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REVIEW ARTICLE

EDITOR'S CHOICE

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Current and future glyphosate use in European agriculture

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Abstract

There has been a longstanding and contentious debate about the future of glyphosate use in the European Union (EU). In November 2023, the European Commission approved the renewal of the use registration for glyphosate for a further 10 years. Nevertheless, the EU Farm to Fork strategy calls for a 50% reduction in pesticide use by 2030. In November 2022, the European Weed Research Society organised a 2 day workshop to identify critical glyphosate uses in current EU cropping systems and to review the availability of glyphosate alternatives. Workshop participants identified four current, critical uses in EU cropping systems; control and management of perennial weeds, weed control in conservation agriculture, vegetation management in tree and vine crops and herbicide resistance management. There are few herbicide alternatives that provide effective, economic, broad-spectrum control of weeds,

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particularly perennial weeds. Mechanical weed control, and in particular, soil cultivation is the most obvious glyphosate alternative. However, this is not possible in conservation agriculture systems and, in general, increased soil cultivation has negative impacts for soil health. Emerging technologies for precision weed control can enable more targeted use of glyphosate, greatly reducing use rates. These technologies also facilitate the use and development of alternative targeted physical weed control (e.g. tillage, lasers, electricity), reducing the energy and environmental costs of these approaches. In tree crops, the use of organic and inorganic mulches can reduce the need for glyphosate use. In general, reduced use of glyphosate will require an even greater focus on integrated weed management to reduce weed establishment in agroecosystems, increase weed management diversity and limit the use of alternative resistance-prone herbicides.

KEYWORDS

conservation agriculture, integrated weed management, perennial weeds, resistance management, site-specific weed management, soil cultivation

1 | INTRODUCTION

Glyphosate-based products have been registered and commercialised in Europe since 1974. For much of that time, glyphosate has been extensively used in global agriculture for broad spectrum weed control. However, in the mid- to late-1990s, the introduction of genetically modified glyphosate-tolerant crops precipitated a large global increase in glyphosate use and sales (though these crops were not registered for use in the EU). In 1994, the total global use of glyphosate in the agricultural sector was 56 296 tonnes of active ingredient increasing to 746 580 t in 2014 (Antier et al., 2020) and with some estimates suggesting use will rise to 920 000 t by 2025 (Maggi et al., 2020). In 1995, 18% of the global volume of glyphosate use was in Western Europe (Woodburn, 2000). However, by 2015, the share of the global sales of glyphosate used in Europe had reduced to 4% (Kleffmann Group, 2017).

Glyphosate has been described as a 'once in a century herbicide' because of its high efficacy, environmental safety and low cost (Duke & Powles, 2008). Nonetheless, glyphosate use has come under scrutiny in the EU, particularly following the classification of glyphosate as a carcinogen by the International Agency for Research on Cancer in 2015. In 2017, following a lengthy discussion and two temporary extensions, its approval was renewed in the EU, although only for a 5 year period (for more details see Kudsk & Mathiassen, 2020). During the subsequent EU renewal process, the European Commission (EC) extended the existing approval by 1 year to 15 December 2023 following updated evaluation timeline requirements from the European Food Safety Authority (EFSA) and the European Chemicals Agency. In July 2023, EFSA officially communicated its conclusion that glyphosate meets all necessary approval criteria outlined in Article 4 of the EU Plant Protection Regulation. In subsequent deliberations, the EC and Member States considered not only EFSA's conclusion but also societal and political factors. On 28 November 2023, the European Commission implemented regulation 2023/2660 renewing the approval for the use of glyphosate for a further 10 years in accordance with regulation number 1107/2009. The new regulation prohibits the use of glyphosate for pre-harvest crop desiccation, sets maximum use rates per hectare per year (reduced from 2.16 to 1.44 kg a.i. ha^{-1} $year^{-1}$ in agriculture) and establishes additional requirements for reducing impacts on environmental quality and biodiversity. The reduction in maximum use rate may reduce control of some perennial, dicotyledenous weeds and could make it more difficult to obtain complete destruction of some permanent/perennial grasslands and cover crops.

Although European use of glyphosate only accounts for 4% of the global sales, it is nonetheless a very important herbicide in Europe and a complete ban on the use of glyphosate is expected to have significant impact on weed management and the profitability of current European agricultural systems. Several studies have been conducted in recent years assessing the economic implications of a glyphosate ban at crop or farm level and these were reviewed by Finger et al. (2023). Estimated losses have ranged from 1 to 2 EUR ha^{-1} in silage maize (*Zea mays* L.) (Böcker et al., 2018) to 553 EUR ha^{-1} in grapevine (Jacquet et al., 2021). Recently, Wynn and Webb (2022) reported that, assuming a worst-case scenario, the total costs at EU-level (before the UK exit) of a glyphosate ban will be 10 500, 1900 and 4220 million EUR for the wheat, (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.) and vines (*Vitis vinifera* L.) sectors respectively. Even with the recent re-registration of glyphosate, EU member states may seek to reduce glyphosate use ensuring that it is only used where and when no alternatives are available, where the agronomic and economic benefits are confirmed or where, for example, new technologies enable targeted applications that could reduce field and farm scale use volumes.

It was in the light of this potential scenario that the European Weed Research Society (EWRS) decided to bring together a group of European weed scientists for 2 days in Prague in November 2022 to discuss critical and expendable glyphosate uses and sustainable ways to reduce the use of glyphosate. Regardless of possible future restrictions on glyphosate use, this discussion is timely. Glyphosate is the most widely used pesticide in Europe and with the EU Farm to Fork strategy requiring a 50% reduction in pesticide use and risk by 2030, considering ways to reduce reliance on glyphosate as a high-volume herbicide is a key consideration to meet this goal. This paper is the outcome of the scientific discussions during the meeting.

2 | CURRENT GLYPHOSATE USE IN EUROPEAN AGRICULTURE

Although glyphosate is the most widely used and intensively discussed pesticide active ingredient in Europe, no collated and publicly available statistics, or data on the volume of glyphosate sales or uses are available. Therefore, in 2019, the European ENDURE network (ENDURE, 2023) initiated a survey to gain insights into the sales and uses of glyphosate in the agricultural sector of Europe and neighbouring non-EU countries. The survey also aimed at classifying glyphosate uses in different crop types for further glyphosate use monitoring studies. The survey covered the 28 EU countries (including UK in 2019) plus four non-EU countries (Norway, Serbia, Switzerland and Turkey; EU28+4) and was based on a questionnaire sent to national contact points in each country (see Antier et al., 2020 for details). For countries where the gathered data were incomplete, estimates using Eurostat data from 2017 were made and subsequently validated by national contacts.

On average, 90% of glyphosate sales at the EU28+4 level in 2017 were in the agricultural sector (Antier et al., 2020). Glyphosate sales represented, on average, 33% of the total sales of herbicide active ingredients but its importance varied considerably between countries with glyphosate accounting for between 15% and 78% of the total national sales of herbicide active ingredients. The survey identified annual cropping systems, perennial tree crops and grassland as the three main agricultural systems in which glyphosate was used, though with different objectives in each system.

In annual crops, the primary uses of glyphosate are for the termination of cover crops, the control of weeds before crop sowing, control of weeds prior to harvest and for crop desiccation (no longer permitted following re-registration). The control of weeds prior to crop sowing, particularly perennial weeds, was highlighted by the workshop participants as one of the most important current major uses of glyphosate in Europe. This practice enables conservation agriculture (CA) by removing the need for inversion tillage, which provides agronomic, ecological and environmental benefits in terms of increased soil health, fertility and carbon sequestration, and reduced fuel consumption.

According to the survey, an average of 25%–52% of the acreage planted with wheat, oilseed rape (*Brassica napus* L.), and maize (*Zea mays* L.) received an annual application of glyphosate in the EU28+4. There was considerable variation between countries in both the area treated and glyphosate use rates (Antier et al., 2020).

In perennial crops, glyphosate is used to control weeds between or within rows of tree crops. On average, 32%–45% of the perennial crop acreage of fruits, olives and vines received an annual glyphosate application in the EU28+4. The use of glyphosate in perennial crops was also identified as an important current use during the EWRS workshop due to a lack of alternative herbicides with comparable efficacy on perennial weeds at late growth stages and the economic disadvantages associated with non-chemical weed management options.

In grassland, glyphosate is used for the renewal of permanent grassland or the control of perennial weeds using site-specific applications. According to the survey, 19% of the temporary grassland acreage was treated with glyphosate.

According to Antier et al. (2020), agricultural use of glyphosate can be classified into a) recurrent uses in farming systems characterised by a high dependence on glyphosate (pre-sowing weed control, perennial weed control, weed control in perennial crops, termination of cover crops) and b) occasional, unplanned uses related to specific climatic or agronomic conditions (e.g. following high precipitation rates resulting in the need for crop desiccation). In the former, glyphosate application is an integral part of the cropping system. Examples of such systems are CA or minimum tillage systems where the use of glyphosate replaces cultivation for weed control, especially for the control of weeds before sowing, and for the termination of cover crops.

