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Opportunities and challenges for harvest weed seed control in European cropping systems

By

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Abstract

The rapid increase of herbicide resistance in some of the most problematic annual weeds, and potential negative impacts of herbicides on human health and the environment have led growers to look for alternative non-chemical weed control. Harvest weed seed control (HWSC) is a non-chemical weed control tactic based on reduction of seed return of primarily annual weed species to the soil seed bank that has been successfully adopted by farmers in Australia. The strategy is to collect and/or destroy the weed seeds in the chaff material during harvest using methods such as chaff carts, bale direct system, integrated impact mills, windrow burning, chaff tramlining and chaff lining or other methods of targeting the chaff material containing the weed seeds. Two biological characteristics are exploited with successful HWSC: the level of weed seed retention at crop harvest above crop canopy height and coincidence of weed and crop maturity. Initial research efforts in Europe have found that there are several candidates for HWSC among weed species with a high importance in European cropping systems. The highest potential has been found for weeds such as *Galium aparine*, *Lolium rigidum* and *Silene noctiflora*. However, there are several challenges for the adoption of these systems under European conditions compared to e.g., Australia. The challenges include that crop and weed maturity are not concomitant which results in lower seed retention values at crop harvest. In addition, there has not been a concerted research effort to evaluate HWSC systems in European cropping systems. Until now, research on HWSC in Europe mainly focused on the rate of weed seed retention in specific weed species. For HWSC to contribute to the mitigation of herbicide resistance and add to the toolbox of integrated weed management measures, there is an urgent need to take HWSC research to the next level. Although HWSC is not functionally equivalent to herbicide application, it may help to reduce herbicide inputs in the long-term when used in combination with other tactics. Future research and development should focus on the evaluation of HWSC strategies for the practical adoption of these tactics in European cropping systems.

Key words: Herbicide resistance, annual weeds, seedbank, chaff fraction, integrated weed management

1. Introduction

Herbicides are, at present, still the major tool to control weeds in most arable cropping systems, but agriculture faces several challenges, which necessitates a change to more diverse integrated weed management strategies (IWM). Harvest weed seed control (HWSC) can be a part of such strategies and this paper highlights the opportunities and challenges connected with this tactic. One of the challenges for continued reliance on herbicide based weed management is that the widespread and persistent exposure of weed populations to herbicide selection pressure has resulted in the development of resistant weed populations (Matzrafi et al. 2021; Peterson et al. 2018; Walsh et al. 2018a). Presently, there are 266 resistant weed species globally, with 153 dicotyledonous and 113 monocotyledonous species (Heap, 2021), of which some are among the most important weed species in Europe including *Alopecurus myosuroides* Huds., *Lolium multiflorum* Lam., *Apera spica-venti* (L.) P. Beauv., *Bromus sterilis* L. and *Papaver rhoeas* L. (Keshtkar et al., 2015; Mahmood et al., 2016; Sen et al., 2021; Stankiewicz-Kosyl et al., 2020). Strict pesticide regulations in the European Union have removed many of the previously most widely used herbicide active ingredients from the market (Hillocks, 2012) and it is expected that some of the herbicides currently used will be withdrawn from the market in the coming years (Kudsk and Mathiassen, 2020) resulting in an even smaller portfolio of active ingredients for resistance management. No-till practices have become more common throughout Europe to reduce costs and preserve soil productivity (Melander et al., 2017). In addition to herbicide resistance, a widespread adoption of conservation agriculture and no-till practices has contributed to an increased infestation with grass and perennial weed species, which in turn leads to an increased use of glyphosate in conventional agriculture (Kudsk and Mathiassen, 2020, Akhter et al 2020a). The future of glyphosate use in Europe is uncertain as the active substance glyphosate is approved in the EU until 15 December 2022 and the renewal of its EU authorization is currently ongoing. A ban of glyphosate will have a higher impact on weed management in Europe than a ban of any other active ingredient (Fogliatto et al., 2020; Kudsk and Mathiassen, 2020). These challenges highlight that now more than ever there is a need for a fundamental shift in weed management practices. Recently, the EU agreed on the Farm to Fork strategy that calls for a 50% reduction in pesticide use in 2030, further adding to the need for alternative weed control measures (European Commission, 2021).

