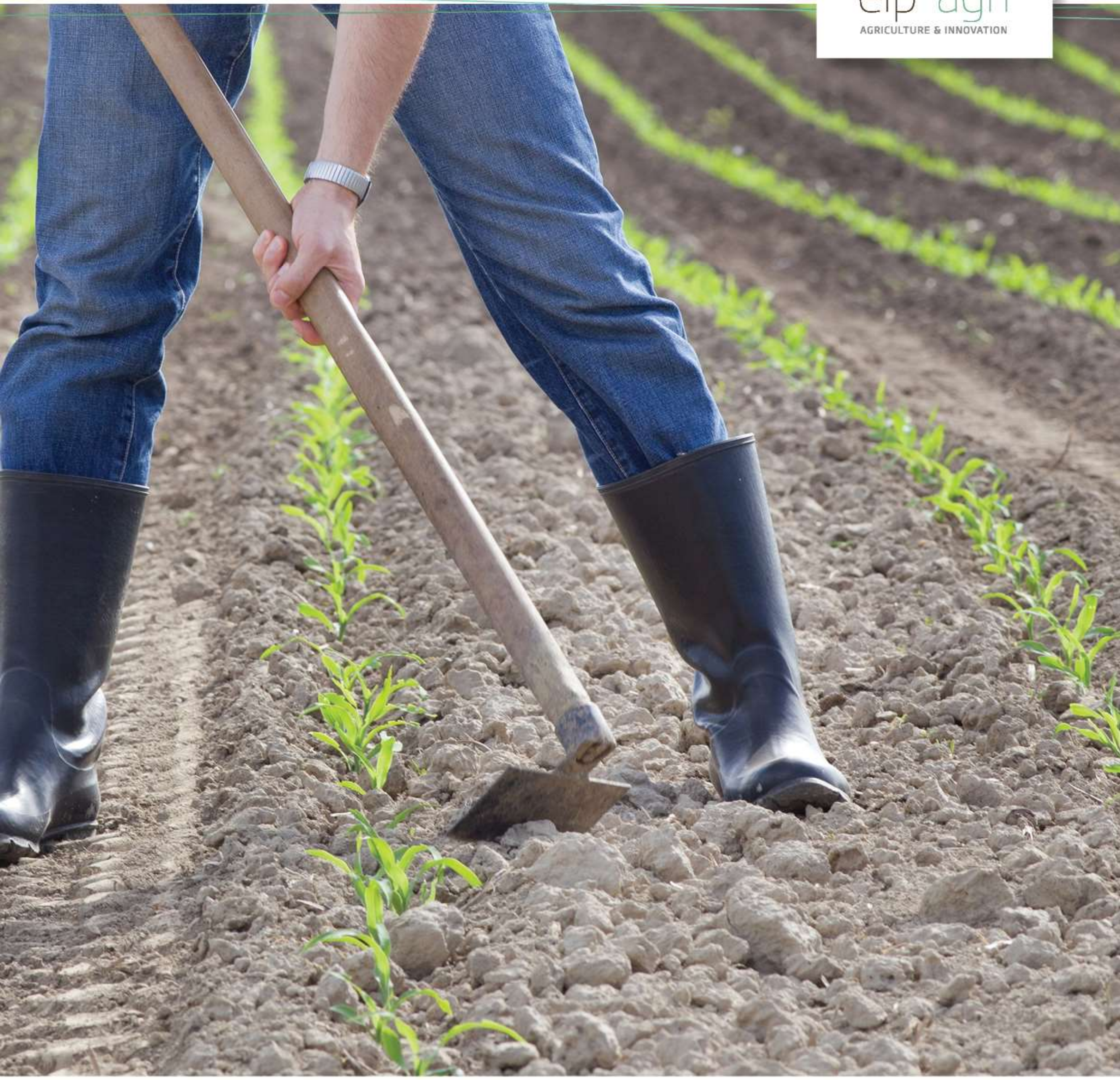
EIP-AGRI Focus Group
Non-chemical weed management in arable cropping systems



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Cropping System Design For Non-chemical Weed Management

Calha IM, Montull J, Jesenko T, Omon B, Chachalis D

INTRODUCTION

Once weeds become established, their interactions with crops and landscapes are in a continuous state of flux, depending on environmental conditions and changes in weed control practices. Their long-term management is never static; it relies on a combination of techniques and strategies. Basic knowledge of the biology of the weeds and their population dynamics is required to prevent and manage resistant populations or control perennial weeds. As pointed by Mortensen *et al.* (2000) "*we should go beyond the notion of regarding weeds as a problem that can be solved solely with herbicides to one that can be managed through a better design of cropping systems*".

The most intensive cropping systems are based on short crop rotations, meaning that major crops are frequently cultivated on the same land – e.g. wheat and maize – thereby reducing some positive agronomic services that could otherwise be provided by crop diversification – Figure 1. The simplification of cropping systems allows for the adaptation of problematic weed species, such as the development of resistant biotypes, the establishment of perennials and a general loss of biodiversity .

