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REVIEW ARTICLE

Integrated weed management systems with herbicide-tolerant crops in the European Union: lessons learnt from home and abroad

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ABSTRACT
Conventionally bred (CHT) and genetically modified herbicide-tolerant (GMHT) crops have changed weed management practices and made an important contribution to the global production of some commodity crops. However, a concern is that farm management practices associated with the cultivation of herbicide-tolerant (HT) crops further deplete farmland biodiversity and accelerate the evolution of herbicide-resistant (HR) weeds. Diversification in crop systems and weed management practices can enhance farmland biodiversity, and reduce the risk of weeds evolving herbicide resistance. Therefore, HT crops are most effective and sustainable as a component of an integrated weed management (IWM) system. IWM advocates the use of multiple effective strategies or tactics to manage weed populations in a manner that is economically and environmentally sound. In practice, however, the potential benefits of IWM with HT crops are seldom realized because a wide range of technical and socio-economic factors hamper the transition to IWM. Here, we discuss the major factors that limit the integration of HT crops and their associated farm management practices in IWM systems. Based on the experience gained in countries where CHT or GMHT crops are widely grown and the increased familiarity with their management, we propose five actions to facilitate the integration of HT crops in IWM systems within the European Union.

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Introduction

Since the introduction of triazine-tolerant oilseed rape (*Brassica napus* L.) in 1981, various conventionally-bred herbicide tolerant (CHT) crops (i.e. traditional plant breeding or bred through spontaneous mutations and mutagenesis) have been grown commercially worldwide, though never on a large scale.[1]. In recent years, there has been an increasing interest among European growers in CHT crops resistant to acetolactate synthase (ALS) inhibitor herbicides (i.e. imazamox). This renewed interest is primarily caused by the lack of effective herbicides for the control of congeneric weed species like *Ambrosia artemisiifolia* L. in sunflower (*Helianthus annuus* L.) and *Brassica* species in oilseed rape, as well as parasitic weeds like *Orobanche spp.* in sunflower. Genetically modified herbicide-tolerant (GMHT) crops were first cultivated in 1996; in contrast to CHT crops, the acreage of GMHT crops has consistently increased,[2] reaching 154 million ha in 2014.[3] An overview of herbicide-tolerant (HT) crops (both CHT and GMHT) grown worldwide is given in Supplemental Table S1.

The rapid adoption of HT crops in general and of GMHT crops in particular, and their associated farm management practices suggest that they have become an important tool for managing weeds. HT crops, to some extent, have changed weed management practices and made an important contribution to the global production of commodity crops. The rapid adoption of GMHT crops is generally attributed to low cost, simplified, more flexible and selective weed management options through the use of broad-spectrum, intrinsically non-selective herbicides (primarily glyphosate), a lower risk for crop injury, and their compatibility with no-till or reduced-tillage systems. In turn, simplification of weed management improved time utilization efficiency and

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contributed to increased farm size in the US[4] (Supplemental Table S2). HT crops and their associated farm management practices also enabled the control of several weed species congeneric to the crop. An example is weedy rice (*Oryza sativa* f. *spontanea*, also known as red rice),[5] which is considered as one of the most troublesome, difficult-to-manage and economically damaging weeds in cultivated rice.[6] Herbicide selectivity is generally based on the crop being able to metabolize and inactivate the herbicide more rapidly than the weed species. In the case of weedy and cultivated rice, no such difference exists due to their genetic similarity. With the introduction of imazamox-tolerant CHT rice varieties, effective control of weedy rice became possible.[6] Similar problems occur in other crops with sexually-compatible weeds such as oilseed rape and sunflower.[7] Another driver for the adoption of HT crops is that they support the adoption of no-tillage or reduced-tillage (conservation tillage) crop production systems. Conservation tillage systems contribute to reducing soil erosion and moisture loss, fossil fuel use, carbon dioxide emissions, nitrogen and pesticide leaching and improving soil structure.[8–10] The abundance of soil-dwelling carabid beetles and spiders has also been shown to increase in conservation tillage systems, as weeds provide a more favorable habitat for these predators, or due to more abundant prey, such as Collembola.[11–13]

Depending on the specific herbicide regime, the adoption of HT crops can pose a number of environmental and socio-economic challenges, one of which is to exacerbate herbicide resistance evolution in weeds. The use of a single herbicide over the landscape for an extended period changes the weed flora, and increases the selection of herbicide-resistant (HR) weed biotypes. HR weed populations have dramatically increased over the last 30 years, including those with multiple herbicide resistances, i.e. resistance to two or more modes of action.[14] Over 100 biotypes of weed species belonging to different families have been reported as resistant to up to seven herbicide modes of action; almost half of the cases have been reported in the last decade.[14] The increased selection pressure imparted by the recurrent use of the same herbicide mode of action causes changes in the relative abundance of weed species, and consequently, weed community diversity. Shifts in weed species composition occur due to their differential natural tolerance to herbicides and other weed management tactics, and/or because of the spread of HR biotypes.[15,16]

Glyphosate is the most widely used herbicide globally. Growers have rapidly increased glyphosate use over the past two decades with the advent of GMHT crops and the loss of glyphosate patent protection in 2000. Currently, 32 weed species have evolved resistance to glyphosate worldwide, many of which have been identified in the US in GMHT cropping systems. These weeds include but are not limited to *Amaranthus palmeri* S. Wats. *A. tuberculatus* (=*A.* rudis) L. *Ambrosia artemisiifolia* L. *A. trifida* L. and various *Conyza* and *Lolium* spp.[14,17] Cultivation of GMHT soybean in Argentina and Brazil has resulted in glyphosate-resistant (GR) populations of *Sorghum halepense* (L.) Pers. and *Euphorbia heterophylla* L.[18,19] The overreliance on glyphosate to control weeds contributed to the evolution of multiple-resistant weed populations.[20–23] Multiple resistances to ALS-inhibiting herbicides and glyphosate is also reported in *Conyza canadensis* (L.) Cronq.[24] In Europe, cases of *Alopecurus myosuroides* Huds. populations with multiple herbicide resistances have been reported in many countries [14] and in Australia multiple resistant *Lolium rigidum* Gaudin is the predominat weed problem.14]