An IWM strategy should include measures that either: 1) prevent establishment of weeds in the crop from the soil seedbank or subterranean organs, 2) reduce competition for resources by increasing the competitive ability of the crop and/or weakening the competitive ability of the weed, and 3) prevent the return of weed seeds and vegetative organs to the soil (Riemens et al 2022; Kudsk et al., 2020). The primary focus of currently available alternative weed control tactics (e.g. stale seed-bed, strategic ploughing, alteration of seeding dates and densities) continues to focus on preventing weed competition during early crop growth stages (Melander et al., 2017; Walsh et al., 2018b). Some weed plants may inevitably escape weed management practices due to delayed emergence or inefficient direct weed control. In most cases, there are no suitable methods to manage escaped weed plants, and they will therefore complete their life cycle, produce seeds, and sustain a viable soil seedbank (Walsh et al., 2013). HWSC aims at reducing seed return to the soil seedbank and has gained increased interest globally (Walsh et al., 2013). Usually, the major portion of weeds seeds collected by the combine harvester exit the harvester as part of the chaff fraction and weed seeds subsequently enter the soil seedbank. HWSC systems collect and/or destroy the weed seeds at harvest and suppress the replenishment of the weed seedbank by exploiting two biological characteristics of targeted weed species: seed retention until crop harvest and concurrent maturation with the crop (Schwartz et al., 2016; Shergill et al., 2020a; Walsh et al., 2013). Tall and erect weed species maturing simultaneously with the crop and retaining high amounts of seeds until harvest have been found to be good targets for HWSC technologies. For example, HWSC has become a key tactic for the management of annual weed species such as *Lolium rigidum* Gaudin in winter cereals in Australia (Walsh et al., 2018b). *L. rigidum* is a key weed in durum wheat producing areas of Southern Europe where the widespread presence of populations with multiple resistance to ALS and ACCase inhibitors is posing a serious challenge to growers (Loureiro et al., 2017; Scarabel et al., 2020; Torra et al., 2021). In Northern Europe, *L. multiflorum* is causing significant yield losses in winter cereal crops. The fact that *L. rigidum* and *L. multiflorum* retain a significant number of seeds until harvest in wheat, indicates that HWSC has potential to manage these two species (Akgun et al., 2008; Blanco□Moreno et al., 2004). The opportunity of collecting and/or destroying weed seeds at crop harvest has already been documented in several other annual weed species in Europe, e.g. *Avena fatua* L. and *B. sterilis* in the UK, *A. fatua*, *Avena sterilis* L. and *L. rigidum* in Spain, and *A. spica-venti*, *A. myosuroides, L. multiflorum*, *Vulpia myuros* (L.) C. C. Gmel., *Spergula arvensis* L., *Sinapis arvensis* L., *Fallopia convolvulus* (L.) Á. Löve and *Stellaria media* (L.) in Denmark (Balsari et al., 1994; Bitarafan and Andreasen, 2020a; Akhter et al., 2020b). Practical implementation of HWSC in Europe could add an additional tactic to the IWM toolbox. In particular, it may limit the regional spread of herbicide resistant weed populations (Walsh et al., 2018b). Yet, the recognition of HWSC as a potential weed management strategy has not gained much attention in Europe compared to Australia, where it has been widely adopted, and the US, where strong efforts are currently being made to include HWSC as a weed control tactic (Beam et al 2019; Schwartz-Lazaro et al 2017a). The focus of the current review is to summarize existing knowledge on HWSC methods, to discuss the opportunities and challenges for the practical implementation of HWSC systems in European cropping systems and to identify areas for further research and development to promote this tactic in this region.

2. Prerequisites for the success of HWSC

High seed retention values at harvest provide the opportunity to collect or destroy retained seeds and reduce seed return to the soil seedbank (Walsh et al., 2013). Seed retention is controlled by weed species or population specific genetic traits as well as environmental conditions (e.g. temperature, humidity, rainfall, soil fertility, wind and moisture) and management practices (e.g. sowing and harvest date) (Maity et al 2021; Tidemann et al., 2017). The relative timing of crop and weed maturity is another key parameter for the success of HWSC. For instance, *A. myosuroides* plants retain higher amounts of seeds in winter barley and winter oil seed rape (early maturing crops) than in winter wheat (late maturing crop) (Unpublished results; Shergill et al., 2020a). Whether a species can be targeted by HWSC also depends on plant architecture as the weed seeds need to be produced at a height where they can be collected during harvest; species with an erect growth habit enhance the seed capturing opportunity during harvest (Soni et al., 2020). *Veronica persica* Poir., *Polygonum aviculare* agg. and *Anagallis arvensis* L. retain up to 60% of their seed at crop maturity, however, weed seed harvest of these species will be poor because of their prostrate growth habit (Bitarafan and Andreasen, 2020c). A stubble height of around 15 cm is considered as the practical minimum harvest height for most growers in Europe (Bitarafan and Andreasen, 2020c). Problematic grass weed species in Europe such as *A. myosuroides*, *A. spica-venti* and *L. multiflorum* are tall growing (>80 cm) upright plants with erect seed heads, making it possible to capture the retained seeds with the harvester (CABI, 2021a, Akhter et al. 2020a, Akgun et al., 2008).

The life cycle of a weed is an important factor that determines the success of HWSC systems. HWSC methods mainly target annual weeds, as propagation of seeds in perennial weeds is subordinate to vegetative propagation. In addition, timing of crop harvest is important as early crop harvest enhances the efficacy of HWSC tactics by increasing the number of captured seeds of species that shed seeds over the harvest period (Bitarafan and Andreasen, 2020b; Shergill et al., 2020a, Ulber, 2022). Crops with a shorter crop cycle that can be harvested earlier provide an opportunity to collect a greater number of weed seeds at harvest. For example, Codina-Pascual et al. (2022) evaluated the fecundity characteristics of *Papaver rhoeas* L. in the crop *Camelina sativa*. *C. sativa* presents a shorter crop cycle than cereals, therefore, can be harvested earlier. The earlier harvest date implies that a lower proportion of weed seeds are matured, and the potential *P. rhoeas* seed rain was reduced between 34 and 70%. These values combined with HWSC could accelerate the depletion of the weed seed bank. The quantity of the chaff fraction produced during crop harvest determines the power requirements of the combiner which is considered an important parameter for the practicalities of some HWSC systems (specifically impact mills). For instance, if a crop produces a large amount of biomass, the integrated impact mill power requirements will increase (Guzzomi et al., 2017).

3. Efficacy and global implementation of current HWSC methods

Different methods for weed seed destruction are available, where the chaff containing the weed seeds is collected and/or destroyed, and managed/processed by using different tactics at harvest.

3.1. Chaff collection

With the chaff collection method, the combine harvester is modified with a collect and transfer mechanism, which delivers the chaff fraction containing the weed seeds into a collecting cart. The collected chaff fraction is then placed in piles for subsequent destruction. This method has been shown to collect and remove high proportions of seeds of *L. multiflorum* (70%), *Amaranthus palmeri* S. Watson (70%) and *Raphanus raphanistrum* L. (95%) (Beam et al., 2019; Norsworthy et al., 2016; Walsh and Powles, 2007). Challenges in manoeuvring the combine harvester due to the rear attached chaff carts, and management of large volumes of chaff has restricted the adoption of this HWSC method in the US and Australia (Shergill et al., 2020a; Walsh et al., 2017).