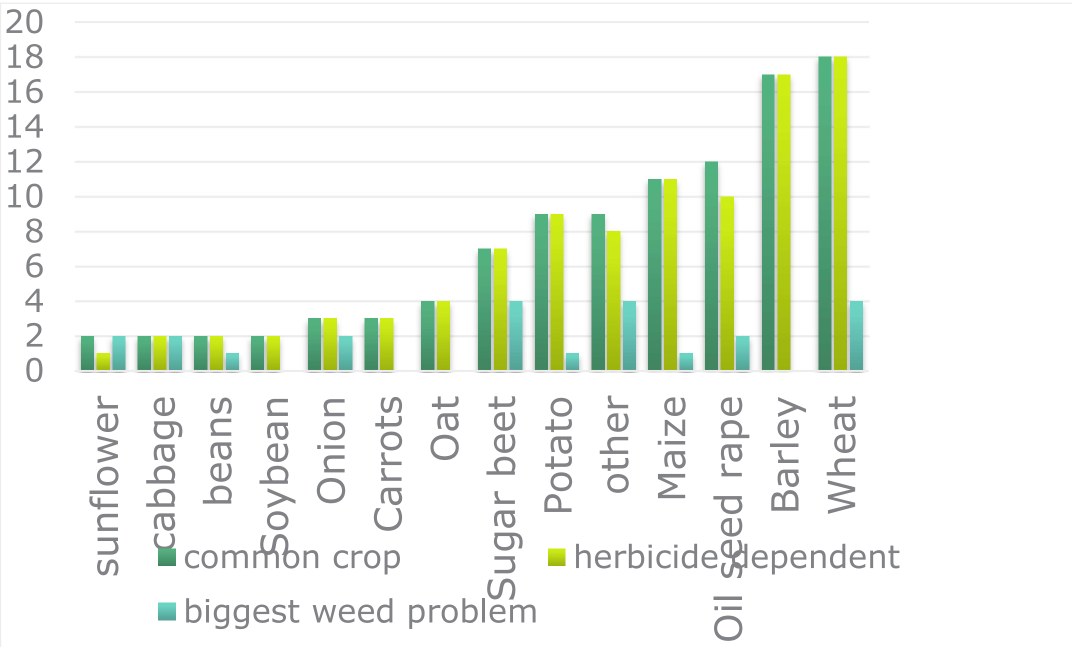


Figure 1 – Major crops in European countries and chemical dependence for weed control

Depending on edaphoclimatic conditions, available area, and affordable technology within a farming system, several options would be taken in consideration before designing a sustainable cropping system for weed management either an ecological (tillage based, biodiversity orientated), conservative (non-tillage, chemical based, environmental orientated) or integrated (rational combination of weed management practices, sustainability orientated) (Powles & Yu, 2010; Jordan & Davis, 2015; Benaragama *et al.*, 2016), namely:

- Knowledge of bioecology of weeds present in the field and/or in the soil seed bank;
- Crop rotation, duration in time and in space;
- Possibility of introduction of livestock 'in farm' or 'in region';
- Preventive and curative measures selected from a 'tool-box' and integrated in a synergistic way;
- Level of technology associated / available within the tool-box;
- Available Decision Supporting Systems (DSS) for selection of crops, type and time of intervention.

WEED BIOECOLOGY- Focus on Soil Seed Bank (SSB)

Understanding the weed function and its cycle is a critical component in non-chemical weed management systems (Fig.1). If such weed functions are incorporated into the design of complex arable cropping systems (fertilization, irrigation, plant protection crop needs), it becomes clearer that successful non-chemical weed management would be a system-based approach with great challenges.

Very few weed seeds from the seed bank actually emerge and produce a plant. Most seeds will die, decompose or be eaten even before germinating. Of those that germinate, some will die before becoming a mature plant (Gulden and Shirtliffe, 2009). When weed seeds remain on the surface, especially when there is sufficient residue cover for predators (no-till), they are exposed to predators, or attacked by pathogens (especially when buried). Another reason for seed death is lethal germination, ie., when seeds germinate and die before reaching the soil surface (**Figure 2**).

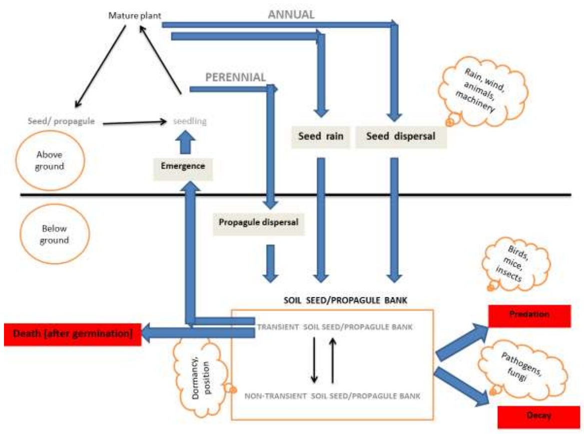


Figure 2. The conceptual framework of weed function based on a plant cycle; divided to above-ground and below-ground functions. It starts from seedlings to mature plants, then proceed to seed rain/dispersal

(annual weeds) or propagule dispersal (perennial weeds), and finally to soil seed bank (SSB). Some critical factors on key steps of the weed cycle are also included.

PREVENTIVE MEASURES – Controlling Soil Seed Bank (SSB)

Preventive methods are based on the key principle to disrupt the regeneration niches of different categories of weeds (annual, perennial) by not only preventing establishment of the competitive weed species but also by modulating weed flora towards less competitive weed species.

Understanding the factors impacting the dynamics of weed seedbanks can help in the development of integrated weed management (Menalled, 2008).

Reducing the input of weed seeds into the seed bank is the most effective way to reduce the weed seed bank. Weeds should be prevented to set seed in the field. Bringing new weeds into a field through different sources is also important (Buhler et al., 1997)

An important strategy to decrease soil seed bank is stimulating weed seed germination and eliminating the weeds seedlings before planting crops (stale seed bed). Predation and decay of weed seed also influences the losses of soil seed bank. Farmers should maintain habitats, for example mulch cover, for weed seed predators.