Evidence from the USA confirms that where there is very intense selection pressure imposed by the frequent (if not exclusive) use of glyphosate accompanied by, a lack of diversity in weed control practices and no mandated herbicide resistance programs to delay resistance evolution in weeds,[25] resistance to glyphosate in weeds evolved and spread rapidly.[26–28] This, in turn, may induce modifications of growers' weed management practices through intensification of herbicide use and use of herbicides with less benign environmental profiles, with consequent adverse environmental effects.[29–32] In regions where GR weeds exist, growers have exacerbated this phenomenon by increasing glyphosate rates and application frequency which further increases the selection pressure on weeds populations leading to more cases of evolved glyphosate resistance.[27,33,34]

Diversification in crop systems and weed management tactics reduces the risk of weeds evolving herbicide resistance(s) and promotes biodiversity.[35] Therefore, the most effective and sustainable use of HT crops would be as a component of an integrated weed management (IWM) approach. IWM advocates the use of multiple strategies or tactics to manage weed populations in a manner that is economically and environmentally sound. The basic goal of IWM is to achieve effective weed control in a manner that provides sustainable economic benefits to growers and society, and minimal impact on the environment.[36] IWM prescribes the use of multiple tactics to suppress weed populations, and to prevent or delay herbicide resistance evolution. The incorporation of HT crops with current integrated approaches to weed management could help ensure their long-term sustainability.

In practice, the potential benefits of IWM with HT crops are seldom realized, as a wide range of technical and socio-economic factors hamper the transition to IWM. Here, we discuss the major factors that limit the integration of HT crops and their associated farm management practices as a component of IWM. Based on the experience gained in countries where HT crops are widely adopted and the increased familiarity in their management, we propose five actions to facilitate the integration of HT crops and their associated farm management practices in IWM systems within the European Union (EU) where currently only CHT crops are grown on a minor scale.

Overview of IWM measures, factors limiting their adoption in the EU and the role of HT crops

Increasing public concerns on the potential adverse effects of pesticides in Europe resulted in the development of new EU policies promoting the adoption of sustainable agricultural practices.[37] The EU Directive on the sustainable use of pesticides (2009/128/EC) aims to reduce risks arising from the use of pesticides in the EU by fostering a mandatory implementation of integrated pest management (IPM). According to this Directive, the adoption of eight principles of IPM is mandatory in the EU.[38] IWM is a component of IPM. IWM prescribes the use of multiple chemical and non-chemical tactics to suppress weed populations, and prevent or delay resistance evolution.[39] In this section, we briefly review some of the tactics that can be used within the framework of IWM, factors that hamper their adoption, and discuss how the access to HT crops is expected to influence their adoption.

Herbicide-based tactics

Herbicides are currently the backbone of weed management in intensive crop production systems.[40] In such systems, effective weed management without herbicides is inconceivable in the short-term. However, improvements and/or adoption of the knowledge and technologies of IWM can achieve large gains in herbicide reduction with consequential lower risks of herbicide resistance evolution. For example, weeds are more likely to evolve resistance to some herbicide sites of action (e.g. ALS inhibitors) than others.[40] Risks attributable to herbicide use can be reduced by scouting for weeds, integrating knowledge of weed biology and ecology, improving application technologies and improving herbicide regimes (e.g. tank mixes of post-emergence herbicides with different modes of action).[35,41] Therefore, the choice of suitable herbicides should also take into account other factors affecting weed resistance evolution such as the frequency, number, dominance and fitness of genes conferring resistance to an herbicide.

Herbicide rotations and mixtures can delay herbicide resistance evolution in weeds.[28] Rotation of effective herbicidal modes of action is the most widely implemented herbicide-resistance management strategy. This practice can delay the evolution of herbicide resistance (except for non-target site resistance which may continue to evolve under this strategy).[42] There is increasing evidence that the use of effective herbicide mixtures is a better tactic than rotating different herbicidal modes of action.[28,42] Yet, neither tactic is likely to prevent herbicide resistance to evolve in weeds, and therefore is not a permanent solution.

Applying reduced rates of herbicides may support a more efficient use of herbicides.[35,43] Several studies have demonstrated that this tactic can maintain effective weed control and sustain economically acceptable crop yields.[44,45] Conflicting results regarding success in using reduced herbicide rates may be due to a variety of factors such as spray volume, droplet size, adjuvants, temperature, humidity, light quality, soil moisture content, weed size and weed species.[44,46] Despite its potential effectiveness, legal factors present practical challenges to the implementation of reduced herbicide rates, as a person or organization recommending reduced rates may be held liable for problems arising from their use. In addition, the use of reduced rates nullifies the guarantee of product efficacy provided by herbicide manufacturers.[47] However, it has been shown that reduced herbicide rates within an IWM system delayed target-site resistance in the soil seed bank of *Avena fatua* L.[48] Sub-lethal herbicide rates can select for non-target site resistance, which is believed to be quantitatively inherited through accumulation of minor genes.[49] However, use of reduced rates is not necessarily synonymous with sub-lethal effects. Weed species differ in their susceptibility to herbicides, and a low rate of one herbicide may be more effective than a full rate of another herbicide. Similarly, a low rate applied under optimal conditions may be more effective than a full rate applied at sub-optimal conditions.[43] As HT crops, in most cases, are tolerant to highly effective and broad-spectrum herbicides, it is likely that the adoption of HT crops will promote the use of reduced rates at least of ALS inhibitors in imidazolinone-tolerant (Clearfield®) crops.