Another major use of glyphosate identified during the EWRS workshop is its application to control herbicide resistant weeds, especially grasses. Some grass weed species in Europe, such as *Alopecurus myosuroides* and *Lolium* spp., have evolved resistance to several selective herbicide modes of action, such as ACCase and acetolactate synthase (ALS) inhibitors. Evolved resistance to glyphosate has been reported in Europe in nine weed species (Heap, 2023), predominantly in perennial tree and vine crops where it is used annually for total weed control. In annual crops, despite intensive glyphosate use for weed control before crop sowing, there have been few reports of glyphosate resistance (Collavo & Sattin, 2014; Comont et al., 2019). Given its apparent low resistance risk, glyphosate is often promoted as a valuable tool for managing and mitigating evolution of resistance to selective modes of action.

3 | CRITICAL GLYPHOSATE USES IN EUROPE

Based on a series of presentations and discussions and further informed by the Antier et al. (2020) study, workshop participants identified the most common uses of glyphosate in European cropping systems, highlighting four critical glyphosate uses in European agriculture (Figure 1). These four critical uses were (i) managing and

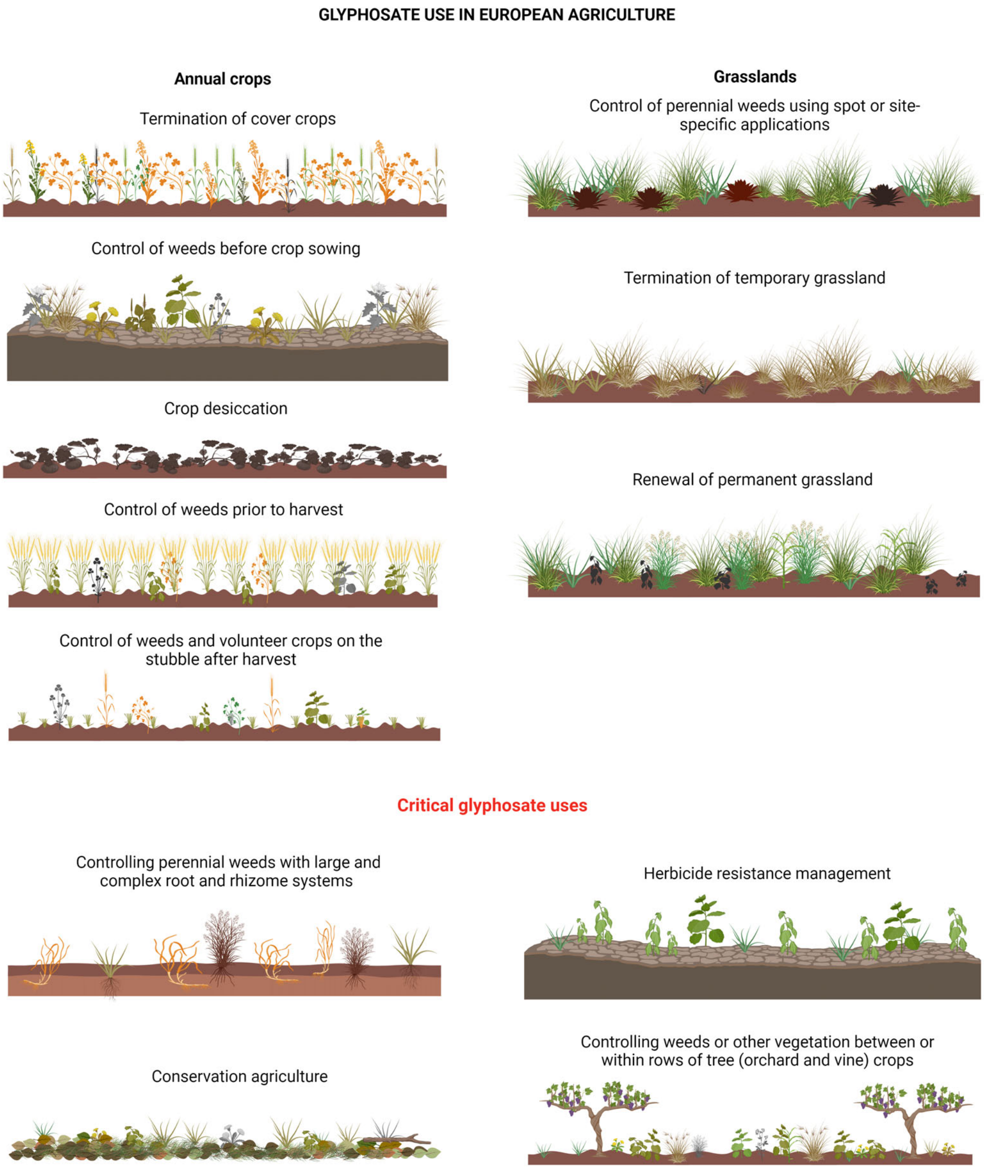

FIGURE 1 A graphical summary of major glyphosate uses in European annual, grassland, tree and vine crops. The four critical uses were identified as those where fewer alternatives are available or where alternatives have known and unknown environmental and economic costs or trade-offs.

controlling perennial weeds in arable cropping systems (ii) chemical weed control in reduced tillage and CA systems (iii) weed control in tree (orchard and vine) crops and (iv) herbicide resistance management. Each of these four uses is discussed further below.

3.1 | Managing perennial weeds

Due to its high systemic phloem mobility *in planta*, glyphosate is very effective at controlling perennial weeds with large and complex root and rhizome systems (e.g., *Elymus repens*, *Cirsium arvense*, *Rumex obtusifolius*, *Cyperus esculentus*, *Cynodon dactylon*, *Sorghum halepense*). Often, perennial species are highly competitive to crops and once established, can be difficult to control without systemic herbicides, especially if their roots/rhizomes are tolerant to tillage. Their roots/rhizomes enable perennial weeds to reshoot following tillage and/or defoliation and, added to this, tillage implements can result in the breakage and movement of propagules (root fragments, rhizomes etc.) within fields, leading to weed dispersal. For these reasons, glyphosate is considered a critical tool for perennial weed control.

3.2 | Conservation agriculture

Currently, glyphosate use is an important component of CA. According to the FAO (ECAF, 2020; FAO, 2023), CA is described as an ecosystem approach to regenerative, sustainable agriculture based on the application of three interlinked principles (i) minimum mechanical soil disturbance (ii) permanent maintenance of a vegetative soil cover and (iii) diversification of species. In 2020, the European Conservation Agriculture Federation (ECAF, 2020) determined that applying herbicides was the most common weed control method used by farmers and regardless of the type of soil management, 88% of farmers used glyphosate to control weeds at pre-sowing or pre-emergence. The use of glyphosate for other purposes, like the termination of cover crops or desiccation before harvest, accounted for 19% of total use.

In a survey conducted by ECAF, 35% of farmers indicated that they could not find a cost-effective alternative to glyphosate (ECAF, 2020). The main alternative to glyphosate in European CA would be to intensify tillage and 38% of the farmers surveyed chose this option if glyphosate were banned. The ECAF survey results identify challenges for the future of CA in the absence of glyphosate, with 32% of the CA farmers indicating they would return to conventional tillage, and 50% that they would adopt a more intensive 'minimum' tillage (ECAF, 2020).

Two further considerations are important. Firstly, it takes several years to overcome the negative effects of tillage-based agriculture when in transition to CA. Secondly, any herbicide replacement should ideally be effective, inexpensive, non-selective, systemic (translocated) herbicide, able to control both annual and perennial weeds, including grasses and broadleaved, and with little or no soil residual effect. Chemical alternatives to glyphosate are currently more expensive and less effective. However, in future CA systems, where there is increased pressure to limit glyphosate (and herbicide use in general), compromises between herbicide efficacy and use, tillage frequency and intensity, and the use of alternative non-chemical controls may become necessary.

3.3 | Weed control in tree (orchard and vine) crops

Conventional practices for managing weeds in tree crops typically involve a combination of mechanical and chemical control methods. Mechanical controls include tillage, mowing, and hoeing in the alleys between tree rows (Mas et al., 2007; Miñarro, 2012). In vine crops, mechanical weeding can also be carried out beneath the crop plants (Valencia-Gredilla et al., 2020). From an integrated weed management (IWM) perspective and with the spread of organic farming in tree crops, other cultural weed control methods including mulching and cover crops are increasingly being used (see Section 4.3.2). Herbicides are commonly used for weed management under the tree rows, with both pre- and post-emergence applications being employed. Glyphosate is the most widely used post-emergence herbicide due to its effectiveness, versatility, and cost-efficiency and glyphosate is used on 50% of the acreage of perennial crops every year compared to 30% for annual crops in Europe (Antier et al., 2020). In this way, glyphosate has enabled and encouraged the adoption of reduced soil disturbance or non-till practices in tree crops, limiting damage to tree roots and reducing soil erosion.