Different strategies are used to minimize inputs to the weed seedbank: killing weeds before they set seed; filling empty niches with cover crops; mowing fields after harvest; moving field borders; controlling weeds with herbicides and cultivation. Composting manure reduces the viability of weed seeds, minimizing weed seed inputs into the seedbank (Menalled, 2008). Crop rotation is also very effective for weed management. The mechanisms by which crop rotation reduces the size of weed seedbanks are related to the use of crop sequences employing varying patterns of resource competition, allelopathic interference, soil disturbance and variable weed management strategies. Proliferation of otherwise well-adapted weed species is reduced by these processes, which provide more diverse environment (Buhler et al.1997).

CULTURAL/ AGRONOMIC STRATEGIES – Focus on the farming system

Cultural and agronomic strategies are key in order to build up a non-chemical arable cropping system. In this context, work should be directed towards two main objectives: a) reducing weed emergence with an array of tactics like crop rotations, primary tillage/minimum tillage/no tillage, stale seed bed, cover/smother crops; and b) improved crop competitive ability aiming to reduce weed competition capacity, using competitive crops/cultivars, allelopathy, superior sowing systems, and fertility. As such, cultural weed control can be envisaged as a typical component of integrated crop management, where the *focus is not only on maximisation of crop production, but also the optimisation of resource use and the minimisation of external inputs* (Harwood, 1990).

The main tools to implement preventive strategies are crop rotations and the use of cover crops, including intercropping.

Rotations

Crop rotations, including winter cover crops, and intercropping can influence the quantity and the weeds species present in spring-planted crops. The previous cropping systems may influence weed pressure during the current growing season, depending on the type of crop produced, the herbicides used, and whether the weeds are controlled or not. Introducing different types of crops into the system can help disrupting the spatial competition between crops and weeds both above and under-ground. Crop rotation of annual and biannual or perennial crops can be effective, as well as Poaceae and Fabaceae crop rotations. These can also help to maintain a positive nitrogen balance and ensure a balance of cash crops and functional crops. Incorporating allelopathic crops to inhibit weed growth could also be considered. These crops are known to produce alelo-chemicals such as glucosinolates from Brassicaceae and benzoxazinoids from Poaceae; other crops have already been identified and used as bioherbicides (Macias et al., 2007).

Sustainable cropping systems require longer rotations, selection of a diversification of main and secondary crops to fulfill soil cover in time (cover cropping) and space (inter-cropping) along with the diversification of curative methods. According to Liebman and Davis (2000), four major ecological mechanism contribute to lower weed pressure in such farming systems:

- reduced opportunities for weed growth and regeneration through resource competition and niche disruption (Malézieux, 2012);
- weed species appear to be more susceptible to phytotoxic effects of crop residues and other organic soil amendments than crop species, possibly because of differences in seed mass;
- delayed patterns of N availability may favor large-seeded crops over small-seeded weeds; and
- additions of organic materials can change the incidence and severity of soil-borne diseases affecting weeds and crops.

Cover crops

Cover crops can be grown with the main crop (living mulches or smoother crops) or before and after growing season between two main (cash) crops (green manure and dead mulches). Including cover crops in crop rotation has many positive effects. Besides other benefits, such as preventing soil erosion and reducing nutrient losses, they have an important role in weed suppression (Creamer et al., 1996). Cover crops have short- and long-term weed control effect, due to direct competition or through other types of interference, primarily allelopathy (Singh et al., 2019). Cover crop during growing cycle suppress weeds with direct competition for light, nutrients and water. When cover crop residues are left on the soil surface as dead mulch or they are ploughed and hence used as green manure, physical, chemical and biological effects occur. Cover crop effects on weeds largely depends upon the cover crop species and management following cash crop, as well as on the weed community composition (Barberi et al., 2003)

Intercropping

Intercropping involves growing more than one crop in the same field at the same time.

The crops may be seeded at the same time (mixed intercropping) or they may be seeded at different times (relay intercropping or pasture cropping). Strip intercropping is a production system where different crops are grown in wide strips (usually the width of a seeder) in the same field.

Intercropping systems can be approached in two ways: a) two or more crops grown together with the goal of maximizing total yield from all intercrop components. Yield of each intercrop component is probably less than when it is grown as a sole crop, but the total yield is more than the sum of intercrop components grown separately; b) one main crop with one or more secondary crops inter-seeded for weed suppression, erosion control, nitrogen fixation, etc., with the goal of maximizing yield of the main crop. Many cover cropping systems would fall into this category as well (sometimes called smother crops) (Millar & Badgery, 2009; Lawes et al., 2014).Intercropping and cover cropping systems tend to suppress weeds better than sole cropping systems (Liebman and Dyck, 1993). However, their introduction in certain regions, such as the Mediterranean climate, may be limited by the lack of precipitation and long drought periods. However, studies by Dorado et al. (2017) and Luna et al. (2019) in Spain confirm the feasibility of these techniques provided that adequate pasture management such as irrigation is present to ensure proper installation and soil cover in the first year of pasture installation, and the need to cut pasture before sowing the main crop by high spring temperatures to reduce competition with the main crop.

If similar importance is attached to the intercrop as to the main crop, then there is nothing standing in the way of successful culture. Good intercrop stocks contribute to soil fertility through a multitude of characteristics. The biological activity of the soil is activated and contributes to the success of the main crop through improved soil structure (Haanke, 2014).

Selecting the appropriate crops and density for mating contributes to reduced infestation and systemic inputs. Another limiting factor is the reduction in area of the main crop and decrease in productivity. The assessment of its sustainability should be considered as a whole and not crop by crop, based on a multicriteria assessment: economic, social and environmental (Ribeiro et al., 2016)

There are also available tools aiming to assist with the decision making process that enables farmers, researchers and other stakeholders, to discover cover crop and living mulch species throughout Europe to assist on designing the cropping systems (OSCAR project, available at **www.covercrops.eu** and CATCHY cover crop project).