Crop rotation

Crop rotation (i.e. temporal diversification) is very effective for managing weeds. Unlike monocultures, crop rotation can favor a more diverse composition of weed communities rather than those dominated by one or few weed species. Crop rotation allows alternative weed control strategies to be used, and enables alteration of patterns and timings of soil disturbance, light transmission through the crop canopy and natural enemies living in the crop, thereby diversifying the selection pressures on weed populations and making it ecologically more difficult for one weed species to dominate a weed community. As crop rotation and weed control strategies often interact,[50] diversity in crop system (which includes both the crops grown in rotation and the associated farm management practices) represents the best practice to mitigate risks related to herbicide resistance.

Despite several benefits, diverse crop rotations are not widely adopted,[51,52] as they can be difficult to implement. The benefits resulting from their adoption may only become apparent in the long-term. Moreover, the adoption of crop rotation will inevitably be hampered by market-driven production strategies (e.g. current demands for biofuel encouraging American growers to grow maize in monoculture at the expenses of soybean, rice and cotton). Moreover, to remain highly competitive in today's global commodity markets, growers need to specialize, limiting their activities to the production of a single or few closely related crops. The efficiency gained by specializing (e.g. using the same planter, harvester and marketing infrastructure for all crops) have led to the wide adoption of monocultures. For example, three crops (maize, soybean and wheat) cover more than two-thirds of the arable land in the US.[53] Other limiting factors are the lack of markets available for a new crop introduced in the rotation and/or low cost per unit product during selling, the lack of suitable herbicide options for all rotational crops in the crop rotation and the necessity to implement weed management systems that are in tune with other pest management measures.

The ownership of arable land is another factor limiting the adoption of diverse crop rotations. In Canada, over 40% of growers rent or lease land,[54] and usually manage it only for short-term duration, which can negatively affect long-term sustainability. The same applies to US growers. For example, in Iowa, a major maize- and soybean-producing state in the Midwest US, over 50% of farmland is rented.[55] In many European countries such as Denmark and Romania, arable land is rented to growers for only a few years. In Denmark, it has been estimated that up to 25% of the land is handed over to another tenant every year (Jensen, pers. comm.). Consequently, growers make decisions based on short-term profits, and therefore rarely consider long-term benefits.

Herbicide-tolerant (HT) crops will provide European growers with more effective herbicide solutions than currently available, enabling them to control a broader spectrum of weeds. Thus, it can be envisaged that access to HT crops and their associated farm management practices will incite some growers to neglect crop rotation as a weed management measure, as this may no longer be a prerequisite to achieve effective weed control. In addition, re-cropping restrictions due to herbicide residue in soil may limit cropping options in the following year.

Cover crops and intercropping

Cover crops compete with weeds for space, light, water and nutrients,[56] and provide a suitable habitat for organisms that feed on weeds.[57] In addition, cover crop residues that remain on the soil surface as mulches have the potential to suppress weeds by reducing light transmittance, soil temperature [58] and by releasing allelochemicals.[59]

The adoption of cover crops also presents some challenges such as extra time requirements for its sowing when time (labor) is limited, additional costs associated with the purchase of seeds, their sowing and termination, reduction of soil moisture, possible build-up of diseases, difficulty to incorporate in the soil with tillage and delay of crop seed germination.[60–62] It is not envisaged that cultivation of HT crops in Europe will have any separate impact on the adoption of cover crops.

Significant benefits can be obtained in terms of weed control when a proper combination of crop species is grown together for spatial diversification.[63,64] Liebman and Dyck [64] suggested that intercropping offers weed control advantages over sole crops in two ways; they (i) suppress weed growth through competition and allelopathy and thus more effectively use available resources at the expense of weeds, and (ii) provide yield advantages either using resources that are not exploitable by weeds or using converting resources to harvestable material more efficiently than sole crops.

Despite the advantages of intercropping, growing two or more crops simultaneously on the same field leads to more complex crop management and possible additional costs that may restrict their use by growers. In the case of HT crops, applying two different weed management systems on a single field may not be practical, meaning that the chosen crops should be tolerant to the same herbicidal active substance. If crop choices or timing differences in crop life cycles are not managed properly, then the two crops can compete with each other for water and nutrient resources, which may have negative effects on crop yield. The complexity of intercropping can make a given cropping system more vulnerable to environmental stresses.

Tillage

When tillage is used in conjunction with other cultural tactics such as cover crops and crop rotations,[50,65] it can markedly reduce weed population densities. Overall, under European conditions, total weed population density and herbicide use tend to be lower under conventional tillage compared to reduced tillage systems, especially for perennial weeds that are markedly decreased under conventional tillage systems.[66,67] In-crop tillage has more potential to directly replace some of the post-emergent herbicides used, though tolerance to in-crop tillage varies by crop type and growth stage.[35]

Greater fuel use, erosion, greenhouse gas emissions and loss of water from soils are the risks of conventional tillage. No or reduced tillage adoption has been associated with HT crops.[68,69] It should be emphasized that no-tillage systems can also be viewed as part of IWM, as weed seeds left on the soil surface have a higher mortality rate, partly due to predation. Moreover, crop residues left on the soil surface can further suppress weed growth.[70]

Use of competitive crop genotypes

The cultivation of competitive crop genotypes (rapid germination and emergence, vigorous seedling growth, rapid leaf expansion, rapid canopy development and extensive root systems) is a potentially attractive option for IWM, as their use does not infer additional costs. For example, crop genotypes with high competitive potential have been identified in cereal crops.[71] The use of competitive plant genotypes alone can result in a 50% reduction in recommended levels of herbicides in wheat.[72] The adoption of HT crops will most likely reduce the focus on crop competiveness; due to the availability of effective herbicidal active substances for weed control such as glyphosate, and breeders will focus on other properties such as yield potential and disease resistance.

Biological control

Biological control aims to suppress weed populations below levels that cause economic injury instead of controlling them. Westerman et al. [73] showed that predation by opportunist invertebrates can substantially reduce the weed seed stock on the soil surface ("biological weed control" as ecosystem service).