3.4 | Herbicide resistance management

In some European cropping systems, glyphosate has become an important component of IWM strategies, particularly with respect to herbicide resistance management. To date in Europe, there have been 427 independent confirmed cases of herbicide resistance evolution (each case represents a unique species by country and herbicide mode of action combination) (Heap, 2023). Of these cases, 174 report resistance to ALS inhibiting herbicide (HRAC group 2), while there are 46 cases of resistance to acetyl-coA carboxylase (ACCase) inhibiting herbicides (HRAC group 1). These numbers indicate an over-reliance on these two herbicide modes of action in European agriculture during the last 40 years, partly due to the withdrawal of much of the 'older' chemistry as a result of the re-current review of active ingredients in the EU. Glyphosate has been used in European agriculture since 1974, yet the first cases of evolved resistance to glyphosate in Europe were only reported in 2004 (Heap, 2023). Currently, there are 34 unique cases of glyphosate resistance reported in Europe. Whilst over-use and exclusive reliance on glyphosate for weed control are undesirable and unsustainable, it is clear that glyphosate carries a relatively low risk of rapid evolution of resistance (in the continued absence of glyphosate tolerant crop use in Europe) compared to other herbicide mode of action classes. This fact makes glyphosate a crucial component of IWM strategies that aim to reduce selection for resistance by maximising herbicide mode of action diversity within and between cropping seasons. For example, the use of false seed beds and delayed crop sowing provides an opportunity to encourage an early emergence of a weed cohort before a crop becomes established (Moss et al., 2007). Controlling these early emerging weed cohorts with glyphosate provides a means to diversify herbicidal weed control and reduce selection for resistance to other pre- and post-emergence herbicide modes of action in situations where the use of weed harrowing is not possible or desirable. Additionally, such glyphosate use could also reduce weed emergence in the following crop and allow for a lower combined herbicide use. In this regard, in Europe where genetically modified glyphosate tolerant crops are not grown, glyphosate maintains a unique position in resistance management and IWM strategies.

4 | OPTIONS FOR REDUCING GLYPHOSATE USE IN EUROPE

While the future regulatory status of glyphosate in Europe remains uncertain, the need to reduce reliance on pesticides by 50% is already established by the EU Farm to Fork strategy. In this context, there is a strong imperative to maintain glyphosate for situations where there are limited effective alternatives, and to seek to develop alternative tools, technologies and systems that reduce reliance on glyphosate. Workshop participants discussed the four critical uses identified above to assess which alternatives are available (Table 1), evaluate the trade-offs associated with their use, determine their technology readiness level (TRL) and identify further research required to maximise their potential and practical adoption.

4.1 | Controlling perennial weeds without glyphosate in annual crops

Here, we distinguish between direct control alternatives for glyphosate (options that result in removal and mortality of established plants)

TABLE 1 A summary of major identified alternatives for critical glyphosate uses and their agronomic advantages and disadvantages.

	Agronomic outcome		
Alternatives for glyphosate uses	**Advantages**	**Disadvantages**	**References**
Physical			
Tillage (not suitable for conservation agriculture)	Loosening of compacted surface soil, incorporation of crop residues, crop root disease control	Removes soil cover which increases the risk of soil erosion, nutrient leaching, CO2 losses negative effect on soil health and structure, weed control efficacy dependent on equipment, frequency of application and climatic and soil conditions. Reduction of important ecosystem services, for example, weed seed predation can increase perennial weed propagation if used incorrectly.	Lindstrom et al. (1992), Westerman et al. (2003), Baumgartner et al. (2007), Reicosky and Archer (2007), Anderson (2009), Davis et al. (2011), Aronsson et al. (2015), Thomsen et al. (2015), Hammermeister (2016) and Cooray et al. (2023)
Mowing	Retains soil moisture, mitigates soil erosion. Can be combined with some competitive crops such as leys and cover crops.	Repeated application required. Not effective against some perennial weed species.	Al-Mufti et al. (1977), Donald (2006) and Soriano et al. (2014)
Flaming/hot steam	Preserving soil structure and preventing leaching of nutrients	Repeated application required, short duration of efficacy, not effective against perennials and weeds at late growth stages, less effective against grass weeds, high operational costs and high greenhouse gas emissions caused by the burning of fossil fuels	Stefanelli et al. (2009), Shrestha et al. (2013), Granatstein et al. (2014), Lisek (2014) and Morselli et al. (2022)
Electro weeding	Preserving soil structure and preventing leaching of nutrients can damage and kill belowground organs of perennial weeds.	Primarily effective against small plants with shallow roots. Repeated application required, especially against large plants, grasses and perennial weeds. Most solutions currently on the market use a lot of energy, and some have a risk of causing fires.	Bloomer et al. (2022), Schreier et al. (2022) and Feys et al. (2023)
Root/rhizome cutters (controlling perennial weeds with large and complex root and rhizome systems)	Minimal soil inversion and disturbance, leading to low risk of erosion/nutrient leaching, loosening of compacted soil. Low energy is used compared to many forms of tillage.	Repeated application required. Does not target annual weeds, especially those with shallow roots. Not yet on the market.	Hakansson et al. (1998), Thomsen et al. (2011), Melander, Munier-Jolain, et al. (2013), Brandsæter et al. (2017, 2020) and Weigel et al. (2023)
Non-chemical termination of cover crops (e.g., roller crimper)	Reduced soil erosion and soil moisture conservation due to biomass on the soil surface, weed suppression	Efficacy of machinery often not sufficient and highly dependent on soil texture, moisture conditions, growth stage of the cover crop and amounts of plant biomass	Kornecki et al. (2009), Frasconi et al. (2019), Ashford and Reeves (2003) and Sportelli et al. (2023)
Dead organic or synthetic mulching	Preserved soil moisture, reduced evaporation and erosion. Organic mulch can provide nutrients and allelochemical effects.	Organic mulch often less effective and durable than synthetic material. High cost of some organic mulches. Inefficient control of many perennial species. Increased soil temperature.	Granatstein and Sanchez (2009), Granatstein et al. (2014), Lisek (2014), Hammermeister (2016) and Żelazny and Licznar-Małańczuk (2018)
Reducing seed production and replenishment of the seed bank (e.g., seed destruction)	Reduced demand for disturbance and competition for succeeding crop management.	Practicalities of different available systems and efficacy on different weed species not widely assessed under European conditions	Bitarafan and Andreasen (2020), Walsh and Powles (2022) and Akhter et al. (2023)

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TABLE 1 (Continued)

	Agronomic outcome		
Alternatives for glyphosate uses	**Advantages**	**Disadvantages**	**References**
Cultural			
Crop rotation diversification	Increased biodiversity and provision of ecosystem services, increased soil fertility and nutrient cycling, disease suppression	Lower profitability of some crop types. More knowledge intensive. Some crops require on-farm investment (e.g., specialised harvesting equipment) and/or off-farm investment (e.g., cleaning and processing facilities).	Liebman and Dyck (1993), Krupinsky et al. (2002), Tamburini et al. (2020), Weisberger et al. (2019), and Colbach and Cordeau (2022)
Increasing crop competition	Reduction of crop yield losses from weed competition and reduced weed seed bank replenishment	Insufficient information on individual competitiveness of crop varieties. Much knowledge and technology development needed to make alternative and more competitive cropping systems/options more viable such as intercropping, variety mixtures etc.	Lutman et al. (2013), Andrew et al. (2015), van der Meulen and Chauhan (2017), Sardana et al. (2017) and Gaba et al. (2018)
Cover crops/living mulch	Provides many side-benefits in addition to weed competition, for example, improved soil quality, reduced erosion, increased biodiversity, crop/livestock integration, water management, host to beneficial organisms (e.g., pollinators, seed predators)	Yield reductions due to competition for water and nutrients, cover crop species/type selection and management important, challenge of cover crop establishment in droughts. Can be hosts to detrimental organisms (e.g., plant diseases, aphids).	Lisek (2014), Mauro et al. (2015), Hammermeister (2016), Montanaro et al. (2017), Żelazny and Licznar-Małańczuk (2018) Duke et al. (2022), Fernando and Shrestha (2023) and van Eerd et al. (2023)
Chemical			
Selective herbicides	Target-specific weed control	Reduced control of larger and perennial weeds, limited weed spectrum. Some selective herbicides have worse environmental and/or health impacts than glyphosate.	Fogliatto et al. (2020)
Natural product-based herbicides (e.g., pelargonic acid)	Direct substitution for glyphosate	Primarily effective against small plants with shallow roots. Repeated application required, especially against large plants, grasses and perennial weeds. Requires high doses for acceptable efficacy, and efficacy highly dependent on environmental conditions.	Kanatas et al. (2021), Ganji et al. (2023) and Loddo et al. (2023)
Spot/patch spraying on stubble	Reduced herbicide costs and reduced environmental impact. Potential to benefit biodiversity and ecosystem services by not spraying all weeds (requires advanced weed species and weed developmental stage identification which is not fully developed currently).	Technical limitations (e.g., different biotic and abiotic disturbances, computational speed). May reduce efficacy as some weeds are misidentified and not treated.	Fernández-Quintanilla et al. (2018) and Allmendinger et al. (2022)

Note: Further details are found in the cited literature and in Section 4.

and indirect, cultural alternatives that reduce the establishment and growth of perennial weeds. The primary direct control alternatives are intensive tillage (e.g., multiple harrowing operations followed by ploughing or short-term fallows at the beginning of the growing season or in mid-summer after the first grassland harvest), selective herbicides, defoliation treatments (e.g., flaming, mowing) and non-tillage and non-herbicide methods that can directly affect roots/rhizomes (e.g., steaming, electricity, solarization) (Ringselle et al., 2020). The primary indirect control methods are effective crop rotations with competitive crops and cover crops. Combining the use of competitive crops and mechanical control can increase the control of some perennial weeds, for example, competitive ley crops that are regularly mowed are effective against some perennial weed species, but not others (Thomsen et al., 2015). Very high cutting-frequencies (e.g., weekly or biweekly) are effective against most species, but not for example *R. obtusifolius* (van Evert et al., 2020).