Competitive/tolerant varieties, including allelopathy

Improving crop competitive ability using allelopathy

The selection of varieties to be included in rotation or cover crops should be based not only on yield or disease tolerance but also on other positive characteristics for weed management. Examples are greater tolerance to weeds, greater competitive ability - such as higher tillering, higher straw or allelopathy. For instance, when using allelopathic rice varieties (*Oryza sativa*), there is a biochemical communication between crop-weed, where the presence of E*chinochloa* species enhances mamolactone production (Olofsdotter et al., 2002), showing that many of these interactions result from secondary metabolism to plants in response to biotic stress and that these metabolic pathways, regulated by quantitative genes, could also be included in breeding programs (Belz, 2007).

Although long-term weed management strategies have the greatest potential for impact on weed pressure in cropping systems, farmers also use many weed management options that can be implemented in a single growing season. Many of these options are agronomic practices that give the crop a competitive edge over weeds, such as crop sowing patterns or fertilization.

Crop sowing patterns (space, time)

The competitive ability of a weed relative to a crop, depends largely on the time of emergence. Ususally, early emerging weed plants are most competitive and more likely to survive and produce the most seed. According to population dynamic models, grain yield loss increased by about 3 % for every day *Avena fatua* plants emerged before wheat or barley (O'Donovan's , 1985; Cousens et al., 1987). However this may not always be the case, specially in weakly competitive crops. Late-planted spring crops and early –planted fall crops generally have fewer *A. fatua* plants than early-planted spring crops or late planted fall crops. Since not all fields on a farm can be planted at the same date, those fields with worst weed infestation could be planted last. The disadvantage of delayed planting is reduced crop yield or quality (Thill et al., 1994).

Besides seeding time, also drilling date influences weed emergence and the window for weed control – a key aspect for many management options. Intensity of crop competition is also influenced by drilling date. The interval between harvesting one crop and drilling the next is important, as a stale seed bed intervention can be used on emerged weeds. Delaying drilling increases the time available for weed control but it can reduce subsequent crop competitiveness, although increased seed rate can help compensate. The effectiveness of delayed drilling will depend on the germination period of the weeds (importante of knowledge of weed biology) and will be most effective for weeds with low dormancy and a clear autumn flush.

Before drilling, aim to kill all emerged weed seedlings using a combination of non-selective herbicide and cultivations. Cultivations however, especially in moist soils, will not kill seedlings and surviving plants will be larger and more difficult to control. Where possible, wait for a weed flush before drilling. Drill fields with low weed populations first, leaving those with high grass weed burdens until last (Moss et al., 2007; ABDH, 2018) .

Fertilization

While good plant nutrition is an important contributor to a vigorous, high-yielding crop, weed growth is also increased by nutrients. Some studies show that weeds can take up nutrients more quickly than crops in early growth stages and can actually accumulate higher concentrations of many nutrients than crops do, depleting soil nutrients and reducing crop yield (Blackshaw et al., 2003). Getting nutrients to the crop and not to the weeds is therefore an important tool for producing a vigorous and competitive crop.

Fertilizer placement and timing can be manipulated to increase the availability of nutrients to the crop and not the weeds. Fertilizer placement can enhance crop competitiveness and reduce interference from weeds. In general, banding fertilizer below the soil surface, rather than broadcasting, helps weeds seedlings get to the nutrients more quickly, increasing crop competitiveness

Different nutrients and fertilizer formulations require different treatment. For example, nitrogen is highly soluble in water and is rapidly moved away from its original placement. Therefore, banding nitrogen is a short-term measure and is most effective when done as close to seeding as possible. That said, it is important to note that placing large amounts of nitrogen fertilizer close to the seed may damage seed and thus reduce competitiveness. Adequate phosphorus levels are also important to rapid early development. Unlike nitrogen, phosphate is not very water soluble, and thus not very mobile. Therefore, phosphate fertilizer should be placed close to the seed.

In a Spanish study with spring wheat, applying P and N fertilizers separately did not affect crop biomass but increased Asteraceae weeds (*Chrysanthemum coronarum* and *Centaurea diluta*) and reduced *Lolium rigidum*'s. For summer weeds, only *Echinochloa crus-galli* showed an increase in biomass with P fertilization. A crop-weed interaction was confirmed that in the presence of certain species of Asteraceae instead of reducing crop yield they contributed to improve it ~~weeds wheat registered an increase in biomass~~ (Brenes et al., 2015). This response raises the question about fertilization and interactions in the soil not only at root level but also with soil microbiota, such as mycorriza. The presence of arbuscular mycorrhiza (AM) enhances nutrient uptake. Theextraradical mycelium (ERM) of mycorrhizas is particularly efficient as a propagule that even plant species usually not hosting mycorrhizal fungi can be colonized (Püschel et al., 2007). Under agricultural systems, ERM can develop on tolerant crops, cover crops (Kabir and Koide, 2000) or natural vegetation that grows before seeding susceptible crops (Brito et al., 2011). The benefits to nutrient uptake, especially accumulation of P, following AM colonization starting from ERM are well documented (Fairchild and Miller, 1988; Goss & de Varennes, 2002).

DIRECT METHODS

Physical Control

The main direct physical control methods include the harrowing, hoeing and flaming. Those methods, on one hand, are significantly less effective compared to chemical solutions (within crop cycle) and, on the other hand, would also promote new flashes of weed problems when mechanical weed control is done.