While there have been a number of successful biological control programs against crop weeds, biological control of weeds presents a range of challenges, including economic feasibility, effectiveness of the control agents, statutory and regulatory constraints for the registration of products, technological constrains in developing bio-herbicides, environmental constrains and difficulties in utilizing pathogens and herbivores as biocontrol agents.[74] In Europe, the procedure for the registration of a given biocontrol agent is time-consuming and resource intensive, and biocontrol agents do not occupy a sizable share of the market.[75] On the other hand, because many European weeds are native the identification of classic biocontrol agents is limited.

The potential impact of HT crops on biocontrol agents could be negative. For example, in arable crops, the most obvious targets for a biological control agent are perennial weeds, but the interest in biological control agents for perennial weeds would likely be reduced for GMHT crops. In contrast, research [76,77] has shown that sub-lethal doses of glyphosate can work in synergy with microbial biocontrol agents as the former temporarily stops the growth of the weed allowing time for the latter to establish and inhibit growth.

Mechanical weeding

Depending on soil characteristics and conditions, mechanical weeding has proven effective on a range of crops. "Intelligent" weeders that offer more advanced ways to control weeds without causing any damage to the crop are under development.[78–80] Therefore, the inclusion of innovative technologies, including advanced sensing and robotics, in combination with new crop systems, might lead to a breakthrough in physical weed control in row crops resulting insignificant reductions, or even elimination, of the need for hand-weeding. Inter-row cultivation and band spraying with an effective herbicide in a HT crop could potentially reduce the risk of HR weeds to evolve. However, mechanical weeding requires greater fuel use, is more time consuming, and may result in more soil erosion, greenhouse gas emissions, loss of water from soils, and cause adverse effects on the flora and fauna if not applied correctly.[81]

The adoption of HT crops can be expected to reduce the interest in mechanical weeding. First, HT crops will provide European growers with effective chemical solutions that are more cost-effective than mechanical weeding provided that growers succeed in delaying evolution of herbicide resistance. Second, HT crops tend to promote conservation or reduced tillage systems that are less conducive to mechanical weeding.

Other tactics

A number of other non-chemical measures can be integrated into IWM for effective weed suppression/management, such as the manipulation of crop seeding date, flaming, harvesting and destruction of weed seeds, management of fertilizers, the use of certified weed-free crop seeds, etc. Several studies have reviewed their advantages and limits,[4,35,82] and these are therefore not considered further here.

Action points facilitating the transitions toward IWM with HT crops

Based on the experience gained in countries where CHT and GMHT crops are widely grown and the increased familiarity with their management,[83] we propose five action points to facilitate the transition towards IWM with HT crops.

Education programs to maintain and improve knowledge of weeds and their management

The occurrence of HR weeds is imposing additional changes in weed management, forcing growers to add more diversity in their herbicide programs, primarily through additional pre-emergence herbicides that provide residual control. Growers, farm managers and advisors will need access to education describing implementation and integration of weed management practices, which may include diversification of crop systems, tillage, cover crops, stale seed beds, zero tolerance for weed escapes in some crops, and most importantly, HR weed management strategies. Moreover, monitoring practical experiences of IWM implementation by growers is paramount to identify factors promoting or hampering the successful uptake of diverse weed management practices and how implementation by other growers could be facilitated. Similar to the US and Canada, information describing and supporting the adoption of IWM by growers is needed in Europe. Maintaining focus on multiple weed management strategies would incite EU growers to consider IWM when growing HT crops.

Weeds can be managed by disrupting their life cycle, but this requires an improved knowledge of their population dynamics. To this aim, several studies since the mid-1990s have called for more research in the area of weed biology and ecology.[84,85] However, devising IWM strategies and tactics that address a diversity of weed species with a diversity of life-history traits is a difficult, but manageable goal. Due to this diversity, robust systems that require ecological insight of multiple species are needed.[86] If weed emergence patterns, length of developmental stages, fecundity, dispersal mechanisms and persistence of weed seed in the soil seedbank (i.e. weed population demography) are well-understood, then practitioners can devise a suite of strategies targeting the life stages most sensitive to management.[82] However, the limited knowledge on weed biology and ecology available to date is merely descriptive with poor information on the mechanisms of weed responses to various production systems.[46] Therefore, more research is needed to fill this knowledge gap.

Prior to the adoption of GMHT crops, weed control required a higher level of knowledge of weed and weed control options.[51] However, the availability of glyphosate on the market simplified weed control, and eroded the growers' knowledge required to implement diverse weed management programs.[4,51] In the US, long-term reliance on GMHT crops led to less expertise in weed management.[51] According to Swanton et al.,[87] IWM is a knowledge-based system that consists of several components including the effect of treatments/tactics on weed populations, weed growth and their development stages, and the critical period for applying control tools. However, both human expertise and financial support dedicated to the crop protection sector in the EU have declined.[88] This is especially true in the area of advisory services to growers as this advice may influence growers' decisions on the possible implementation of sustainable crop management practices. Paradoxically, the increasing occurrence of HR weed populations worldwide and the decreasing availability of effective herbicides will inevitably require more knowledge, planning time, cost and risk by growers than in the past.[89]

Revision of current stewardship programs

Stewardship programs may include both mandatory and recommended practices.[90] Growers need sufficient information, so that they understand the importance and rationale for IWM programs and the need to adopt best management practices (BMP). However, available information does not necessarily translate into an increased adoption of BMP, as there is usually a gap between evidence-based BMP and current practice. However, there is an increased need of information (e.g. multi-pronged approach, including strengthening monitoring programs, development of BMP on-farm demonstrations, grower/advisor education, awareness of longer term risks, etc.) in those situations where HR weeds are most likely to evolve. Product stewardship programs, technical guidelines and label recommendations, as proposed by the registrant(s), are provided to educate growers on how to effectively manage the evolution of HR weeds and develop sustainable long-term management strategies.[27,91] Nonetheless, hitherto experiences with HT crops have shown this has not been sufficient to ensure a sustainable deployment of the technology. Therefore, we suggest changes to the current stewardship programs that are described below.