Tillage can have several positive agronomic effects, for example reducing plant diseases and preparing the soil for the next crop (especially relevant in northern Europe). However, intensive tillage can have a negative effect on soil health and structure and can increase the risk of soil erosion and nutrient leaching by increasing the period of time when soil is bare (Aronsson et al., 2015; Klik & Rosner, 2020). Intensive tillage is also difficult to combine with cover crops (Melander, Munier-Jolain, et al., 2013). Negative effects can be reduced to some extent by avoiding late season tillage, but in regions with a high risk of erosion (e.g., parts of Spain) even a few days without a crop or residue cover can carry significant risks. New tillage tools such as root/rhizome cutters, uprooting and rhizome removal technology, and precision hoeing present new opportunities to control perennial weeds with less soil inversion and associated risks of soil erosion (Ringselle et al., 2020). Prototypes of the vertical and horizontal root cutters have been tested against multiple perennial weed species, showing that the horizontal root cutter can reduce the expansion of *C. arvense* (Weigel et al., 2023) and the vertical root cutter can reduce *E. repens* in a growing grass-clover crop to the benefit of the crop (Ringselle et al., 2018) but that vertical root cutters are less effective in compacted soils (Ringselle et al., 2023) Precision hoeing, where the depth and angle of the hoeing implement can be continuously adjusted, could potentially be a more environmentally benign method for controlling perennial weeds, but the TRL is still low and the effect against perennial weeds is not very well studied (Gerhards et al., 2022). Machines that pull rhizomes from the ground (e.g. Kvikfinn) are already commercially available, but they are quite soil disruptive and are primarily effective against species with shallow roots/rhizomes such as *E. repens* (Lötjönen & Salonen, 2016).

As European cropping systems endeavour to transition towards net zero carbon emissions, it is also critical to recognise that intensive tillage requires more energy consumption than glyphosate use, and that some of the non-chemical alternatives to tillage (e.g., microwaves, electricity) are even more energy demanding. Emerging technologies that enable more precise targeting of weeds could significantly reduce the energy requirements of non-chemical alternatives in future (Coleman et al., 2019). However, using these technologies to enable targeted glyphosate spraying may be more resource efficient as alternatives such as electrical weed control, which can kill roots/rhizomes without soil cultivation, often require multiple passes and/or long treatment times to kill perennial weeds, especially established plants (Feys et al., 2023).

In Europe, the main current barrier to targeted glyphosate spraying on stubbles and/or for early season control of emerging weeds (so-called green on brown technology, see Allmendinger et al., 2022) is the low cost of glyphosate and the relatively high costs of precision spraying equipment, meaning that effective control of weeds (including perennial weeds) is still less costly and more efficient using conventional spraying systems. Increasingly, the ambition for image-based weed detection technologies is to develop algorithms that can distinguish weeds from crops and therefore enable the selective removal of weeds from crops (green on green technology, Allmendinger et al., 2022), though identifying specific weed species is still problematic, especially in crops and cover crops (Coleman et al., 2022). So far, using image-based mapping and identification is only feasible for some species (e.g., *C. arvense*, Rasmussen et al., 2021). As technologies continue to evolve and are brought to EU markets at affordable costs, the prospects for enabling and requiring targeted glyphosate application to reduce field-scale use rates for the control of perennial (and other) weeds present a promising way to greatly support EU herbicide use reduction targets. In Australia, real-time vision-guided weed control using green on green technology is resulting in up to 90% reduction in herbicide use in fallow (uncropped) fields (Beckie et al., 2019).

Using indirect control methods, such as diverse crop rotations and cover crops, to control perennial weeds would bring many benefits, such as increased biodiversity, soil health, and economic resilience (Beillouin et al., 2021). Moreover, using indirect methods in an IWM context to control perennial weeds would bring more weed diversity, and potentially prevent dominance by a few highly competitive, resistance-prone annual weed species (Adeux et al., 2019; Storkey & Neve, 2018). However, profitability-constraints hinder the adoption of many 'beneficial crops' such as leys that have the potential to control perennial weeds including *C. arvense* and *S. arvensis*. For other species, for example, *E. repens*, there is a need for more studies on how different cropping system approaches could sufficiently reduce the need for glyphosate applications without using intensive tillage (Ringselle et al., 2020).

4.2 | Glyphosate alternatives in CA

Weed control has been one of the main challenges for reduced soil tillage systems, so the discovery and introduction of selective (2,4 D, dicamba) and non-selective (paraquat, glyphosate) herbicides have facilitated the spread of CA all over the world, especially in dry regions. The extent of glyphosate use in CA systems depends on the intensity and frequency of tillage operations. No-till and reduced tillage systems rely more on glyphosate (Andert et al., 2018) due to higher pressure from perennial weeds, volunteer crops and weed species that prefer low disturbance systems (Lutman et al., 2013).

In CA systems, glyphosate is used to terminate cover crops, and to control volunteer crops, and surviving weeds before crop sowing. Replacement of glyphosate with selective herbicides in systems presents several constraints: reduced weed control spectrum, less effective control of larger weeds, difficulties with controlling perennial weeds and the increased risk of herbicide resistance (post-emergence applications). To be able to conduct CA with reduced use or even without glyphosate, we propose four alternative and synergistic non-chemical methods: (i) crop rotation diversification, (ii) non-chemical termination of cover crops, (iii) enhancing crop competitiveness, and (iv) introducing perennialised grain crops.

4.2.1 | More diverse crop rotation

Weeds typically emerge seasonally and are associated with specific crops. Diversification of species is one of three pillars of CA (FAO, 2023) and implementing more diverse field-specific crop rotations can effectively lower weed pressure and reliance on glyphosate. In this context to provide farmers with profitable crop options, research including modelling, and advances in breeding technologies and management practices for resilience to climate change is needed (Colbach & Cordeau, 2022). However, even with diverse crop rotations, the absence of glyphosate and minimal soil disturbance may lead to the establishment of problematic weeds, and especially perennial weeds like *C. arvense* and *E. repens*. To tackle this, ongoing research focuses on managing creeping perennials through, for example, low soil disturbance methods using mechanical tools that cut roots/rhizomes horizontally or vertically based on weed species (Brandsæter et al., 2017, 2020; Ringselle et al., 2018; Thomsen et al., 2015).

4.2.2 | Termination of cover crops

When cover crops are present, their efficient termination is crucial for weed-free seedbed preparation and to limit competition with the main crop (Rosario-Lebron et al., 2019) – the common method is glyphosate use. Alternatively, cover crops can be killed by winter frost in cold-temperate regions or actively destroyed through mowing, roller crimping, or other herbicide applications. Roller crimpers have emerged as a sustainable approach to terminate cover crops and create natural mulch in reduced tillage systems (Antichi et al., 2022; Kornecki, 2020). The discussion around tillage versus roller crimper approaches has attracted interest in Europe (Navarro-Miró et al., 2019), yet detailed research is needed to assess the effectiveness of prototypes across different soil textures, moisture conditions, and biomass levels, aiming to improve the tool and broaden its applicability (Sportelli et al., 2023). However, it is important to remember that for some cover crops, the use of a roller crimper alone may not be sufficient. Miville and Leroux (2018) found a glyphosate application prior to rolling winter rye mulch is crucial to achieve effective cover crop termination. Without glyphosate, there was rye regrowth that competed with the subsequent crop. Another option is using herbicides like pelargonic acid for cover crop desiccation. Ganji et al., 2023 found it reasonably effective within a week, but further research is needed to ensure its suitability for on-farm use and to refine technical application details.

4.2.3 | Competitive crops and cultivars

Gaba et al. (2018) showed that the effect of crop competition on the weed assemblage was much stronger than the effect of nitrogen fertiliser and even weed control. In the presence of a strong suppressive cultivar, annual weed species will have reduced seed production, which is a viable part of a long-term strategy in CA for weed control (Andrew et al., 2015; Melander, Nørremark, & Kristensen, 2013). To manage creeping perennial weeds in CA, closing gaps in competition by subsidiary crops (cover crops, catch crops, either under-sown in the main crop or established after harvest) is also an important strategic option (Favrelière et al., 2020; Teasdale et al., 2007; Thomsen et al., 2015).