3.2. Narrow windrow burning

The narrow windrow burning method concentrates the straw and chaff fraction into narrow lines using a chute attached at the rear of the combine harvester. These narrow lines are later burned to destroy the weed seeds in the chaff fraction. It is one of the most efficient and cost effective HWSC methods, and is currently being widely used in Australia (Walsh et al, 2017a). Previous studies have shown that narrow windrow burning can kill nearly 100% of the seeds of *A. palmeri*, *L. rigidum*, *Sorghum halepense* (L.) Pers. and *R. raphanistrum* present in the narrow windrows (Norsworthy et al., 2020; Norsworthy et al., 2016; Walsh and Newman, 2007). The fire risk, fire bans and environmental pollution put practical limits to the implementation (Walsh et al., 2018b).

3.3. Chaff lining and chaff tramlining

Chaff lining and chaff tramlining are recently developed innovative HWSC methods that have gained popularity primarily due to their low cost. These methods confine the chaff material into narrow rows either between the crop stubble rows (chaff lining), behind the combine harvester or on dedicated wheel tracks of the combine harvester in a controlled traffic farming system (chaff tramlining). Both chaff lining and chaff tramlining are established using an attachment on the rear of the combine harvester that funnels the chaff into rows. The confinement of the chaff fraction places seeds under conditions that are less favourable for seedling emergence due to the cover of plant material (Walsh et al., 2021). The chaff rows in chaff lining need to be kept undisturbed, as any disturbance in the chaff layer provides opportunity for weed seedling emergence. In comparison with other HWSC systems, limited research is available on the efficacies of these methods.

3.4. Bale direct system

The bale direct system comprises a square or round baler attached to the back of the combine harvester producing bales from the straw and weed seed containing chaff fraction during harvest. The baled material can be used for livestock feed. The bale direct system has been shown to collect and remove high amounts (up to 95%) of *L. rigidum* seeds from the field (Walsh and Powles, 2007). High power requirements, low market values for the baled products, and risk of spreading herbicide resistant weeds seeds via transportation of bales have limited the wide adoption of this method in Australia (Shergill et al., 2020a; Walsh et al., 2017a).

3.5. Integrated impact mill

Different types of impact mills including Seed Terminator, integrated Harrington Seed Destructor (iHSD), Seed Control Unit (SCU), which fit within the body of the combine harvester, have been developed in Australia. These mills destroy the weed seeds in the seed-bearing chaff material inside the combine harvester during harvesting operation. After processing of the chaff fraction by the mill, the crop and weed residues are returned to the field. The impact mill systems are very compatible for conservation agricultural practices, where the intention is to retain crop residues in the field. In a stationary mill testing using a test stand equipped with an iHSD, Schwartz-Lazaro et al. (2017b) documented 100% seed destruction of *Ambrosia trifida* and *A. palmeri*in USA. In a study including ten weed species with a high relevance in the US soybean production, the iHSD was demonstrated to be highly effective in destroying seeds of all the species tested, with 86% to 100% weed seed destruction. A limitation to the adoption of the impact mills are a high initial purchase costs and high prerequisites in terms of power supply for the impact mill system (Shergill et al 2020b).

3.6. Other HWSC methods

Recently, Glasner et al. (2019) evaluated a new HWSC method under Northern European conditions, where the chaff material were placed on the straw swath and the weed seeds were removed from the field by baling the chaff and straw together. The baling of chaff and straw together was found useful to avoid weed seed return with a weed seed collection up to 60%. Heat treatment of weed seed containing chaff with exhaustive temperature inside a combine is another innovative HWSC method evaluated by Glasner et al. (2019). In this method, the chaff material is exposed to the hot exhaust gas from the combiner to kill weed seeds before returning the chaff fraction to the field. A heat treatment of the chaff material with the exhaust gas of the combine for 10s during harvest suppressed *Centaurea cyanus* L. germination by 99%.

Tall growing weed species such as *A. myosuroides* and *Lolium* species provide an opportunity to cut the weed seed heads above the crop canopy before seeds mature. In the “Top Cut Collect” approach, weed seed heads are cut just above the crop canopy and are removed from the field. The cutting action will trigger the regrowth of seed head, and the potential for seed to mature before harvest is maintained but could potentially be targeted in an integrated approach with a combine fitted with an impact mill at harvest.

4. Implementation and viability of different HWSC methods in Europe

HWSC methods such as chaff lining, direct bale, impact mills are technologies that are likely to become important tools in arable farms under European conditions. However, some challenges described in the following may halt a widespread adoption of these tactics.

4.1. Chaff collection

Collection of chaff piles for livestock feed could be a viable option under European conditions, as the seeds of many problematic weeds do not survive digestion by cattle and sheep (Blackshaw and Rode, 1991; Stanton et al., 2002). Management of large volumes of chaff and finding end uses for this material may hinder the uptake of this tactic under European conditions.

4.2. Narrow windrow burning

In Australia, the adoption of narrow windrow burning is higher compared to other HWSC tactics due to its greater efficacy and lower cost. Nevertheless, narrow windrow burning is not an option in Europe as burning is prohibited as per EU regulation 1259/1999.

4.3. Chaff lining and chaff tramlining

In Northern Europe, yields of wheat are higher and wheat crops produce a greater amount of residue biomass compared to average Australian grain crops, which suggests that chaff lining with high biomass could provide satisfactory weed seed kill rates due to a greater barrier to weed seedling emergence (Walsh et al. 2021). Moreover, weed seeds will germinate in the chaff lining rows, which potentially could be controlled using a more targeted approach (Shergill et al, 2020a; Walsh et al 2018b). Further, seed kill rate could be higher for chaff of canola, barley and rye crops than wheat, because of their allelopathic effect (Modhej et al., 2013). The lower implementation costs of chaff tramlining and chaff lines make them more economically viable that allows growers to funnel the weed seed containing chaff fraction in concentrated lines but there is no experience using this method in European cropping systems.