The physical control methods are also known to be less flexible due to their dependence on soil conditions (soil moisture) that might delay operations beyond critical stages for weed control. At the same time, their effectiveness is more significant in the long-term (weed escapes, weed seed production) and this promotes the build-up of the soil seed bank.

Technology advancements to improve the intra-row mechanical weed control such as high-tech torsion/finger weeders, harrows, hoes and flame weeders

Direct physical control methods should be fully integrated with the overall crop/weed management system, particularly with cultural practices such crop/cultivar choice, tillage operations, and other agronomic practices.

In row crops, intra-row weeds constitute a major challenge. In this case, research has mainly aimed at replacing laborious hand-weeding with mechanization. A number of research projects looking at direct physical control methods ? have focused on optimizing the use of thermal and mechanical weeding methods against intra-row weeds, such as flaming, harrowing, brush weeding, hoeing, torsion weeding, and finger weeding. New methods are now being the focus of research , including robotic weeding for row crops with abundant spacing between individual plants and band-steaming for row crops developing dense crop stands (Mellander et al., 2005)

The role of technology and precision agriculture for non-chemical weed management is the subject of a separate **mini-paper.**

Biological control

In 1971, bioherbicides were defined as substances intended to reduce weed populations without degrading the environment and could be distinguished between biochemical and microbial herbicides. Biochemical herbicides include microbial metabolites, plant-derived compounds, and certain naturally occurring chemicals; and microbial herbicides are those containing living or dead, plant-pathogenic or nonpathogenic microbes mixed in or not with their metabolites (Copping and Menn, 2000; Bailey, 2014).

Biological control by means of microorganisms that naturally co-habitateon crops is a promising alternative to the use of herbicides, provided that the biocontrol agent (BCA) is carefully selected and characterized, potential hazards for human health are fully assessed, and its identification is made possible. Among the several biotic agents that can be used in biological control, the phylloplane bacteria are an unexplored alternative, especially when compared to the rhizobacteria (Lindow & Leveau, 2002).

On a global scale, only 13 bioherbicides derived from micro-organisms or natural molecules are currently available on the market. The first bioherbicides were marketed in the 1980s. The market share of bioherbicides represents less than 10% of all biopesticides (i.e. biofungicides, biobactericides, bioinsecticides, and bionematicides) (Charudattan, 2001). Only a few countries have bioherbicides on their markets (Bailey, 2014): USA (4); Canada (3), Ukraine (1) and France (1) herbicide Beloukha (pelargonic acid).

The use of bioherbicides has been a feasible method of weed control in several cases. Development and use of bioherbicides can help to diversify weed control options and supplement other curative techniques. Bioherbicides could help increase both the efficacy of individual weed control techniques and the overall efficacy of the IWM systems to manage weeds: managing soil seed bank (Kremer and Kennedy, 1996; Wagner and Mitschunas, 2008); Increasing the efficacy of mechanical weeding (Melander et al., 2005); Increasing the suppression effect of crop cultivars; Terminating of cover crops; Managing herbicide resistant populations (Cordeau et al., 2016). Recently, more innovative programs have been developed in the use of bioherbicides, such as: cut stump treatments in which risk analysis is based on epidemiological rather than host range data; exploitation of niche markets in the leisure industry; and the use of mixtures of pathogens to control complex of weeds (Babu et al., 2003).

THE ROLE OF DSS IN NON-CHEMICAL WEEDING

Since weeds in winter wheat and especially in maize are of major concern, herbicide input for these crops has large impacts to the environment, but it also significantly affects cost efficiency for farmers. Experiences from Denmark, Germany and other countries have shown that farmers are willing to invest in decision support systems if these bring results in terms of cost efficiency. Therefore, projects like DSS-IWM (Design and Customization of an Innovative Decision Support System for Integrated Weed Management (https://ictagrifood.eu/node/36643)will develop a tool for Integrated Weed Management that combines economic and environmental benefits.

The DSS concept recently designed and validated in Denmark by IPM Consult Ltd (IPMC) as a 'proof-of-concept' has been designed on the basis of analyses of existing DSS for Integrated Pest Management (IPM). Recent research on decision supporting systems have shown that the herbicide dosage can very often been reduced without losing efficacy or even yield. Since the project will deal with maize and winter wheat growing in the partner's countries Denmark, Germany and Spain, DSS-IWM potentially covers a wide range of arable land in different climatic situations within Europe. Based on the planned structure and implementation, the results of DSS-IWM could be easily extrapolated to other European countries at a later stage.

The main results of the newly scheduled project will be the following: DSS-IWM

a) is ready for online use for weed control in maize and winter wheat,
b) provides reliable decisions and considers national conditions,
c) enables to consider thresholds for weed densities,
d) includes economic calculation on treatment costs,
e) offers mechanical options wherever possible,
f) facilitates herbicide resistance management,
g) is the basic platform for uses in other crops and countries.

All in all, the project DSS-IWM will create nationally adapted tool-boxes for more efficient integrated weed control in maize and winter wheat, two major crops in Europe. There is also a high potential for using DSS-IWM outside of the three participating countries. However, before the tool is ready for commercial use, the system has to be significantly improved.

Because of the well-known large interest in using different decision supports systems and because of the scheduled professional release of DSS-IWM, a long-term viable product can be expected in Europe. This new decision support system will not only help farmers, but will also support advisors in giving more accurate ? and efficient recommendations fully covering the IPM principles.