4.2.4 | Cultivation of perennial and perennialised annual crops

Perennial forage crops like lucerne, clover, and grasses play a positive role in reducing the soil seedbank of annual weeds. Increasing their presence in crop rotations and harvesting them before weed seed dispersal benefits subsequent crop establishment in CA systems. Another area of research focuses on perennialised annual crops, aiming to make crop production more sustainable through reduced tillage, increased soil cover and carbon sequestration. Notably, efforts have been made to develop a perennial grain crop called Kernza® from intermediate wheatgrass (IWG) and a perennial rice (Zhang et al., 2023). Initial studies on Kernza® demonstrated low autumn weed biomass over 4 years, though spring weed biomass remained high (Duchene et al., 2023). Weeds did not significantly affect IWG yields, likely due to differing ecological requirements. Further research is necessary to confirm the efficacy of perennialised crops in weed management, particularly for perennial species, while ensuring acceptable yields for farmers.

4.3 | Weed management in tree crops with reduced glyphosate use

Here, we consider three broad categories of approach that could reduce the need for, and extent of, glyphosate use for broad spectrum non-selective weeds in tree crops. Cover crops between trees/vine rows can suppress weeds during their active growth and through residue management (Fogliatto et al., 2020). Dead/organic mulches offer a glyphosate-alternative option to manage intra-row weeds (Cabrera-Pérez et al., 2022). The role of precision agriculture methods is also considered critical for IWM in perennial crops (Fogliatto et al., 2020).

4.3.1 | Cover crop selection

Cereals are characterised by high biomass production and competitiveness (Sharma et al., 2021). In Greek olive groves, *Festuca* *arundinacea* Schreb. (tall fescue) reduced glyphosate-resistant *Conyza albida* Willd. ex Spreng. (fleabane) density by 77% (Travlos et al., 2017). Mauro et al. (2015) reported that *Avena sativa* L. (oats) reduced weed biomass by 58%–71% in orange orchards in Italy. In Spanish vineyards, barley cultivars suppressed *Cynodon dactylon* (L.) Pers. (bermudagrass) by shading the ground at the beginning of stolon formation (Valencia-Gredilla et al., 2020).

Legumes provide a considerable degree of weed suppression while enriching the soil with nitrogen (Das et al., 2021). In Turkish hazelnut orchards, *Vicia villosa* Roth (hairy vetch) resulted in 95% lower weed biomass (Isik et al., 2014). *Vicia sativa* L. (common vetch) reduced weed biomass by 53% in citrus orchards infested with *Avena sterilis* L. (sterile oat) and *Capsella bursa-pastoris* L. Medik. (shepherd's purse) (Kolören & Uygur, 2007). In Italian apricot orchards, weed biomass decreased by 32%–41% and weed seed bank decreased by 54% in *Trifolium subterraneum* L. (subterranean clover) plots (Restuccia et al., 2020; Scavo et al., 2021).

Crucifers have excellent allelopathic potential against weeds containing glucosinolates which are hydrolysed into allelochemicals such as isothiocyanates upon plant decomposition (Haramoto & Gallandt, 2004), meaning that weed suppression is also achieved through residue management. *Sinapis alba* L. (white mustard) and *B. juncea* (L.) Czern. (oriental mustard) reduced weed biomass (up to 60%) in Greek citrus orchards and vineyards in France (Fourie et al., 2015; Kanatas et al., 2021). In Spain, Alcántara et al. (2011) found that white mustard residues reduced *Chenopodium album* and *Amaranthus* spp. biomass and delayed weed emergence by 3–4 weeks; leaving mulch on the soil surface was the optimal management method. Furthermore, autonomous mowers can improve efficacy as shown by Peruzzi et al. (2023) who repeatedly mowed a grass cover crop reducing *Conyza* spp. density by 61%–84%. However, a disadvantage of cover crops is that they cannot suppress intra-row weeds. To address this, Martinelli et al. (2022) used mowers that cut the cover crop and move the residue to the intra-row area.

Mixtures of species with different characteristics create a cover crop serving multiple functions (MacLaren et al., 2019). From the perspective of weed management, the complementarity of functional traits improves biomass production and weed suppression (Ranaldo et al., 2020). For instance, Haring and Hanson (2022) smothered weed growth in almond orchards with a cereal rye-legume-crucifer mixture. Moreover, a barley-legume mixture outcompeted *Oxalis pes-caprae* L. (Bermuda buttercup) in olive groves in Greece (Volakakis et al., 2022).

4.3.2 | Dead and organic mulches

Mulch is any bulk material placed on the soil surface to control weeds and/or preserve moisture. Environmentally-friendly organic mulches suppress weed emergence by creating a physical barrier intercepting light/temperature and through the release of allelochemicals inhibiting weed seed germination (Cabrera-Pérez et al., 2022). Recent studies showed that lignin-rich materials such as chopped pine wood, pruning waste, almond shell etc. decompose slowly facilitating long-term suppression of intra-row weeds in orchards/vineyards (Cabrera-Pérez et al., 2022; Goh & Tutua, 2004; López-Urrea et al., 2020). Finally, the exploitation of pruning waste and other organic materials as mulch in orchards can reduce the carbon footprint associated with transport for the removal of this waste and promote a circular economy and by-product reuse (López-Urrea et al., 2020).

4.3.3 | Precision weed control

Site-specific weed management in perennial crops can be another alternative to glyphosate. Real-time information-based patch spraying sensors, like Weedseeker®, or Weed-it® are now commercially available (Fernández-Quintanilla et al., 2018). While glyphosate is still available in Europe, these systems could clearly optimise its use and reduce environmental impacts. For other herbicides, these sensors should be improved to differentiate grass from broadleaf weeds, to selectively apply ACCase-inhibitors or auxin mimics respectively for their control.

For physical weed control in tree crops, there is also potential to develop precision agricultural machinery. Site-specific mechanical weeders or camera-guided hoes might be adaptable to remove weeds between rows and/or in-row, depending on the set-up and cost-effectiveness (Fernández-Quintanilla et al., 2018; Walsh et al., 2020).

4.4 | Glyphosate use in an IWM and resistance management context

The utility of glyphosate for herbicide resistance management was established above. In theory, resistance management can be achieved by all chemical or non-chemical means that minimise selection pressure for weed resistance. If the use of glyphosate must be reduced, it will be necessary to place greater emphasis on non-chemical control options (Riemens et al., 2022). Four of these options are discussed below; reducing weed establishment in crops, increasing crop competition, reducing seed production and replenishment of the seed bank, and targeted mechanical control.

4.4.1 | Reducing weed establishment in crops

In cases where the dominant weed species emerge slightly before, or at the same time, as the crop, it can be possible to delay crop sowing to enable early emerging weed cohorts to be controlled before crop establishment (see Section 4.4.1). For example, in Europe, the grass weeds *A. myosuroides* and *Apera spica-venti* typically emerge in early autumn, and delaying crop sowing by 3–4 weeks can provide an opportunity for early season control and reduce in-crop weed densities (Chauvel et al., 2001; Lutman et al., 2013). Glyphosate plays a key role for enabling these approaches, often via the use of a stale seed bed, such that early weed germination and emergence is encouraged and early emerging weeds are controlled with glyphosate. Repetitive mechanical control of stale seed beds can achieve similar results, though this is not always feasible (Lamichhane et al., 2018) and has the potential to incur a range of other soil health and energy consumption costs. In the case of a total ban of glyphosate, and where mechanical weed control is not possible or desirable, it will be necessary to use other broad-spectrum herbicides. Pelargonic acid may also be used, though it is generally recognised to have lower efficacy and higher costs than glyphosate (Ganji et al., 2023).

Crop rotation effectively reduces establishment of well-adapted weed species. In annual crop sequences, weed populations are subjected to different ecological filters, potentially reducing population sizes of individual weed species by suppressing propagule numbers over time, and thus affecting weed seedbank dynamics (Gurusinghe et al., 2022; Weisberger et al., 2019). Optimising these cultural weed control methods requires detailed knowledge of weed biology and ecological interactions (Schwartz-Lazaro et al., 2021).

4.4.2 | Increasing crop competition

More competitive crop species, for example, barley, can reduce weed growth and ultimately limit weed seed set (Lutman et al., 2013). Similarly, the use of more competitive crop cultivars, which have early vigour, planophile leaf angles, extensive tillering and/or exude allelopathic chemicals, can lead to a competitive advantage for crop plants over weeds (Andrew et al., 2015; Lutman et al., 2013; Seavers & Wright, 1999).

Crop competition can also be increased by higher sowing densities and altered sowing techniques and row spacing. For example, increasing the crop density of winter wheat from 100 to 200 or 300 plants m^{-2} reduced the number of *A. myosuroides* seed heads by 17% and 32% respectively (Lutman et al., 2013). In addition, uniform and faster soil coverage obtained by precision seeding leads to better weed suppression than crop stands established by drill seeding (Olsen et al., 2005). Equidistant sowing with optimised spacing could enhance the effect of weed suppression by crop competition. Conversely, increasing row spacing may enable and optimise other weed management techniques such as finger weeders, hoes or hoeing robots, though crop competitiveness versus weeds may be reduced and crop-crop intra-specific competition increased.