4.4. Bale direct system

Despite its great potential under European conditions, the unavailability of markets for the baled material could somewhat limit the adoption of this method in the region. The higher biomass production per unit area under European conditions would result in a substantial amount of baled material if this approach was widely adopted..

4.5. Integrated impact mill

HWSC methods such as impact mills systems can be viable in European crop production conditions, where they would be an acceptable option for conservation agriculture. Nonetheless, each technology has specific challenges that affect the efficacy of HWSC implementation. For example, early invented chaff mills cost around 75,000 - 104,000 Euros. Given that current prices are already half of these costs; it is believed that with mass manufacturing the cost could be further reduced. Moreover, currently available impact mills need up to 100 horsepower, which can lead to a 12 - 20% reduction in combine efficiency. The increased power requirement increases fuel consumption by 4.5 L/ton of grain (Hartzler, 2018), though this number could vary across different crop and harvest conditions. At the moment, high investment costs for the mills and high-power requirements are limiting the adoption of the impact mills at the individual farm level in Europe. However, contractors could potentially offer harvesting services with combines equipped with an impact mill for fields with heavy weed infestations. In addition, uneven maturity of the crop and weed is common under European conditions, therefore, a higher amount of green material during harvest could negatively impact on the performance of the mill by blocking the chaff flow (Shergill et al., 2020b).

4.6. Other HWSC methods

Limitations associated with these alternative HWSC methods may limit the adoption in Europe. For example, by baling the chaff and straw together 40% of the chaff material was included in the bales and left on the ground after baling. Wind can also spread the weed seed containing chaff material from the top of straw swath before baling. In addition, turning around the swath that is often needed to dry the wet swath before baling which can result in weed seeds falling to the ground or being carried away by wind. Collection of the chaff with an accompanying trailer was suggested to overcome limitations of this HWSC approach; but it reduced the efficiency of the combine by 10-25% (Shergill et al 2020a). Although the concept of using heated exhaust gas from the combiner to target the weed seed containing chaff fraction has shown promising results with efficacy up to 90%, some limitations such as insufficient availability of heat, wet chaff material and restricted exposure time of heat due to harvesting velocity may decrease the efficiency of this approach (Glasner et al., 2019). The HWSC concepts proposed by Glasner et al. (2019) are in principle possible, but future research is needed to implement these methods as alternative approaches to the current HWSC methods.

The top cutting of weed seed head above the crop canopy is another promising method that allows growers to prevent the weed seed return to the soil seedbank, but requirement of even crop canopy height and dependence of this method with other HWSC method may limit the adoptability of this tactic. For some weed species such as *A. myosuroides*, the formation of new tillers and seed heads after cutting that might still mature before harvest could also be an issue. Moreover, this method will not be practical over a large area and will have its justification only in specific situations e.g., for fields with severe weed infestations.

5. Harvest weed seed control as a new weed management tool in Europe

5.1. What we know about the potential of HWSC in Europe

HWSC was introduced in Australia with a focus to target herbicide resistant weeds (Walsh and Powles, 2014) and it is now being adopted for the same purpose in North America in some cropping systems (Shergill et al., 2020a; Shirtliffe and Entz, 2005). To date research on the potential of HWSC in Europe is mainly focused on timing of seed shattering and seed retention of problematic annual weeds. In Europe, the first study focusing on collecting weed seed chaff material was published in Sweden focusing on changes in the weed flora in space and time when chaff material was collected at crop harvest (Fogelfors, 1982). This study concluded that collection of chaff and straw containing seeds of range of species including *Galeopsis* spp., *Chenopodium album*, *Stellaria media*, *Polygonum* spp., and *Galium aparine* during crop harvest is a useful tactic to manage soil seed bank. An insight study by Griepentrog and Brandt (1985) highlighted the potential of chaff collection for weed control in organic farming in Germany. The next three decades did not see any literature on HWSC in Europe, except for a few studies that focused primarily on weed seed dispersal and reported weed seed retention data (Balsari et al., 1994; Barroso et al., 2006; Blanco□Moreno et al., 2004). More recent studies focusing on HWSC as a potential weed control strategy in Europe was published in 2019-2020 (Bergonzoli et al., 2020; Glasner et al., 2019), these studies introduced two HWSC methods in the region.

5.1.2. Weed seed retention studies

Several studies conducted across Europe examined seed retention of important annual weeds in cereals crops and observed variable proportions of seed retention. Certain weed features are a pre-requisite for the success of HWSC technologies and based on these parameters, weed species were classified as good, intermediate, low and poor candidates of HWSC (Table 1). This classification was dependent on the crop, in which the weeds were growing, and it was mainly determined by the ratio of weed seed retention at crop harvest, growth habit and plant height as reported in the literature (Bitarafan and Andreasen 2020c, Shergill et al., 2020a; Walsh et al., 2018b).