Cover entire crop rotation sequences

Agricultural systems in the USA are based either on very short and simple crop rotations or on monoculture systems. This situation tends to exacerbate HR weed problems. In Europe, reduced or minimum tillage have been promoted through subsidies, and there is an increasing trend in recent years to adopt this practice. For example, in France, 34% of the major arable crops were in reduced tillage. BMP, built on long crop rotations, are pivotal to mitigate the risk of HR weed evolution, especially in HT crops that have closely related and sexually-compatible weed species (e.g. wild rice, sea beet, wild sunflower and wild and weedy oilseed rape relatives).[1] To this aim, the new EU common agricultural policy advocates that at least three crops are grown on a farm; this requirement is expected to promote crop diversification, though three crops may not be sufficient to ensure sustainable crop diversity. However, Beckie et al. [92] found that growers that included three or more crop types on their farm had significantly less incidence of HR weeds compared with those that grew less than three. Another alternative could be different herbicide systems in one crop since changing crop does not necessarily change the selection pressure. Control of volunteer crop plants and difficulty to achieve the optimum timing for weed control is another important risk associated with HT crops, and this should be explicitly addressed in stewardship programs. For example, currently grown CHT oilseed rape varieties resistant to imazamox or tribenuron are also resistant to the ALS-inhibitor herbicides used in the crops grown in rotation with oilseed rape. Weed control strategies provided by industry and extension services should be more crop rotation-oriented than what is actually done and practical solutions should be promoted to control volunteers.

Make training courses for growers mandatory

To ensure that growers follow training and fully understand the stewardship programs, effective preparatory courses are needed. To improve the stewardship in North America, technology-user guides have been developed by companies and disseminated to growers. However, growers may not read or adopt these recommendations. This problem can be overcome by making training sessions mandatory for growers. In particular, recommendations on herbicide-user practices and HT crop rotation frequency thresholds would be useful.

Maximize stewardship compliance via farmer contracts and other legal means

The reason behind the current problem of HR weeds in HT crops is that either effective stewardship programs have not been developed or growers did not adopt them wherever they have been developed. In theory, herbicide resistance stewardship includes the need for compliance monitoring by regulatory agencies about the effectiveness of the stewardship plan, but in practice very little monitoring is done. For example, to limit HR evolution in weedy rice populations during the introduction of IMI-tolerant rice varieties, several restrictive and complementary guidelines were made available to ensure sound user practices.[93] The guidelines advocated purchasing and using only certified seeds, using residual herbicides to increase weed control, control of all weedy rice escapes, herbicide rotations with alternative modes of action and the suspension of the cultivation of HT rice in the same field after one harvest for at least 1 year. However, there are reports from Italy of herbicide resistance evolution in weedy rice populations 5 years after introduction of CHT rice.[94] Similar observations were made in Greece.[95] The consequence of poor HT crop stewardship is also a reality for an increasing number of growers in the Americas.[2] Prevention and mitigation strategies for HR weed management are generally understood, but there has been little will or reason to implement these strategies in spite of industry incentives. Therefore, growers that grow HT crops should be required to sign a stewardship agreement and complete stewardship training before adopting HT crop technologies. Moreover, growers should be subject to more vigorous stewardship and consistent compliance monitoring as those implemented for GMHT cotton in Australia.[96]

To reduce the risk of herbicide resistance evolution in Europe, cultivars with HT traits should be introduced in rotation with those with non-HT traits within the framework of BMP. To this aim, effective stewardship plans should be developed and monitored for compliance. In addition, certification tests, audits, compliance incentives, crop insurance, databases of non-compliant growers, sales restrictions and fines for non-compliance may help maximize stewardship compliance.

Demonstrate to growers with practical examples that BMP leads to higher profitability in the long-term

The Benchmark Study with GMHT crops in the US revealed that although the cost of BMP are occasionally higher, this increase is compensated by higher crop yields that results in net returns similar to or greater than those based on simplified management practices.[97] This means that growers can adopt BMP with confidence that they will not negatively affect their net returns in the short-term, and will help mitigate HR weed problem in the long-term. To provide similar practical examples in Europe, it is crucial that demonstration trials that include IWM practices integrated within crop rotation systems involving HT crops are supported. In addition, growers need sufficient practical examples and information so that they understand the reasons for adopting IWM programs and the need to utilize BMP, especially in those situations where weed resistance is most likely to evolve. Although advisory services should still be reinforced in many parts of Europe, they are in general present and can therefore play a crucial role in facilitating growers for the adoption of IWM strategies.

Increase growers' awareness about the need to enhance biodiversity

Redesigning crop systems in a manner that reduces the size and interference capacity of weed populations might be one step forward in proactively reducing the need for herbicides.[35]

Delayed or less intense in-crop weed management can promote diverse weed communities and deliver benefits for farmland biodiversity.[91,98,99] Growers might learn to tolerate higher weed population densities at certain periods of the growing cycle, as long as these weeds do not cause economic losses. For GMHT fodder beet (*Beta vulgaris* Mangelwerzel) treated with glyphosate, significant improvements in weed flora and arthropod fauna have been reported with careful herbicide management according to label recommendations or with delayed applications, although weed seed production was reduced.[100] Less intense in-crop weed management with glyphosate applied to a proportion of the field or crop can also maintain desired levels of biodiversity. In GMHT sugar beet, this can be achieved either by over-the-row band spraying to allow early season weed growth between, but not within, crop rows, or by overall spraying early to allow some later emerging weeds. Weeds occurring between rows after an early over-the-row band spraying could be controlled by a later broadcast treatment.[101–103] Some weeds can be left for a longer period between the crop rows without causing yield loss; these weeds can support beneficial invertebrates during the early to mid-season,[102] and produce seed in the autumn as food for birds.[104] These effects can only be achieved if growers do not apply long soil residual herbicides at sowing. In the US, the use of residual herbicides applied at crop sowing is now the general recommendation due to widespread occurrence of GR weed species.