4.4.3 | Reducing seed production and replenishment of the seed bank

In Australia, and increasingly in other global agroecosystems, several harvest weed seed control (HWSC) tools are widely used to target weed seeds during crop harvest to prevent seedbank inputs (Walsh et al., 2017). While narrow-window burning cannot be used in Europe due to legal restrictions, the other methods, such as seed destructors (impact mills), chaff tramlining, chaff carts, and the bale-direct system, have potential as a component in IWM but have yet to be widely used in European agriculture (Kudsk et al., 2020). The potential for HWSC is low to intermediate for early shedding weeds like *A. myosuroides* or *A. spica-venti* or for short stature weeds like *Polygonum aviculare*. Weeds such as *Galium aparine* or *L. rigidum* can be effectively targeted by HWSC systems (Akhter et al., 2023). It may also be possible to selectively remove or reduce seed set on unripe inflorescences that emerge above the crop canopy using mowing or electrical weeding to reduce seed set of early shedding species. However, these practices can induce production of new seed heads (Akhter et al., 2023).

4.4.4 | Targeted mechanical control

The manifold possibilities of mechanical weed control including ploughing, harrowing and hoeing require considerable expertise and investment and are more dependent on environmental influences than chemical measures. Implements for the selective removal of weeds between crop rows such as finger weeders must be used in the early growth stages of the weed and are highly effective for weed species with shallow and compact root systems, such as *A. sterilis* (Asaf et al., 2023). Camera-steered hoes with a hydraulic side shifting control are widely available for row crops, however, sensor-based technology for precision mechanical weed control is still in development (Machleb et al., 2020). Furthermore, it is anticipated that autonomous robots mounted with image-based sensors to detect weeds will be able to precisely target mechanical and physical control techniques to remove weeds that have survived chemical treatments due to herbicide resistance (Machleb et al., 2020).

5 | CONCLUSIONS

Even in Europe, where genetically modified glyphosate tolerant crops are not cultivated, glyphosate has become a critical component of many crop and weed management systems Several factors have contributed to sustained increases in glyphosate use: it is inexpensive and highly effective with a broad spectrum of weed control, including hard to control perennial weeds; it is generally considered to have low environmental toxicity; it facilitates the adoption of reduced tillage and CA approaches, minimising the need for weed and cover crop control by soil cultivation or disturbance and; it is a relatively low resistance risk herbicide that can be used in combination with, for example, false seed beds to reduce weed establishment in crops, thereby reducing the need for in-crop control by resistance-prone modes of action. These agronomic and economic attributes account for glyphosate being the most extensively used pesticide in Europe and, as such, glyphosate use contributes to concerns about the negative impacts of excessive pesticide use on environmental quality, biodiversity and low cropping system diversity in the EU.

The EU Farm to Fork strategy clearly emphasises the need to reduce reliance on pesticides. Our analysis and discussion has highlighted some areas where this will pose a challenge. Glyphosate is the most important herbicide for the control of perennial weeds due to its systemic properties. Other herbicide modes of action such as auxins and ACCase inhibitors are available for in-crop control of perennial broadleaved and grass weeds respectively but their efficacy and versatility are lower than that of glyphosate. Without glyphosate, more mechanical weeding will be necessary in many fields, and this will increase fuel consumption and the risk of soil erosion.

Perhaps the greatest of these challenges relates to consequences for CA where many glyphosate alternatives inevitably lead to heavier reliance on soil cultivation for weed control and cover crop termination. In the event of a complete glyphosate ban, and where weed populations are high, it is currently difficult to envisage sustainable weed management without a return to a higher dependence on soil cultivation, which was also broadly acknowledged by EU authorities. The further development of root and rhizome cutters for controlling perennial weeds may have a place in CA and conventional systems in the future. Glyphosate use can, however, be reduced in CA systems through judicious crop rotation to reduce weed populations, non-chemical (and non-cultivation) based termination of cover crops and the use and development of systems for 'see and spray' site-specific glyphosate applications. In tree crops, the most promising approaches are to increase the use of cover crops and mulches to reduce weed establishment, and precision weed management to target remaining weeds, either using glyphosate where still permitted or mechanical control with camera-guided hoes. Finally, concerns were raised about the consequences of a loss of glyphosate for herbicide resistance management as this would put further pressure on resistance-prone modes of action and compromise some IWM strategies which rely on glyphosate use.

Very few tools in agriculture are indispensable and though glyphosate is a critical component of many current systems, alternatives can contribute to future weed management systems. Banning glyphosate or dramatically limiting its future use may precipitate systemic and agroecosystem level impacts, resulting in trade-offs in weed management efficacy, crop yield and profitability, soil health, and biodiversity. It is important that these trade-offs are anticipated and that research to optimise the cost, efficacy and environmental benefit of alternatives is prioritised.

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CONFLICT OF INTEREST STATEMENT

X. Belvaux is an employee of Bayer Crop Science, a manufacturer of crop protection products including glyphosate. Some other co-authors are currently in receipt of research funding from manufacturers of crop protection products. These authors declare no conflicts of interest and have provided independent scientific opinions and insights during the EWRS workshop and subsequent manuscript preparation.

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REFERENCES

Adeux, G., Vieren, E., Carlesi, S., Bàrberi, P., Munier-Jolain, N. & Cordeau, S. (2019) Mitigating crop yield losses through weed diversity. *Nature Sustainability*, 2(11), 1018–1026. Available from: https://doi.org/10.1038/s41893-019-0415-y

Akhter, M.J., Sønderskov, M., Loddo, D., Ulber, L., Hull, R. & Kudsk, P. (2023) Opportunities and challenges for harvest weed seed control in European cropping systems. *European Journal of Agronomy*, 142, 126639. Available from: https://doi.org/10.1016/j.eja.2022.126639

Alcántara, C., Pujadas, A. & Saavedra, M. (2011) Management of Sinapis alba subsp. mairei winter cover crop residues for summer weed control in southern Spain. *Crop Protection*, 30(9), 1239–1244. Available from: https://doi.org/10.1016/j.cropro.2011.04.007

Allmendinger, A., Spaeth, M., Saile, M., Peteinatos, G.G. & Gerhards, R. (2022) Precision chemical weed management strategies: a review and a design of a new CNN-based modular spot sprayer. *Agronomy*, 12(7), 1–21. Available from: https://doi.org/10.3390/agronomy12071620

Al-Mufti, M.M., Sydes, C.L., Furness, S.B., Grime, J.P. & Band, S.R. (1977) A quantitative analysis of shoot phenology and dominance in herbaceous vegetation. *Journal of Ecology*, 65, 759–791.

Anderson, G. (2009) *The impact of tillage practices and crop residue (stubble) retention in the cropping system of Western Australia*. Western Australia Department of Agriculture and Food. Bulletin No: 4786. pp. 1–93.

Andert, S., Bürger, J., Mutz, J.E. & Gerowitt, B. (2018) Patterns of pre-crop glyphosate use and in-crop selective herbicide intensities in northern Germany. *European Journal of Agronomy*, 97, 20–27. Available from: https://doi.org/10.1016/j.eja.2018.04.009

Andrew, I.K.S., Storkey, J. & Sparkes, D.L. (2015) A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Research*, 55(3), 239–248. Available from: https://doi.org/10.1111/wre.12137

Antichi, D., Carlesi, S., Mazzoncini, M. & Bàrberi, P. (2022) Targeted timing of hairy vetch cover crop termination with roller crimper can eliminate glyphosate requirements in no-till sunflower. *Agronomy for Sustainable Development*, 42(5), 87. Available from: https://doi.org/10.1007/s13593-022-00815-2

Antier, C., Kudsk, P., Reboud, X., Ulber, L., Baret, P.V. & Messéan, A. (2020) Glyphosate use in the European agricultural sector and a framework for its further monitoring. *Sustainability (Switzerland)*, 12(14), 5682. Available from: https://doi.org/10.3390/su12145682

Aronsson, H., Ringselle, B., Andersson, L. & Bergkvist, G. (2015) Combining mechanical control of couch grass (*Elymus repens* L.) with reduced tillage in early autumn and cover crops to decrease nitrogen and phosphorus leaching. *Nutrient Cycling in Agroecosystems*, 102(3), 383–396. Available from: https://doi.org/10.1007/s10705-015-9712-7

Asaf, E., Rozenberg, G., Shulner, I., Eizenberg, H. & Lati, R.N. (2023) Evaluation of finger weeder safety and efficacy for intra-row weed removal in irrigated field crops. *Weed Research*, 63(2), 102–114. Available from: https://doi.org/10.1111/wre.12571

Ashford, D. & Reeves, D. (2003) Use of a mechanical roller-crimper as an alternative kill method for cover crops. *American Journal of Alternative Agriculture*, 18(1), 37–45. Available from: https://doi.org/10.1079/AJAA200232

Baumgartner, K., Steenwerth, K.L. & Veilleux, L. (2007) Effects of organic and conventional practices on weed control in a perennial cropping system. *Weed Science*, 55(4), 352–358. Available from: https://doi.org/10.1614/ws-06-171