Differences in temporal seed shattering patterns within a weed species have been reported for European conditions. For example, seeds of *A. spica-venti*, *V. myuros, L. multiflorum* and *A. myosuroides* in Denmark started seed shattering at 1690, 1567, 1646, 1387 degree days (°C) in the 2017-18 growing season, and at 2249, 2165, 2213, 1870 degree days (°C) in the growing season of 2018-19 (Akhter et al., 2020a). An unusual wet autumn and a dry and warm summer characterized the 2017-18 growing season, whereas the weather conditions were closer to normal in the growing season of 2018-19. Similarly, Bitarafan and Andreasen (2020b) found differences in shattering patterns between two growing seasons in Denmark for *A. myosuroides* and *A. spica-venti* and concluded this was because of different environmental conditions (temperature and rainfall). Moreover, the unpredictable weather conditions particularly in the Northwestern parts of Europe often result in a delay of harvesting operations. A delayed harvest can lead to fewer weed seeds captured by the harvester due to seed shedding (Akhter et al 2020a). Different levels of seed retention in *Avena* spp. were also reported across European sites and years (Barroso et al., 2006; Feldman and Reed, 1974; Wilson 1970). For *V. myuros* and *L. multiflorum*, a field study showed that the amount of seed retention at maturity was significantly influenced by crop competition, where lower seed retention was observed for plants grown in competition with winter wheat compared to pure weed stands, whereas such effects were not observed for *A. myosuroides* and *A. spica-venti* (Unpublished results). In contrast, a higher seed retention was observed by Burton et al. (2016) for weed plants growing under strong competitive conditions than for those grown under less competitive conditions. It is difficult to extrapolate results between geographically distant regions as conditions, such as the length of the growing season varies considerably. Under Australian conditions *Lolium* spp. retained twice the ratio of seeds in comparison with *Lolium* spp. from the great plains area in the US (Soni et al, 2020; Walsh et al., 2018b). In general, the lack of synchronised maturity of crop and weed species in Europe compared to North America or Southern Australia results in lower level of seed retention at crop harvest, and thus reduces HWSC efficacy. For instance, at wheat crop maturity in Western Australia, *A. fatua* had high seed retention rates (84%) but seed retention for this species was low at the time of wheat harvest in Europe (10-20%) (Barroso et al., 2006; Walsh and Powles, 2014).

5.2. Opportunities for HWSC in European cropping systems

Wheat is the most widely grown crop in Europe and constitutes 44% of total European cereal production (Eurostat, 2021). Wheat production is a prime candidate for HWSC in Europe because of the threat posed by winter annual grass weeds. Herbicide resistant *L. rigidum* populations currently represent the main problems for wheat growers in Southern Europe, causing significant economic losses due to yield reduction and higher costs for additional herbicide applications. HWSC tactics could provide an important contribution to manage *L. rigidum*. The concurrent maturity of *L. rigidum* with winter wheat indicate that HWSC has a potential for the control of this weed species. For *L. multiflorum*, the situation in Europe is very similar to Australia where the high frequency of herbicide resistant *L. rigidum* populations triggered the introduction of HWSC tactics. *A. myosuroides*, *A. spica-venti* and *L. multiflorum* are the main winter annual grass weeds in wheat production in central and North-western Europe, with an increasing number of cases of resistance and multiple resistance to the most widely used post-emergence herbicides; acetolactate synthase (ALS) and acetyl-Coenzyme A carboxylase (ACCase) inhibiting herbicides (Keshtkar et al., 2015; Mahmood et al., 2016). The concurrent maturity of *L. multiflorum* with winter wheat provides an opportunity to collect its seeds during harvest and reduce seed return to the soil seedbank. Because of low seed retention at crop harvest in *A. myosuroides* there is reduced potential for HWSC in winter wheat but it might potentially have a greater efficacy in the earlier maturing winter barley or oilseed rape (Bitarafan and Andreasen 2020; Walsh et al. 2018b; Akhter MJ, Unpublished results). Although *A. myosuroides* sheds its seeds before crop maturity, it usually grows taller than the winter wheat (Akhter, 2020). The height of *A. myosuroides* provides an opportunity to cut the seed heads above the crop canopy before the seeds mature (BBCH 60-71) (Akhter et al 2020a). An added advantage of cutting the heads could be that the seed head regrowing from the cut plants will mature later and could potentially be targeted by HWSC tactics during crop harvest. *A. spica-venti* is ranked as one of the most competitive grass weed in winter wheat production systems in Europe (Akhter et al., 2021). The level of seed retention and its concurrent maturity with winter wheat indicate the potential of HWSC against *A. spica-venti* (Table 1). *A. fatua* and *Avena sterilis* are other problematic weeds in Europe. High variability of reported seed retention (10-84%) suggest that it will be difficult to predict the impact of HWSC on *Avena* spp. population dynamic. *Poa annua* L. is another frequently found weed species in Europe, particularly in Northern European countries (Andreasen and Streibig, 2011), however, because of the low plant stature, and multiple generations during a season, it is a poor candidate for HWSC. Recently, *V. myuros* has become a problematic weed in Northern Europe (Akhter et al 2020a). Due to its natural tolerance against ACCase inhibiting herbicides, there are only few herbicides available to control *V. myuros* and most only provide relatively low efficacies (Akhter, 2020c). *V. myuros* showed concurrent maturity with winter wheat (Unpublished results), therefore, HWSC could be helpful in managing *V. myuros*. Panicles of *V. myuros* are, however, not upright but bend downwards (San Martín et al., 2021), therefore, a low crop harvest height is needed to collect seed during harvest.

Broadleaved weeds of winter cereal and spring cereal crops, such as *Capsella bursa-pastoris* (L.) Medik., *Geranium molle* L., *S. media, F. convolvulus* and *S. arvensis* showed intermediate level of seed retention, erect growth habit and weed seeds present at a height where they can be collected during harvesting, and were classified intermediate candidate of HWSC (Bitarafan and Andreasen, 2020a; Bitarafan and Andreasen, 2020c). *Papaver rhoeas* L., is another broad leave species infesting winter cereals (Torra and Recasens, 2008). According to parameters used for considering HWSC, *P.*

rhoeas is classified as intermediate candidate for HWSC. The control of *P. rhoeas* with HWSC would be increased if crop harvest is advanced for one or two weeks (Westerman *et al*., 2012).