"Big data" and "augmented reality" would also play a role in DSS in the near future. Accuracy in big data analysis may lead to more trustful decision making, and better decisions can result in greater operational efficiency, cost reduction, and reduced risk. Challenges related to the use of big data include data ownership, analysis, capture, data curation, searching, sharing, storage, transfer, visualization, querying, and information privacy. Augmented reality is another technology that could be used to provide timely information ? on aspects of weed biology and management practices. For example, scouting of weeds could integrate weed identification with relevant information on potential yield losses, management options, and alerts about herbicide-resistant populations (Westwood et al., 2018).

INTEGRATED WEED CONTROL - Examples

Opportunities for integrated weed management are illustrated in this section with two examples, one herbicide-resistance case and a perennial weed in Mediterranean countries: ***Lolium rigidum* in wheat in Spain** and *Cyperus rotundus* **in hortoindustrial crops in Portugal**

Example 1 (annual weed) – Integrated control of herbicide resistant *Lolium rigidum* in extensive rainfed crops in Spain

Lolium rigidum Gaud. is one of the most common weed species in winter cereals in Northeastern Spain. Herbicide resistance has been growing since the mid 90's and exclusive herbicide use is not enough in many cases. A unique study focusing on the long-term effects of cultural control methods for combating herbicide-resistant rigid ryegrass (*Lolium rigidum*). The IWM strategies tested in this research included crop rotation, delayed sowing, and different herbicide programs such as PRE-emergence plus POST-emergence or POST only. The aim was to demonstrate to farmers different alternatives to control a *L. rigidum* population resistant to ALS and ACCase inhibitors herbicides.

Three different crops in rotation were treated with five herbicides each. In autumn wheat were tested Prosulfocarb, Clortoluron, Iodosulfuron + Mesosulfuron, Propoxicarbazone+ Iodosulfuron and Pyroxulam; spring barley was treated with Clortoluron, Beflubutamide + Isoproturon, Pinoxaden, Iodosulfuron and Tralkoxidim in the spring peas for grain were tested Prosulfocarb, Pendimethalin + imazamox, Propizamide, Fluazifop and Tepraloxidim. From the results obtained in this demonstration it was concluded that the effect of sowing in late January was enough to avoid applying herbicides against *L. rigidum* in the barley crop. The efficacies of herbicides used in peas were higher than those authorized in wheat and barley. In winter wheat, infestation of 90 plants/m2 *L. rigidum* justified, from the economic point of view, the herbicide treatment to control it. The yield loss in harvest produced by the infestation of 15 plants/m2 of *L. rigidum* in spring barley did not justify the treatment. In field pea crop, an infestation of 10 plants/m2 *L. rigidum* caused yield losses justifying an herbicide treatment. For the control of this *L. rigidum* biotype the best solution was to change to different crops like spring barley or field pea due to the different sowing time than the winter wheat.

Example 2 – *Integrated control of a perennial weed (Cyperus rotundus) in* hortoindustrial crops

Weeds are becoming major problems in horto-industrial cropping systems in Ribatejo (Center Portugal). Herbicide use represents a high value in framer's crop itinerary albeit increasing risks of soil and water contamination and loss of biodiversity. A operational group partnership – HORTINF – developed a project aiming to adapt existing technologies to the Ribatejo hortoindustrail cropping system with an IWM approach (https://ec.europa.eu/eip/agriculture/en/find-connect/projects/hortinf). Problematic weeds included perenial species such as nutsedge, in potato and tomato and also broomrape, a parasitic weed to industrial tomato.

Nutsedge *(Cyperus rotundus* L.) is a serious weed in intensive hortoindustrial farming areas in Portugal. These C4 plants are remarkably shade intolerant and suffer from diminished growth under closed canopies (Lati et al., 2011). Successful management strategies should concentrate on depleting existing tuber reserves and suppressing new tuber production (Stoller et al. 1972). A combination of different control methods seems to be the solution for nutsedge control in potatoes. Crop rotation with maize, potato and broccoli is frequent although only a long rotation with pasture of alfafa (*Medicago sativa*) for three years could reduce the production of nutsedge tubers. Vertical tillage combine with other practices, such as repeated mowing / clipping (Bangarwa et al., 2012; Ring Sella et al., 2018) followed by sowing of a high competitive cover cropping (Poaceae/ Fabaceae mixture) can be usefull in *C. rotundus* control. Stale seed bed at the end of potato crop cycle to enhance weed emergence, followed by application of non-selective herbicide – glyphosate (systemic) or pelagornic acid (contact). The latter requires sequential applications to be effective (41 % efficacy) however is not an effective season-long weed control agent, because it does not reduce underground tubers (Webber et al 2014). These techniques could be complemented with grazing of soil tubers by swines (biological control) after crop harvest (MacDonald et al., 2015). This strategy involves long rotation, animal husbandry, and complementary use of chemical control associated to stale seed bed technique. What hinders the implementation of longer crop rotations and how to overcome those constrains are questions that still need to be arisen.

CO-DESIGN OF NON-CHEMICAL CROPPING SYSTEMS

Re-design of farming systems invite us to think and act in a systemic way, integrating several scales and time steps, to consider the interactions between techniques as such, and between techniques and their socio-institutional contexts of application (Meynard et al., 2012).

The diversification of crops and productions can become compatible with farm specialisation, if the cohabitation, or even complementarity, between farms opting for different specialisations, is organised at territory level (Lemaire 2007).

A redesign of farming systems is necessary (Meynar et al., 2012) and co-design is a way to achieve it . Co-design of cropping systems requires that farmers and advisers, working as a team,~~? working in co-creation? ,~~ are involved in redesigning and implementing ~~the~~ new cropping systems in order to overcome previous gaps. Working this way also allows the farmers of the group to identify their own differences. This characterized differences allows farmers to learn from each other. The decision-schema is the articulation between "results to be achieved" and "combination of management functions" (resulting in technical "levels");The analysis of farmers differences focuses both on the way they are satisfied (Expected Results) and on the combinations of their techniques (Partial Effects).