Beckie, H.J., Ashworth, M.B. & Flower, K.C. (2019) Herbicide resistance management: recent developments and trends. *Plants*, 8(6), 161. Available from: https://doi.org/10.3390/plants8060161

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V. & Makowski, D. (2021) Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology*, 27(19), 4697–4710. Available from: https://doi.org/10.1111/gcb.15747

Bitarafan, Z. & Andreasen, C. (2020) Seed retention of ten common weed species at oat harvest reveals the potential for harvest weed seed control. *Weed Research*, 60(5), 343–352. Available from: https://doi.org/10.1111/wre.12438

Bloomer, D.J., Harrington, K.C., Ghanizadeh, H. & James, T.K. (2022) Micro electric shocks control broadleaved and grass weeds. *Agronomy*, 12(9). Available from: https://doi.org/10.3390/agronomy12092039

Böcker, T., Britz, W. & Finger, R. (2018) Modelling the effects of a glyphosate ban on Weed Management in silage maize production. *Ecological Economics*, 145, 182–193. Available from: https://doi.org/10.1016/j.ecolecon.2017.08.027

Brandsæter, L.O., Mangerud, K., Helgheim, M. & Berge, T.W. (2017) Control of perennial weeds in spring cereals through stubble cultivation and mouldboard ploughing during autumn or spring. *Crop Protection*, 98, 16–23. Available from: https://doi.org/10.1016/j.cropro.2017.03.006

Brandsæter, L.O., Mangerud, K., Andersson, L., Børresen, T., Brodal, G. & Melander, B. (2020) Influence of mechanical weeding and fertilisation on perennial weeds, fungal diseases, soil structure and crop yield in organic spring cereals. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, 70(4), 318–332. Available from: https://doi.org/10.1080/09064710.2020.1728371

Cabrera-Pérez, C., Valencia-Gredilla, F., Royo-Esnal, A. & Recasens, J. (2022) Organic mulches as an alternative to conventional under-vine weed management in Mediterranean irrigated vineyards. *Plants*, 11(20), 2785. Available from: https://doi.org/10.3390/plants11202785

Chauvel, B., Guillemin, J.P., Colbach, N. & Gasquez, J. (2001) Evaluation of cropping systems for management of herbicide-resistant populations of blackgrass (*Alopecurus myosuroides* Huds.). *Crop Protection*, 20(2), 127–137. Available from: https://doi.org/10.1016/S0261-2194(00)00065-X

Colbach, N. & Cordeau, S. (2022) Are no-till herbicide-free systems possible? A simulation study. *Frontiers in Agronomy*, 4, 1–21. Available from: https://doi.org/10.3389/fagro.2022.823069

Coleman, G.R.Y., Stead, A., Rigter, M.P., Xu, Z., Johnson, D., Brooker, G.M. et al. (2019) Using energy requirements to compare the suitability of alternative methods for broadcast and site-specific weed control. *Weed Technology*, 33, 633–650. Available from: https://doi.org/10.1017/wet.2019.32

Coleman, G.R.Y., Bender, A., Hu, K., Sharpe, S.M., Schumann, A.W., Wang, Z. et al. (2022) Weed detection to weed recognition: reviewing 50 years of research to identify constraints and opportunities for large-scale cropping systems. *Weed Technology*, 36, 1–50. Available from: https://doi.org/10.1017/wet.2022.84

Collavo, A. & Sattin, M. (2014) First glyphosate-resistant *Lolium* spp. biotypes found in a European annual arable cropping system also affected by ACCase and ALS resistance. *Weed Research*, 54(4), 325–334. Available from: https://doi.org/10.1111/wre.12082

Comont, D., Hicks, H., Crook, L., Hull, R., Cocciantelli, E., Hadfield, J. et al. (2019) Evolutionary epidemiology predicts the emergence of glyphosate resistance in a major agricultural weed. *New Phytologist*, 223(3), 1584–1594. Available from: https://doi.org/10.1111/nph.15800

Cooray, A., Rejesus, R.M., Aglasan, S., Li, Z. & Woodley, A. (2023) The impact of conservation tillage intensities on mean yields and yield risk. *Soil Security*, 12, 100096. Available from: https://doi.org/10.1016/j.soisec.2023.100096

Das, B., Kandpal, B. & Lembisana Devi, H. (2021) Cover crops for orchard soil management. In: Islam, R. & Sherman, B. (Eds.) *Cover crops and sustainable agriculture*. Boca Raton: Taylor Francis, CRC Press, pp. 147–168. Available from: https://doi.org/10.1201/9781003187301-10

Davis, A.S., Daedlow, D., Schutte, B.J. & Westerman, P.R. (2011) Temporal scaling of episodic point estimates of seed predation to long-term predation rates. *Methods in Ecology and Evolution*, 2, 682–890. Available from: https://doi.org/10.1111/j.2041-210X.2011.00119.x

Donald, W.W. (2006) Mowing for weed management. In: Singh, H.P., Batish, D.R. & Kohli, R.K. (Eds.) *Handbook of sustainable weed management*. Routledge, Taylor & Francis, Food Products Press, pp. 329–372.

Duchene, O., Bathellier, C., Dumont, B., David, C. & Celette, F. (2023) Weed community shifts during the aging of perennial intermediate wheatgrass crops harvested for grain in arable fields. *European Journal of Agronomy*, 143, 126721. Available from: https://doi.org/10.1016/j.eja.2022.126721

Duke, S.O. & Powles, S.B. (2008) Mini-review glyphosate: a once-in-a-century herbicide. *Pest Management Science*, 64, 319–325.

Duke, J.M., Johnston, R.J., Shober, A.L. & Liu, Z. (2022) Barriers to cover crop adoption: evidence from parallel surveys in Maryland and Ohio. *Journal of Soil and Water Conservation*, 77(2), 198–211. Available from: https://doi.org/10.2489/jswc.2022.00062

ECAF. (2020) *Making sustainable agriculture real in Europe with conservation agriculture: judicious use of glyphosate in integrated weed management*. Brussels, Belgium: ECAF.

ENDURE. (2023) Available at: http://www.endure-network.eu [Accessed 23 September 2023].

van Evert, F.K., Cockburn, M., Beniers, J.E. & Latsch, R. (2020) Weekly defoliation controls, but does not kill broad-leaved dock (*Rumex obtusifolius*). *Weed Research*, 60(2), 161–170. Available from: https://doi.org/10.1111/wre.12407

FAO. (2023) Conservation agriculture. Available at: http://www.fao.org/conservation-agriculture [Accessed 23 September 2023].

Favrelière, E., Ronceux, A., Pernel, J. & Meynard, J.M. (2020) Nonchemical control of a perennial weed, *Cirsium arvense*, in arable cropping systems. A review. *Agronomy for Sustainable Development*, 40, 31. Available from: https://doi.org/10.1007/s13593-020-00635-2

Fernández-Quintanilla, C., Peña, J.M., Andújar, D., Dorado, J., Ribeiro, A. & López-Granados, F. (2018) Is the current state of the art of weed monitoring suitable for site-specific weed management in arable crops? *Weed Research*, 58, 259–272. Available from: https://doi.org/10.1111/wre.12307

Fernando, M. & Shrestha, A. (2023) The potential of cover crops for weed management: a sole tool or component of an integrated weed management system? *Plants*, 12, 752. Available from: https://doi.org/10.3390/plants12040752

Feys, J., De Cauwer, B., Reheul, D., Sciffer, C., Clercx, S. & Palmans, S. (2023) Impact of electrocution on shoot and tuber vitality of yellow Nutsedge (*Cyperus esculentus*). *Agriculture (Switzerland)*, 13(3), 696. Available from: https://doi.org/10.3390/agriculture13030696

Finger, R., Möhring, N. & Kudsk, P. (2023) Glyphosate ban will have economic impacts on European agriculture but effects are heterogenous and uncertain. *Communications Earth & Environmant*, 4, 286. Available from: https://doi.org/10.1038/s43247-023-00951-x

Fogliatto, S., Ferrero, A. & Vidotto, F. (2020) Current and future scenarios of glyphosate use in Europe: are there alternatives? *Advances in Agronomy*, 163, 219–278. Available from: https://doi.org/10.1016/bs.agron.2020.05.005

Fourie, J.C., Kruger, D.H.M. & Malan, A.P. (2015) Effect of management practices applied to cover crops with biofumigation properties on cover crop performance and weed control in a vineyard. *South African Journal of Enology and Viticulture*, 36(1), 146–153. Available from: https://doi.org/10.21548/36-1-947

Frasconi, C., Martelloni, L., Antichi, D., Raffaelli, M., Fontanelli, M., Peruzzi, A. et al. (2019) Combining roller crimpers and flaming for the termination of cover crops in herbicide-free no-till cropping systems. *PLoS One*, 14(2), 1–19. Available from: https://doi.org/10.1371/journal.pone.0211573

Gaba, S., Caneill, J., Nicolardot, B., Perronne, R. & Bretagnolle, V. (2018) Crop competition in winter wheat has a higher potential than farming practices to regulate weeds. *Ecosphere*, 9(10). Available from: https://doi.org/10.1002/ecs2.2413