While managing uncropped land and field margins for biodiversity may be relatively simple, management of in-crop HR weeds can be more difficult to achieve in practice.[105,106] Managing weeds within the crop to support biodiversity involves the risk of reducing crop yield [107] and the long-term build-up of problem weed communities through seedbank replenishment.[108] Increased crop yields have historically been coupled with a decline in botanical diversity.[109] This suggests that in some situations there may be a trade-off between the botanical biodiversity and crop yield. There is a continual challenge in maintaining effective weed control while sustaining beneficial weed species at economically acceptable levels.[108,110] Hence, more robust tools are required for assessing beneficial weed communities in terms of the ecological functions they provide to the ecosystem and their effect on crop yield, and ultimately to identify if threshold levels exist that are economically acceptable and ecologically significant for these weeds.[108,110,111] In contrast to integrated management of insects or pathogens, economic thresholds that trigger herbicide application is a fading concept in North American weed management because of the increased focus on weed seed control to mitigate HR weed population abundance. A similar trend has been observed in Europe realizing that economic thresholds cannot take into account the long-term effects that are more important with weeds than with diseases and pests.

Foster awareness-raising programs and coordinated responses

Following numerous reports of GR weeds, several educational programs have been launched in the US. It is expected that awareness and growers' responses will rise following the increased frequency of GR weeds. A survey across six states in the US has highlighted that crop rotation is likely to be adopted as a mitigation practice to address problems with GR weeds by growers in the Midwest US, although the response was not the same across the Southeast US.[31] Encouraging results are reported also from Australian grower surveys; these highlighted growers' awareness of HR weeds and associated cost, thereby promoting the adoption of integrated solutions for the mitigation of the risk related to the evolution of HR weeds.[112] However, these studies also highlighted that growers prefer alternative herbicides to non-chemical means to obtain the highest economic return on investment.

While considering the European context, it is also advisable that HR weed management is considered for the implementation of IPM principles,[38] as foreseen under Directive 2009/128/EC. In addition to the traditional herbicide label that outlines the contents of the product and standard directions for its use, other specific means for communicating IWM should be considered while developing awareness-raising programs to increase adoption of sustainable long-term weed management strategies and practices.[27,82,99]

Integration of socio-economic studies to understand and change growers' attitude and behavior

Increasing global focus on HR weed management has shifted from science to socio-economic factors that may impact proactive adoption of BMP for HR weed management – i.e. the human element.[113] These approaches are vital in the USA and Canada to understand why growers are so reluctant to adopt mitigation practices for HR (and especially GR) weed management. Indeed, numerous studies have highlighted that growers in the US are not fully committed to adopt mitigation strategies.[32,114] In the Benchmark Study in the Midwest and southern US,[97] the authors reported that the management of HR weeds based on integrated practices as recommended by academics was sustainable from economic and agronomic points of view, but the challenge was to convince growers to adopt such practices. They showed that alternative weed control strategies are not significantly accepted and adopted even by growers that were aware that these strategies would lead to better results. Importantly, weed management is only one of many decisions that growers must address. Key to any decision by growers is the perceived economic cost and time requirement in the immediate future. When benefits of a decision are not readily apparent or are only realized over the long-term, growers will generally adhere to their initial short-term decisions.

A recent study from the US [87] highlighted substantial barriers that reduce the willingness of growers to adopt the components of an IWM system. In particular, IWM systems were perceived as unreliable, resulting in increased risk of weed control failure. The acceptance of IWM by growers will depend on their perceived risk to management, individual management capability and environmental interactions that will influence the economic viability of the crop system. The adoption of IWM is usually hindered by the fact that chemical means are often the first and only choice of growers as synthetic herbicides are perceived as an effective, rapid and cost-effective solution for weed management problems.[4]

The EU has already taken some measures to foster the adoption of sustainable weed management practices, through several action plans for the sustainable use of pesticides. Besides the directive for the sustainable use of pesticides (EU Directive 128/2009/EU), other options that EU Member States could adopt include financial incentives or regulatory penalties to overcome obstacles limiting the adoption of alternative non-herbicidal weed management practices.[2]

One of the questions for researchers and policy-makers is to understand why growers are not adopting prevention and mitigation strategies for HR weeds, even when incentives are provided. One major reason is that growers greatly discount long-term potential rewards (e.g. delaying herbicide resistance evolution) for short-term rewards (e.g. actual profits). For example, in Italy, growers frequently grow imazamox-tolerant rice varieties for more than 2 consecutive years, increasing the selection pressure exerted by imazamox and fostering the evolution of HR red rice.[115] There have also been cases where prevention and mitigation strategies for HT crop management are well-known, but not adopted even with incentives provided by industry.[2] Understanding the drivers of farmer reluctance to adopt sustainable practices and how this reluctance could be overcome are the prerequisites for enhanced adoption of IWM practices.

Similar to North America, in some EU countries, there is an increasing recognition of the importance of socio-economic sciences to understand growers' behaviors and foster the adoption of IPM. For example, inclusion of socio-economic considerations in the development and implementation of IPM strategies is one of the major pillars within the French national action plan Ecophyto (http://agriculture.gouv.fr/ecophyto).

Development of adequate public policy

Public policies can formulate and implement strategies associated with alternative programs that facilitate interaction amongst growers, crop consultants, cooperative extension personnel and the pest control industry to manage HR weeds. A recent study [89] emphasized that there is an unwillingness of weed researchers to conduct IWM research that includes non-herbicide-based approaches, mainly because herbicide efficacy research is more easily funded and less complicate to conduct. Incentives from public policies are thus needed to provide more leadership in non-herbicidal weed management in order to generate credible IWM data to be provided to growers.