A co-design approach requires (i) to clearly describe what is intended and expected by the cropping system (CS), and (ii) to describe the CS as a set of interactions between partial-effect practices. In fact, the interactions are as important as the techniques themselves (Sebillotte, 1990).

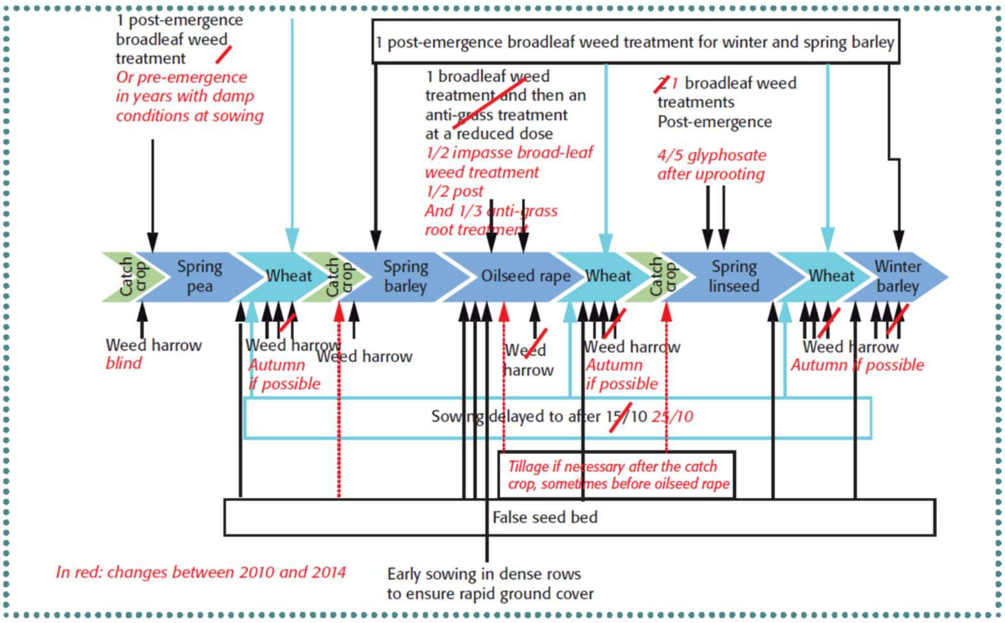
These interactions show the important added-value of the systemic design, particularly in the case of weed management. Starting with the permisse that the weed flora interacts with the crop, and that the multi-year system determines a competition at a time T, the resultant are ~~of~~ the successive interchanges in a multi-year period. In the case of weed management, the R level of redesign is becoming necessary everywhere. (Efficiency- Substitution- Re-conception (Hill and Mc Rae, 1995).

This approach allows to at least describe an initial situation, to understand how weed management ~~happens~~ evolves over a period of time. There is a certain inertia of the CS? (related to soil seed bank) which justifies looking at the cropping system trend over a long period time.

But the same approach can design an adjusted CS or a more unbalanced CS.

The first level of such co-design approach is rotation. Does this feature affect the reduction / increase function of the soil seed bank ? If yes, how: through the periods of preferential sowing and emergence, but also from cultivated species and their affinity for weed species that are often close to crop species, or finding conditions of development for others. Rotation also contributes to the functions of avoidance and attenuation.

The second level is the design of annual itineraries. At this level, all the control tools involved in weed management and having an effect in controling weed competition are described. It is also important to describe how each management practice works in practice. Chemical control tools should be described only after the other management techniques.



<u>Expect Input</u>

Tolerable presence of weeds up to the first zone above the crop

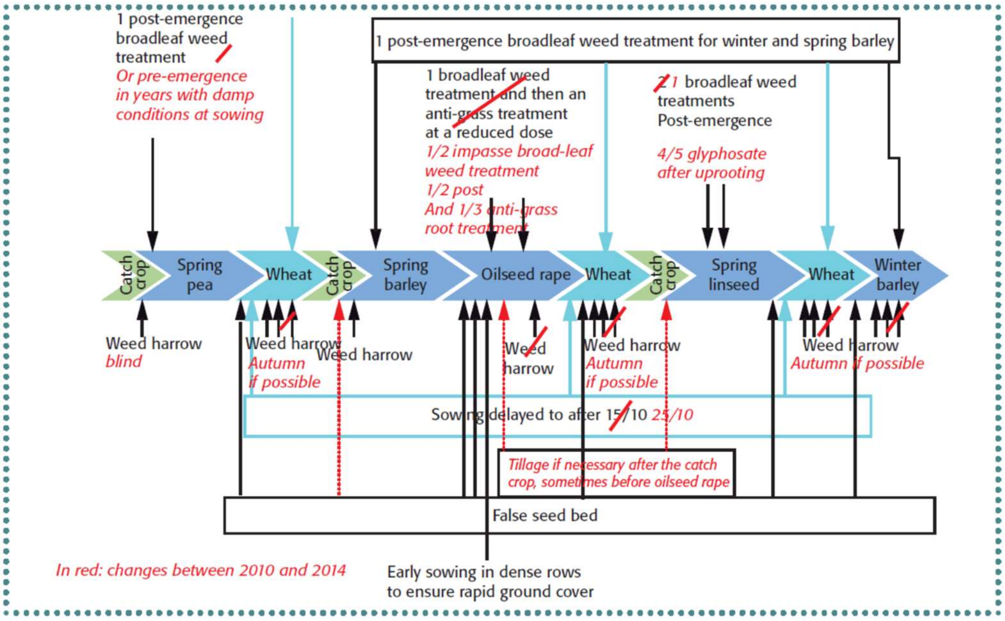


Figure 3 – Co-design of cropping systems - description of cropping system at two levels: planned rotation (long term) and annual crop (short term).