Aside from wheat, there is a potential for HWSC technologies in other major crops in Europe such as grain maize, grain sorghum and oilseed rape. In grain maize and grain sorghum, *Chenopodium album* L. and *Echinochloa crus-galli* (L.) P. Beauv. are important weed species across Europe. *Amaranthus* sp. and *S. halepense* are two species that frequently occur in these crops in Southern Europe. Seed retention studies under Northern European conditions suggested intermediate HWSC efficacy against *C. album* (Bitarafan and Andreasen, 2020c) (Table 1). Data from studies carried out in Australia and the US have demonstrated high seed retention in *Amaranthus* spp (98%), and intermediate seed retention in *E. crus-galli* (41%), indicating potential of HWSC against these weed species (Schwartz-Lazaro et al., 2017). In Southern Europe, soybean producers are facing increasing problems in controlling ALS-resistant *Amaranthus* spp. populations and resistance problems are increasing after the identification of ALS-resistant *A. palmeri* populations in Italy and Spain (Milani et al 2021; Torra et al 2020). Given that extremely high seed retention was reported for several *Amaranthus* spp. across many sites in the US under different environmental conditions (Schwartz-Lazaro et al 2021), these species are ideal candidates for HWSC in spring crops also in Southern Europe. There is no published information on *S. halepense* weed seed retention at maturity under European conditions, but a high level of seed retention at crop harvest (approx. 75%) was observed during assessments conducted for three years in soybean fields in Northern Italy with some variability across sites (Loddo D, personal communications). Further, a study from the US demonstrated high level of seed retention in *S. halepense* (>96%), making this species a potential candidate for HWSC (Schwartz-Lazaro et al., 2021b). The potential of HWSC against other important weeds in Europe is presented in the Table 1.

5.4. HWSC and IWM

An effective IWM approach limits weed germination, crop-weed competition and seed return to the soil seedbank (Kudsk et al 2020b; Riemens et al 2022). HWSC is a strategy that targets weed seeds at harvest and reduces seed return and ultimately limits weed density and thus crop-weed competition. To achieve sufficient weed control and to prevent further losses of viable herbicide options, farmers will have to change their practices and adopt more IWM approaches. IWM approaches should combine several weed management tactics, where the combined effect of early and late season weed control tactics can reduce weed populations to low levels (Walsh et al. 2013). HWSC, as a late season weed control strategy, is a potential tactic that farmers could consider. A simulation study from the US using the PAM (Palmer Amaranth Management) model assessed the impact of HWSC in combination with a standard weed management program practiced in maize and soybean. The results from this analysis showed that HWSC, applied annually with an efficacy of 50%, could reduce the size of the seed bank of *A. palmeri* up to 73% in 5 years (Shergill et al., 2020a).

To demonstrate the potential of HWSC on *L. multiflorum* in European cropping systems, we performed a case study using the DK-RIM (Danish Ryegrass Integrated Management) model (Sønderskov et al 2020) to visualize the long-term impact of different levels of HWSC on the development of a population of *L. multiflorum* in winter wheat-spring barley crop rotation. Population densities were assessed in terms of number of *L. multiflorum* seeds in the soil per m^{-2} at the beginning of the following season over a period of 10 years. In the DK-RIM model, a density of 20 *L. multiflorum* plants m^{-2} was used to initiate the simulations. This density represents a significant weed control problem that is likely to stimulate the adoption of an alternative weed control technique. Details on the DK-RIM model and employed parameters are described in Sønderskov et al. (2020). The herbicide programme for winter wheat was prosulfocarb pre-emergence followed by iodosulfuron-methyl-sodium post emergence. The herbicide program for spring barley consisted of iodosulfuron-methyl-sodium post emergence. Three levels of HWSC efficacy (30%, 60% and 90%) were included plus a control treatment without application of HWSC. The DK-RIM predicted that a HWSC efficacy of 30% reduced the size of the seed bank by 45 and 65% after 5 and 10 years, respectively, compared to the control treatment, while an increasing HWSC efficacy resulted in soil seed bank reductions between 75 and 90% after 5 years and reductions above 90% after 10 years (Fig. 1). The study suggests that an annual application of HWSC practices could potentially diminish the weed seed bank significantly when included as part of a IWM program that also includes effective herbicide use.

6. Potential for weed adaptation to HWSC

Adaptation or resistance evolution has been observed to evolve when weed populations are repeatedly exposed to strong selection pressure in terms of specific weed management strategies (Diggle et al., 2001; Neve and Powles, 2005). Adaptation to hand weeding, mowing and grazing has been reported worldwide (Barrett and Wilson, 1981; Chavana et al., 2021; Gould, 1991; McKinney and Fowler, 1991). HWSC technologies will, like other weed management tactics, exert a selection pressure, and if that selection pressure is strong enough, adaptation will evolve to counteract HWSC. Various adaptive traits could reduce the amount of retained seeds at harvest. Early flowering is an important potential approach for weed plants to escape HWSC tactics (Ashworth et al., 2016; Walsh et al., 2013). Early flowering in response to different environmental conditions has been reported in populations of several agronomically important weeds e.g., *S. media*, *R. raphanistrum*, *V. myuros*, *S. halepense* (Akhter et al., 2020a; Ashworth et al., 2016; Lososová and Simonova, 2008), showing their potential to adapt as a response to repeated selection pressure. Moreover, evolutionary changes in the timing and intensity of seed shattering can also occur in weeds, for example, adaptation in seed shattering patterns has been reported in a range of species including *S. halepense, R. raphanistrum*, *Oryza sativa* (Ellstrand et al., 2010; Shergill et al., 2020a).

Implementing HWSC could result in shifts in the weed flora. For example, HWSC could control only those weed species susceptible to this tactic which may result in an increased future abundance of weed species not targeted by HWSC (Shergill et al., 2020a). Although weed adaptation to HWSC has not yet been reported in field experiments, the potential remains and must be taken into account when designing HWSC approaches (Ashworth et al., 2016; Walsh et al., 2013).

Recognising that weeds will adapt to HWSC as to any other weed management tactic, there is a common understanding that HWSC methods need to be used in a way that long term efficacy of these tactics remains intact. For example, the combination of HWSC with crop rotation would contribute to the delay in the adaptation of the biology of weeds to these techniques.