Setting up herbicide-use reduction targets in major field crops, together with the inclusion of financial incentives or penalties in agricultural programs to support this policy, represent a long-term goal for governments in consultation with crop commodity groups. Concomitantly, industry incentives must expand to improve grower adoption of BMP for HT crops. For example, if short-term economics drives the decision-making process, then increased adoption by growers will require industry and government incentives. As mentioned previously, in addition to the directive on the sustainable use of pesticides (EU Directive 128/2009/EU), the new common agriculture policy encourages the adoption of crop diversification in the EU. Unlike in North America, practices such as crop rotations and cover crops are commonly adopted by European growers, creating an opportunity to mitigate risks of HR weed evolution across HT crop systems. In addition, measures within the new EU common agricultural policy that aim to foster biodiversity are likely to favor the diversity of weed communities in field margins, thereby maintaining species richness and mitigating HR weed evolution.[116]

Regulatory revisions

Within the EU, the use of GMOs is regulated by Directive 2001/18/EC for their release into the environment, and Regulations (EC) No 1829/2003 and 503/2013 for derived food and feed products. According to GMO legislation, GMOs are subjected to a risk assessment before they can be placed on the market in Europe. In this process, risk assessors evaluate any possible risk that the deployment of GMOs may pose to humans, animals and the environment. The decision on the level of acceptable risk, and thus whether a GMO can be commercialized, is taken by risk managers (including policy-makers and regulators) who weigh policy options to accept, minimize or reduce characterized risks.

The approval of pesticides, including herbicidal active substances, is regulated by Regulation (EC) No 1107/2009 (repealing Directive 91/414/EEC) and the Regulations (EU) No 283/2013 and 284/2013, which establish the data requirements. The use of pesticides, including their environmental impact once on the market, is regulated by the sustainable use Directive 2009/128/EC. Regulation (EC) No 1107/2009 establishes that a pesticide can be approved only if its use is safe, i.e. if its use does not cause unacceptable effects to humans, animals and environment.

Clarifying the interplay between GMO and pesticide legislation to avoid duplication and gaps in assessment

Directives 2001/18/EC and Regulation (EC) No 1107/2009 are both relevant for the environmental risk assessment of GMHT plants and their associated weed management practices. Directive 2001/18/EC requires the assessment of "possible immediate and/or delayed, direct and indirect environmental impacts of the specific cultivation, management and harvesting techniques used for the genetically modified higher plant (GMHP) where these are different from those used for non-GMHPs", meaning that an assessment of the possible environmental impacts of the use of the complementary herbicides compared to those of current weed management practices applied to non-GM crops of the same species is required in the EU. In addition, the use of the complementary herbicide in a GMHT crop requires a new approval according to EU pesticide legislation, because it is a new use of the herbicide. This raises the issue of interplay between GMO and pesticide legislation in the EU.

As indicated by Ehlers,[117] an effective interplay would avoid duplication and gaps in the environmental risk assessment, and thus the possibility that conflicting decisions on pesticide usage are made under the two legislative frames.[117] Principally, there are no scientific reasons for assessing the effects on the environment of the use of herbicides in GMHT crops and non-GM crops according to different standards.

The environmental risk assessment under Regulation (EC) No 1107/2009 does not currently include studies of impacts on biodiversity within agro-ecosystems although it explicitly mentions biodiversity as a protection goal. In contrast, this is required under Directive 2001/18/EC in relation to GM plants. The assessment of GMHT crops and their associated weed management practices includes evaluating potential effects on farmland biodiversity, while this is not a requirement for non-GM crop herbicide regimes.[117–122] Due to these different legal requirements, the environmental impact of a herbicide used on a GMHT crop is currently assessed differently than the same herbicide used on CHT crops.

The European Commission is currently in the process of revising Annexes II and III of Directive 2001/18/EC, and aims to clarify the interplay between GMO and pesticide legislation to avoid duplication and gaps in assessment.

Specifying operational protection goals

Environmental risk assessment is an important analytical scientific tool that helps regulatory decision-making. Robust environmental risk assessments begin with an explicit problem formulation where plausible and relevant exposure scenarios and the potential adverse effects from those exposures are identified. Risk is then characterized by testing specific hypotheses about the likelihood and severity of adverse effects.[123–130] The first part of problem formulation establishes the context for the assessment by identifying which of the potentially exposed and susceptible components of the environment – species, habitats, services, etc. – are valued by civil society and/or protected by relevant laws or policies. This exercise establishes the so-called environmental policy protection goals: environmental components that should be protected and taken into account when conducting environmental risk assessments to support regulatory decision-making. These protection goals can vary between jurisdictions, but their overall aim is to limit harm to the environment, including biodiversity and ecosystems, caused by human activities.

However, policy protection goals, such as protecting biodiversity, are often too generic and vague to be useful for environmental risk assessment, and need to be translated into specific, operational ones.[131–135] Operational protection goals have to delineate the environmental components that need to be protected, where and over what time period, and the maximum impact that can be tolerated. Yet, reaching agreement on what to protect presents challenges,[121,131,132] Therefore, risk managers have not yet clearly defined "how many weeds" or "what type of weeds" are desired in arable fields and at the landscape level to provide ecological services,[122] and "which environmental changes are harmful". Stakeholders have divergent positions on what is of value and why in the EU.[121,131,132,136] Several stakeholders do not regard the presence of weeds in arable fields as a good thing, since it is likely to affect crop yield and quality. These stakeholders emphasize that in-field crop yield should be maximized, as this would reduce the extent to which semi-natural and natural habitats are converted into arable land.[137] However, other stakeholders are of the opinion that the delivery of food production and biodiversity conservation should be reconciled at the field level.[138] To increase farmland biodiversity at the level of farm ecosystems, they advocate sustaining the populations of weed species that support farmland biodiversity and are adapted to the cropped area of the field, as these beneficial weeds can be distinct from the flora found in non-cropped land, which typically represents a small percentage of the total area of the farm.[108–110,139,140] They also consider that providing plant resources only on non-cropped land is insufficient to reverse declining trends in farmland biodiversity.