A future challenge is to develop shareable tools to redesign Cropping Systems (CSs) at EU scale, describing a typology of CSs highly representative of edaphoclimatic conditions and associated weed problems.

THE FUTURE KNOWLEDGE GAPS AND DEVELOPMENT NEEDS

Many questions arise when designing new cropping systems. For instance, spatial and temporal diversification of systems leads to different crop mixtures, new equipment and management of these systems and the interaction with other pests and diseases. It will be difficult for growers to adopt technology that is perceived as being costly, time-consuming or complicated (Shaner and Beckie, 2014).

What are the obstacles and incentives for farmers to adopt those strategies that cope with sustainable cropping systems and integrated weed management ??

A number of factors may hinder a broad introduction of cultural methods for non-chemical weed management through diversification of cropping systems. For example, issues related to technical implementation of IWM strategy concerning applicability, efficacy, reliability and compatibility among curative weed control measures. Other issues include conflicts that arise if cropping practices that are beneficial to weed management have adverse effects on other objectives (Bastiaans et al., 2008). Also the process of specialization of farmers, explained by the greater ease of acquiring technical control, the amortization of agricultural equipment and the organization of work with some crops in which the farmer specializes (Magrini et al., 2018). Lack of regional infractructures to support changes in cropping systems, such as new crops and produts, and markets for those new crops. For instance, long rotations with permanent crops , like pastures, requires local animal husbandry or industry (feed mills or pellets for alfafa; dairy infrastructures).

There are not only one possible cause responsible, but several, depending on region and farmer, concerning for example socio-environmental constraints, limited market oportunities, lack of knowledge or technology. Different farmtypes require diferente strategies. Feasibility of technologies depends on farm dimension, from small scale to large scale farmers. Farmers option between precision agriculture (curative methods) , conservation agriculture, agroecologic, based on preventive me and cultural methods. What are the keys factors that need to be adressed ? Table 1 summarises a list of knowledge gaps and research needs for the future.

<u>Table 1 – The future knowledge gaps and research? needs for sustainable weed management</u>

Weed biology and crop interaction

Limited information is available on the benefits of cover cropping for weed control in vegetable systems. Research is needed to determine appropriate cover crop species for greater weed suppression and limited phytotoxicity in vegetable production systems. More research is also needed on perennial weed responses to cover crops and conservation tillage systems (Saini & Singh, 2019).

New research should look at the needsin different countries and regions in order to understand 1) the influence of different tillage systems on weed seedbank dynamics for different type of weeds; 2) how to encourage the weed seed predation and decay; 3) The influence of soil microorganisms on soil seed bank; 4) Effects of different crop rotations on the weed seedbank; 5) Long-term experiments with integration of preventive and direct methods; 6) Simplification of methods to assess soil seed bank: with biomolecular probes; technology (x-ray) and automation (robots to collect soil samples).

Biological control

More research effort should be devoted to 1) New Sources of Bioherbicide Candidates; 2) Developing techniques for the cultural and genetic enhancement of bioherbicidal organisms; 3) Increase knowledge about the mechanisms underlying these effects . It is important to achieve consistent efficacy with biocontrol agents, as well as to evaluate potential impacts on human and ecosystem health; 4) Evaluate bioherbicides in field trials in different crops and different regions. At present, BCA efficiency is usually lower than that obtainable with chemical control. Bioherbicides should be assessed concurrently with other weed management techniques in cropping systems experiments. A better understanding of the ecology of field-applied antagonists may lead to an optimization of formulations, and time and mode of application, with beneficial effects on the level of protection obtainable; 5) Develop and evaluate formulations to improve performance and standardization of selected bioherbicides. Although there is a considerable number of candidate species that have been considered for this purpose, the major challenge to successful implementation of this strategy is the development of techniques to maintain consistent efficacy in field conditions.

Other constrains are a) Strict Legislation. The existing legislation concerning authorization should be simplified and be more flexible, taking in account that the concept of biopherbices is broad; b) Lack of Quality and Sufficient Quantities of Materials for Affordable Prices and c) Better cooperation should be established between research and BP manufacturers to put research results into practice.

Precision agriculture and robotics technologies

Technology advancements are needed to improve the intrarow mechanical weed control such as high-tech torsion/fingerweeders, harrows, hoes and flame weeders.

Direct physical control methods should be fully integrated with the overall crop/weed management system particularly with cultural practices such crop/cultivar choice, tillage operations, and other agronomic practices.

Specific crops need specific technologies. Although a wide range of single technological solutions exist, they are not always useful in practise. The technologies and machinery (equipment) are more developing for wider spread crops. Existing technologies and machines are not always effective enough, they are often too expensive. Especially small farmers have problems with cost-effective technology solutions.

Knowledge tranfer

Requires that farmers and advisers are involved and participate in all processes of development and implementation of solutions for those gaps. New aproaches are needed to encourage new decisions

An holistic approach not only at farmer level at but region level, particularly important in preventing the spreading of new weeds and introdcution of new tehnologies, could gather not only farmers but also other stakeholders, involving municipalities, operaters of roads, railways and other decision makers.

Adapted from Neve *et al*. (2018); Westwood et al. (2018)

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