7. Future research needs

To date research in Europe has mainly focused on weed seed retention studies. Results from these studies clearly demonstrate the need for continued research efforts on HWSC. Based on crop and weed biological parameters, we have classified the susceptibility of weeds to HWSC under European conditions. From the studied weed species, three were classified as good candidates for HWSC, thirteen species showed intermediate susceptibility, and five species showed low level of susceptibility to HWSC (Table 1). However, this information was derived from studies in a limited number of crop types. Further research is needed to assess the potential of HWSC for a range of crops including soybean, corn and sugar beet. Several weed species, such as *S. halepense*, *P. annua*, *Elymus repens*, *Amaranthus* spp. and *E. crus-galli*, are equally important in European cropping systems, but no data on seed retention rates are available on these weed species in the European region. Future studies are needed to determine the proportion of seed retention on these weed species in order to evaluate their susceptibility to HWSC. Future research should also evaluate the potential influence of environment and agronomic factors such as temperature and wind on seed shattering.

The next step for the research should be to evaluate different HWSC methods to enable the adoption of these tactics in the European cropping systems. More specifically there is need to assess the practicalities of different available HWSC systems, evaluate their efficacies and usage in different crop rotations, determine required operating costs and suitability across different regions and cropping systems in Europe. Another important task is to conduct long-term and on-farm studies to support the adoption of HWSC systems across the continent. Considering reasons mentioned above (section 4), chaff lining and tramlining, and integrated impact mills should be given priority in the long term HWSC evaluation. There are some reports suggesting that impact mills will be less effective when crop residues contain high moisture contents (>12%) at the time of harvest (Schwartz-Lazaro et al. 2017b; Walsh et al. 2018b). The introduction of impact mill systems into European cropping systems will require to evaluate the influence of frequent cold and humid harvest environments on the efficiency of impact mills.

Seed persistence in the soil plays a role in determining the success of HWSC. Species with short seed persistence can easier be exploited with HWSC compared to species with long seed persistence. For example, HWSC would show results faster if targeting seeds with short longevity in soil (like many grasses) compared to species with long longevity (like many broadleaved weeds). Future research should evaluate the potential impact of seed persistence on the success of HWSC. Moreover, there is a need to assess the long-term impact of HWSC strategies on weed populations dynamics when integrated with other IWM tools to understand its significance in weed management programs. For example, it can be expected that late sowing might delay weed maturity and consequently reduce seed shattering and increase the efficacy of HWSC. Future studies should also assess the impact of sowing date on the efficacy of HWSC. There are several challenges that can hamper the practical implementation of HWSC in Europe, and farmers should be involved in research activities to drive HWSC adoption.

To date research on HWSC has been conducted mainly in Northwestern European countries, and in a limited number of crops, while little research has been performed in other parts of Europe. It is not clear whether results from Northwestern Europe are representative for other European countries with dissimilar weed flora, climatic conditions, cropping systems, geography, land holdings and economic conditions. Further research is needed in other parts of Europe to address the knowledge gap.

8. Conclusion

For annual weed species which retain a significant proportion of their seeds until crop harvest, HWSC is an effective IWM tool for disrupting the reproductive cycle. The need for alternative non-chemical weed control options due to widespread evolution of herbicide resistance and a decreasing number of available herbicide active ingredients make HWSC an interesting tactic in Europe. Weed seed retention studies highlighted the potential of HWSC for weed species with specific characteristics. HWSC shows a high potential in winter wheat cropping systems because of the threat posed by winter annual grass weeds with life cycles similar to the autumn sown crops. Nonetheless, research to evaluate the different HWSC approaches in commercial fields is lacking but is needed to understand the impact of HWSC systems on weed population dynamics. To promote the practical implication of HWSC in Europe, the regional differences in cropping systems, occurrence in weed species and the climatic conditions that influence the adoption of this tactic must be understood. Other HWSC challenges in European production systems are a longer growing season, later harvest and more humid conditions at harvest, particularly in Northwestern Europe, compared to regions where HWSC is adopted in Australia. Like the evolution of herbicide resistance in weeds enable them to sustain herbicide use, weeds may adapt to the continuous use of HWSC systems through selection of plant traits such as early seed shattering, lodging and shorter plant height that allows plants to escape HWSC methods. Therefore, as recommended for other weed control tactics, diversity in weed management approaches is essential on the long-term to achieve sustainability of this tactic. In addition to practical obstacles, a collective effort is required to overcome the barriers among farmers to adopt HWSC in IWM strategies in Europe.

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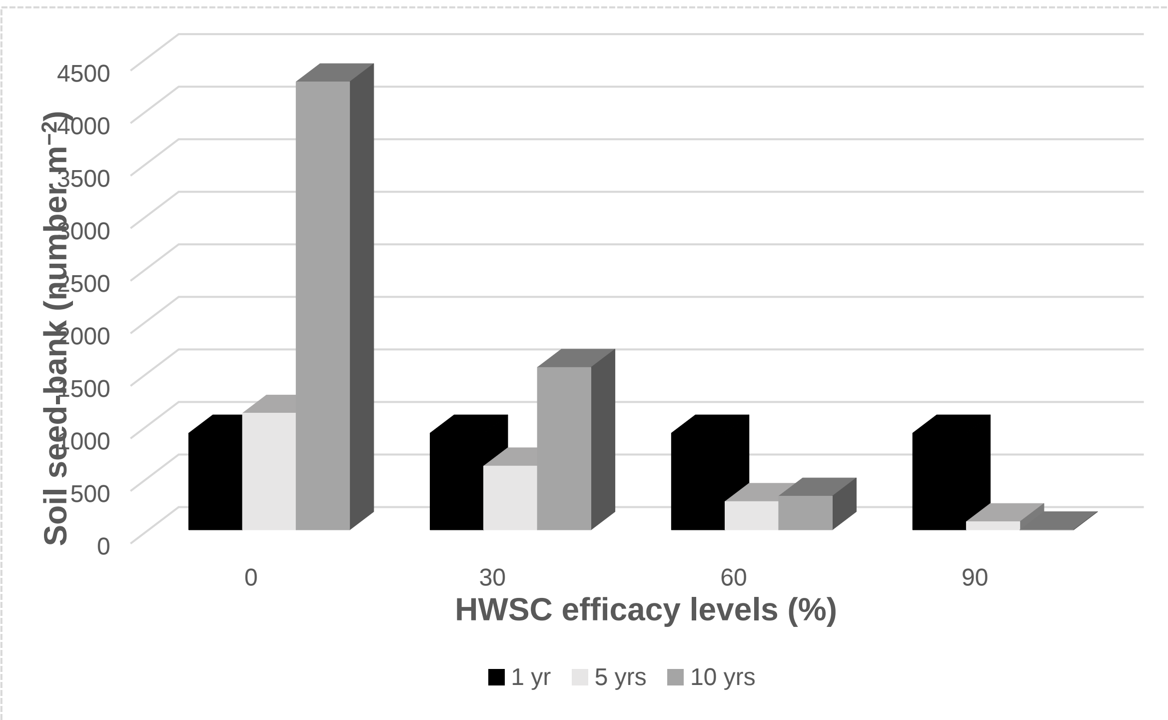