Improved communication between risk assessors and risk managers would help to clarify the often divergent positions on what is of value and why, and reveal the underlying values and ideals held by the different stakeholders. This communication would also be essential to reach agreement on operational protection goals, which must be set before environmental risk assessments are conducted, as they define the framework in which scientists and risk assessors operate when performing environmental risk assessments. If what constitutes environmental harm is not defined at the beginning of the environmental risk assessment, then one cannot discover harmful effects by scientific research.[132–136,141–143]

Broadening the scope of environmental risk assessments

The main objective of most risk-based legislation regulating the use of GMOs and pesticides in Europe is to ensure a high level of environmental protection. The focus therefore is on the assessment of risks only. Legislation does not explicitly consider whether the deployment of GMOs fulfills wider socio-economic and ecological aspirations,[144] or meets other policy objectives.[142,145,146]

Protection is often seen as preserving a baseline condition in Europe; it is not seen as improving the environment. In other words, a missed opportunity to improve the environment (e.g. by minimizing negative side-effects of agriculture) is not regarded as an environmental risk. Ideally, however, new technologies should be assessed not only for their risks to human and animal health and the environment, but also on their potential benefits (i.e. opportunities). Weighing the potential for environmental harms and their associated costs against the potential for environmental benefits may enable risk managers and decision-makers to place these into the context of risks and benefits of current agricultural systems. This could contribute to achieving greater environmental sustainability in agricultural and land management systems,[118,143] provided that clear policy objectives for sustainable agriculture are set. Considering potential environmental benefits as well as risks may enable an interpretation of the precautionary principle that is explicitly linked to the ideal of sustainable development [146,147] through a proper evaluation of the options available for decision-making and estimation of the costs and benefits associated with possible decisions as well as the costs of inaction.[148]

Several scientific risk assessment bodies have suggested that the adoption of a specific method of crop management (whether GM or conventional) should be based on consideration of the overall environmental consequences, and that such consideration will require a broader and more balanced legislative oversight.[118,149] A paradigm shift would be required to change from risk assessment, as it is currently practiced, to a more sophisticated assessment that balances risks and benefits.[149] The status quo, in which risk assessment is interpreted very narrowly in terms of adverse effects, is not tenable, suggesting that decision-support tools should be built that enable risk assessors to better consider effects of whole farming systems.

Moving towards product-based legislation

In Europe, a technology-based regulatory system governs the regulation of GMOs. A GMO is thus mainly characterized by the breeding technique used to produce it. Directive 2001/18/EC provides a list of techniques in its Annexes IA and IB that: (1) result in genetic modification; (2) are not considered to result in genetic modification; or that (3) result in genetic modification, but yield organisms that are excluded from the scope of the Directive. However, currently there is a disparity in the assessment of the environmental impact of GMHT crops in comparison with HT crops with similar phenotypic characteristics.[120,122,134,150–152] So far, plants obtained through plant breeding techniques other than genetic engineering fall outside the scope of EU legislation from the perspective of environmental risk, although their cultivation might pose environmental safety concerns similar to those of GMHT crops with similar phenotypic characteristics.[153] Given that CHT plants are obtained through traditional plant breeding techniques or mutagenesis instead of genetic engineering, they are not considered "genetically modified" under current EU GMO legislation and are not subjected to particular safety assessments prior to their commercial release. Therefore, some authors have argued that the EU regulatory approach lacks consistency. According to these authors, there are no convincing arguments in favor of applying more stringent regulatory requirements for one particular plant breeding technique if another technology might result in similar environmental impacts.[119,120,127] Product-based legislation, such as implemented in Canada, would regulate all HT plants in a similar manner, whether developed through genetic engineering or any other plant breeding technique. Those who analyze risks would then recognize that the real choice is not between GMHT plants and their associated weed management practices that are perceived as inherently risky and CHT plants and traditional weed management that are perceived as completely safe. Both crop systems have positive and negative environmental effects, which should be considered.[119,132]

Conclusions

The adoption of HT crops and their associated agronomic practices may facilitate the achievement of effective weed management and overcome increasing HR weed problems as well as other environmental issues associated with the intensification of agriculture. However, the management of HT crops should integrate sustainable practices and measures. Effective weed management without herbicide use is not presently conceivable in conventional intensive farming systems. Therefore, herbicide diversity needs to be considered as a key tactic for weed control. In the long-term, crop systems less reliant on herbicides should be considered as a research priority. The adoption of more diverse crop production practices is essential to mitigate the risk of weed resistance evolution, which has proven a very difficult problem to manage. Although such sustainable practices may be more costly for growers to implement in the short-term, they will be beneficial in the longer term, especially if appropriate policies and incentives are put in place. As many incentives to simplify agricultural practices exist, a simple stewardship plan is not sufficient. For this reason, there is a need to work on several fronts.

The cultivation of crops with CHT traits presents similar weed management challenges and agronomic risks as those with GMHT traits.[120] However, the EU regulatory framework clearly distinguishes these crops, as all GMHT crops are regulated while CHT crops are not subjected to regulatory oversight. This is paradoxical because the cultivation of HT crops in North and South America has clearly revealed that the most severe environmental problems resulting from their cultivation are primarily related to agronomic factors (particularly herbicide-use practices) instead of genetic or biological factors. Herein, we highlight that CHT crop cultivars require the same diverse management strategies as GMHT cultivars to address environmental issues, as they present similar advantages and disadvantages. We therefore encourage EU risk assessors and risk managers to consider our perspectives on the sustainable deployment of

HT crops within IWM crop systems, irrespective of the plant breeding technologies used to obtain these crops.

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Disclosure statement

The views or positions expressed in this publication do not necessarily represent in legal terms the official position of the European Food Safety Authority (EFSA). EFSA assumes no responsibility or liability for any errors or inaccuracies that may appear. This commentary does not disclose any confidential information or data. Mention of proprietary products is solely for the purpose of providing specific information, and does not constitute an endorsement or a recommendation by EFSA for their use. The authors declare no competing financial interests. The authors alone are responsible for the content and writing of this article.

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