential and soil water capacity. In this scenario, crop rotation diversification should be considered, but should be built around key cash crops that have no specific management problems. To support this transition, the agri-food systems should open up to new products. On the other hand, regions with highly diversified crop production may need to focus more on local and high-value market opportunities to increase produce value. Overall, there seems to be a need for innovations in the agri-food systems connected to innovations in specific cropping and farming systems (Meynard et al., 2017).

The appropriate weed management approach will also partly depend on the macro-ecology of weed communities with some regions (characterised by lighter, less fertile soils) having an inherently more diverse, less competitive weed flora. At a smaller scale, in specific areas of fields (for example compacted headlands or corners) it will be difficult to control weeds without intensive herbicide use and these areas may be more appropriate for alternative land uses.

Therefore, solutions need to be developed locally, through a participatory approach including all stakeholders relevant for the local agri-food systems. This is the only approach by which new strategies that are relevant for local stakeholders can be developed. In France, a farmer cluster approach (Vereijken, 1992, 1999) was recently re-introduced to increase the uptake of IPM solutions by farmers (http://www.ecophytopic.fr/concevoir-son-systeme/presentation-du-reseau-de-fermes-dephy). This approach focusses on peer-to-peer knowledge transfer in a small group of 15–20 farmers from the same region. A 'facilitator', most often an advisor, guides the group in the discussion and in decision making. This approach takes into consideration the regional basis of IPM solutions and provide knowledge support for the farmers to ensure a successful holistic IPM approach. Working in small groups and linking up to other groups of similar farmers helps to identify some of the key barriers. The farmer cluster concept is currently being rolled out in other EU countries as part of the EU project IWMWORKS (https://www.ipmdecisions.net/about-the-project/ipmworks/).

5.3. Focus on redesign of weed management

The recent Farm to Fork strategy, calling for an overall reduction of 50% in the use and risk of chemical pesticides and 50% in the use of the more hazardous pesticides in the EU in 2030, has affirmed the ambition of the EU to reduce the reliance on pesticides. We argue that the framework we present here can be a useful tool to promote implementation of IWM in practice and consequently contribute to implementation of the SUD.

It is time to shift the current focus from the use of tactics from only one or two pillars of the IWM framework (increased efficiency or substitution of herbicides) to an operationalization of the use of multiple tactics from all pillars to redesign weed management strategies, thus moving on to the final step of the ESR-paradigm. The presented framework can aid as a tool for agronomists, applied scientists, farmers and advisors during their joint effort to redesign weed management strategies. Application of the IWM approach should help avoid herbicide resistance (HR) development. In the cases where HR exist, the IWM framework can help develop diversified weed management strategies able to eliminate the herbicide resistant weed population. For farmers that already have severe HR problems, HR can therefore become a driver for increased IWM uptake. As weeds are closely associated with the crops, the path towards IWM will contain many of the steps required to develop integrated pest management. Pest management, including IWM, is an exemplar for continuing active involvement to obtain sustainability, because agroecosystems will have to adapt to changing ecological and economic conditions to deliver both food and ecosystem services such as water conservation, carbon sequestration and pest control (Pretty, 2018). The ongoing glyphosate controversy reflects this challenge. Reduced tillage, in particular conservation agriculture, is being promoted as a cropping practice providing some of the above mentioned ecosystem services but due to the lack of soil tillage farmers depend more on the use of glyphosate than farmers practicing inversion tillage (Andert et al., 2018). A ban of glyphosate in the EU will therefore challenge farmers practicing conservation agriculture more than other farmers (Kudsk and Mathiassen, 2020), and changes to their current cropping system will be necessary to stay sustainable.

We emphasise the need to develop an IWM approach targeting weed communities, not only individual species. Our approach, based on five pillars, aims to manage and regulate the weed community over the whole cropping system, instead of a single season-single crop-single year. This holistic approach is equally important for soil-borne pests and diseases as it is for weeds. Where above-ground insect pests and diseases may be introduced in the field during the growing season, the propagules of belowground insect pests, diseases and weeds are often already present in the field. Measures and tactics applied in one year will affect the population development of these organisms in following years. The five pillars: diverse cropping systems, cultivar choice and establishment, field/soil management, direct control and the cross cutting action of monitoring and evaluation are nevertheless important for the management of both above- and belowground insect pests, diseases, nematodes and weeds. Crop diversification affects the population dynamics of all pest, although both positive as well as negative effects on insect and disease management have been observed (Ratnadass et al., 2012). (Lamichane et al., 2016) identified the combined use of cultural, physical and mechanical tactics, biological and chemical tactics, and the use of resistant varieties as a possible way to increase the effectiveness of crop protection. The adoption of the approach presented in this paper may be a step towards the development of new cropping systems with a reduced reliance on pesticides for weed, pest and disease management.

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