Figure 1. Results from three scenarios generated by the DK-RIM (Danish - Ryegrass Integrated Model) modelling the impact of different efficacy level of the HWSC tactic on the long-term soil seedbank of *Lolium multiflorum* in wheat–barley crop rotation over 10-year period. The herbicide program used in winter wheat and spring barley was pre-emergence prosulfocarb (Boxer, 800 g L^{-1} prosulfocarb, Syngenta Crop Protection A/S, Denmark) followed by post-emergence iodosulfuron-methyl-sodium (Hussar Plus OD, 0.14 L ha^{-1}, Bayer A/S, Germany) and post-emergence iodosulfuron-methyl-sodium (Hussar Plus OD, 0.14 L ha^{-1}, Bayer A/S, Germany), respectively.

Table 1. Growth characteristics, seed-retention values and estimated potential for HWSC for commonly found weeds at crop maturity in European cropping system. The crop and country indicate where the related studies were conducted.

Species	Seed retention (%)	Stem type	Plant height (cm)	HWSC potential	Crop, Country	References
Alopecurus myosuroides	29-37	Erect	80	Low	Wheat, Denmark	(Bitarafan and Andreasen, 2020b; CABI, 2021a)
	14				Wheat, Denmark	(Unpublished results)
Apera spica-venti	16-53	Erect	129	Intermediate	Wheat, Denmark	(Bitarafan and Andreasen, 2020b; Akhter et 2020c)
	22				Wheat, Denmark	(Unpublished results)
Avena species	20	Erect	120	Low	Wheat, UK	(Holm et al., 1977; Schulz et al., 2014; Feldman and Reed, 1974)
	10-20				Wheat, UK and Spain	(Barroso et al., 2006)
	84				Wheat, Germany	(Walsh et al., 2013; Wilson, 1970)
Anagallis arvensis	62	Procumbent and ascending stem	10-40	Poor	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Holm et al., 1977)
Bromus hordeaceus	41	Erect, rarely ascending	100	Intermediate	Wheat, Denmark	(Glasner et al., 2019)
Bromus diandrus	40-50	Erect to ascending	30-90	Intermediate	Wheat, UK and Italy	(CABI, 2021b)
Capsella bursa-pastoris	53	Erect	10–50	Intermediate	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Korsmo et al., 1981)
Cirsium arvense	11	Erect	150		Wheat, Denmark	(Glasner et al., 2019)
Chenopodium album	67	Erect	20-90	Intermediate	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Korsmo et al., 1981),
Fallopia convolvulus	44	Decumbent to erect	200	Intermediate	Oat, Denmark	(Bitarafan and Andreasen, 2020a; Korsmo et al., 1981)
Galium aparine	100	Ascending, sometimes erect	120	Good	Wheat, Denmark	(Glasner et al., 2019; CABI, 2021c)
Geranium molle	58	Erect	15-30	Intermediate	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Chen and Wang, 2005)
Lolium multiflorum	62	Erect	88	Intermediate		(Unpublished results ; Akgun et al., 2008)
Lolium rigidum	96	Erect	90	Good	Wheat, Spain	(Blanco□Moreno et al., 2004)

Papaver rhoeas	20-32	Erect to ascending	20-80	Intermediate	Winter cereals, Spain	Westerman et al (2012)
Persicaria maculosa,	32	Prostrate, ascending or erect	30–100	Low	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Korsmo et al., 1981)
Polygonum aviculare	59	Procumbent or ascending	5–60	Poor	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Korsmo et al., 1981)
Sinapis arvensis	67	Erect to ascending	30-60	Intermediate	Oat, Denmark	(Bitarafan and Andreasen, 2020a; Korsmo et al., 1981)
Silene noctiflora	96	Erect to ascending	25-60	Good	Oat, Denmark	(Bitarafan and Andreasen, 2020c; McNeill, 1980)
Sonchus arvensis,	23	Erect	60-150	Low	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Korsmo et al., 1981)
Spergula arvensis	45	Prostrate to erect	15-40	Intermediate	Oat, Denmark	(Bitarafan and Andreasen, 2020a; Korsmo et al., 1981)
Stellaria media	56	Ascending to erect	20-60	Intermediate	Oat, Denmark	(Bitarafan and Andreasen, 2020a; Korsmo et al., 1981)
Veronica persica	52	Prostrate	10-50	Poor	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Holm et al., 1997),
Viola arvensis	34	Prostrate, ascending or erect stem	15-35	Low	Oat, Denmark	(Bitarafan and Andreasen, 2020c; Korsmo et al., 1981)
Vulpia myuros	64	Erect or ascending,	117	Intermediate	Wheat, Denmark	(Unpublished results; Akhter et al 2020c)