Ganji, E., Grenzdörffer, G. & Andert, S. (2023) Estimating the reduction in cover crop vitality followed by Pelargonic acid application using drone imagery. *Agronomy*, 13(2), 354. Available from: https://doi.org/10.3390/agronomy13020354

Gerhards, R., Andújar Sanchez, D., Hamouz, P., Peteinatos, G.G., Christensen, S. & Fernandez-Quintanilla, C. (2022) Advances in site-specific weed management in agriculture—a review. *Weed Research*, 62, 123–133. Available from: https://doi.org/10.1111/wre.12526

Goh, K.M. & Tutua, S.S. (2004) Effects of organic and plant residue quality and orchard management practices on decomposition rates of residues. *Communications in Soil Science and Plant Analysis*, 35(3–4), 441–460. Available from: https://doi.org/10.1081/CSS-120029724

Granatstein, D. & Sanchez, E. (2009) Research knowledge and needs for orchard floor management in organic tree fruit systems. *International Journal of Fruit Science*, 9(3), 257–281. Available from: https://doi.org/10.1080/15538360903245212

Granatstein, D., Andrews, P. & Groff, A. (2014) Productivity, economics, and fruit and soil quality of weed management systems in commercial organic orchards in Washington state, USA. *Organic Agriculture*, 4(3), 197–207. Available from: https://doi.org/10.1007/s13165-014-0068-0

Gurusinghe, S., Haque, K.M.S., Weston, P.A., Brown, W.B. & Weston, L.A. (2022) Impact of rotational sequence selection on weed seedbank composition in Australian Broadacre crops. *Agronomy*, 12(2), 375. Available from: https://doi.org/10.3390/agronomy12020375

Hakansson, I., Steneberg, M. & Rydberg, T. (1998) Long-term experiments with different depths of mouldboard ploughing in Sweden. *Soil Tillage Research*, 46, 209–223. Available from: https://doi.org/10.1016/S0167-1987(98)00099-3

Hammermeister, A.M. (2016) Organic weed management in perennial fruits. *Scientia Horticulturae*, 208, 28–42. Available from: https://doi.org/10.1016/j.scienta.2016.02.004

Haramoto, E.R. & Gallandt, E.R. (2004) Brassica cover cropping for weed management: a review. *Renewable Agriculture and Food Systems*, 19(4), 187–198. Available from: https://doi.org/10.1079/raf200490

Haring, S.C. & Hanson, B.D. (2022) Agronomic cover crop management supports weed suppression and competition in California orchards. *Weed Science*, 70(5), 595–602. Available from: https://doi.org/10.1017/wsc.2022.48

Heap. (2023) The international herbicide-resistant weed database. Available at: www.weedscience.org [Accessed 23 September 2023].

Isik, D., Dok, M., Ak, K., Macit, I., Demir, Z. & Mennan, H. (2014) Use of cover crops for weed suppression in hazelnut (*Corylus avellana* l.) in Turkey. *Communications in Agricultural and Applied Biological Sciences*, 79(2), 105–110.

Jacquet, F., Delame, N., Vita, J.L., Huyghe, C. & Reboud, X. (2021) The micro-economic impacts of a ban on glyphosate and its replacement with mechanical weeding in French vineyards. *Crop Protection*, 150, 105778. Available from: https://doi.org/10.1016/j.cropro.2021.105778

Kanatas, P., Antonopoulos, N., Gazoulis, I. & Travlos, I.S. (2021) Screening glyphosate-alternative weed control options in important perennial crops. *Weed Science*, 69(6), 704–718. Available from: https://doi.org/10.1017/wsc.2021.55

Kleffmann Group. (2017) The economic relevance of glyphosate in Germany. Available from: https://www.gkb-ev.de/publikationen/2017/17-08-24-studie-engl.pdf

Klik, A. & Rosner, J. (2020) Long-term experience with conservation tillage practices in Austria: impacts on soil erosion processes. *Soil and Tillage Research*, 203, 104669. Available from: https://doi.org/10.1016/j.still.2020.104669

Kolören, O. & Uygur, F.N. (2007) Investigation on weed control methods in citrus orchard in Çukurova region–Turkey. *Asian Journal of Plant Sciences*, 6(4), 708–711.

Kornecki, T.S. (2020) Influence of recurrent rolling/crimping on cover crop termination, soil strength and yield in No-till cotton. *AgriEngineering*, 2(4), 631–648. Available from: https://doi.org/10.3390/agriengineering2040042

Kornecki, T.S., Price, A.J., Raper, R.L. & Arriaga, F.J. (2009) New roller crimper concepts for mechanical termination of cover crops in conservation agriculture. *Renewable Agriculture and Food Systems*, 24(3), 165–173. Available from: https://doi.org/10.1017/S1742170509002580

Krupinsky, J.M., Bailey, K.L., McMullen, M.P., Gossen, B.D. & Turkington, T.K. (2002) Managing plant disease risk in diversified cropping systems. *Agronomy Journal*, 94, 198–209. Available from: https://doi.org/10.2134/agronj2002.1980

Kudsk, P. & Mathiassen, S.K. (2020) Pesticide regulation in the European Union and the glyphosate controversy. *Weed Science*, 68(3), 214–222. Available from: https://doi.org/10.1017/wsc.2019.59

Kudsk, P., Sønderskov, M., Bonin, L., Gonzalez-Andujar, J.L., Jensen, J.E., Melander, B. et al. (2020) Iwmpraise – an EU horizon 2020 project providing integrated weed management solutions to European farmers. *Outlooks on Pest Management*, 31(4), 152–159. Available from: https://doi.org/10.1564/v31_aug_02

Lamichhane, J.R., Debaeke, P., Steinberg, C., You, M.P., Barbetti, M.J. & Aubertot, J.N. (2018) Abiotic and biotic factors affecting crop seed germination and seedling emergence: a conceptual framework. *Plant and Soil*, 432, 1–28. Available from: https://doi.org/10.1007/s11104-018-3780-9

Liebman, M. & Dyck, E. (1993) Crop rotation and intercropping strategies for weed management. *Ecological Applications*, 3, 92–122. Available from: https://doi.org/10.2307/1941795

Lindstrom, M.J., Nelson, W.W. & Schumacher, T.E. (1992) Quantifying tillage erosion rates due to moldboard plowing. *Soil and Tillage Research*, 24(3), 243–255. Available from: https://doi.org/10.1016/0167-1987(92)90090-X

Lisek, J. (2014) Possibilities and limitations of weed management in fruit crops of the temperate climate zone. *Journal of Plant Protection Research*, 54, 318–326. Available from: https://doi.org/10.2478/jppr-2014-0048

Loddo, D., Jagarapu, K.K., Strati, E., Trespidi, G., Nikolić, N., Masin, R. et al. (2023) Assessing herbicide efficacy of Pelargonic acid on several weed species. *Agronomy*, 13(6), 1511. Available from: https://doi.org/10.3390/agronomy13061511

López-Urrea, R., Sánchez, J.M., Montoro, A., Mañas, F. & Intrigliolo, D.S. (2020) Effect of using pruning waste as an organic mulching on a drip-irrigated vineyard evapotranspiration under a semi-arid climate. *Agricultural and Forest Meteorology*, 291, 108064. Available from: https://doi.org/10.1016/j.agrformet.2020.108064

Lötjönen, T. & Salonen, J. (2016) Intensifying bare fallow strategies to control *Elymus repens* in organic soils. *Agricultural and Food Science*, 25(3), 153–163. Available from: https://doi.org/10.23986/afsci.55533

Lutman, P.J.W., Moss, S.R., Cook, S. & Welham, S.J. (2013) A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*. *Weed Research*, 53(5), 299–313. Available from: https://doi.org/10.1111/wre.12024

Machleb, J., Peteinatos, G.G., Kollenda, B.L., Andújar, D. & Gerhards, R. (2020) Sensor-based mechanical weed control: present state and prospects. *Computers and Electronics in Agriculture*, 176, 105638. Available from: https://doi.org/10.1016/j.compag.2020.105638

MacLaren, C., Swanepoel, P., Bennett, J., Wright, J. & Dehnen-Schmutz, K. (2019) Cover crop biomass production is more important than diversity for weed suppression. *Crop Science*, 59(2), 733–748. Available from: https://doi.org/10.2135/cropsci2018.05.0329

Maggi, F., la Cecilia, D., Tang, F.H.M. & McBratney, A. (2020) The global environmental hazard of glyphosate use. *Science of the Total Environment*, 717, 137167. Available from: 10.101a6/j.scitotenv.2020.137167

Martinelli, R., Rufino-Jr, L.R., Desiderio, D.R., Alcántara-De La Cruz, R., Monquero, P.A. & de Azevedo, F.A. (2022) The impacts of ecological mowing combined with conventional mechanical or herbicide management on weeds in orange orchards. *Weed Research*, 62(6), 431–445. Available from: https://doi.org/10.1111/wre.12557

Mas, M.T., Poggio, S.L. & Verdú, A.M.C. (2007) Weed community structure of mandarin orchards under conventional and integrated management in northern Spain. *Agriculture, Ecosystems and Environment*, 119(3–4), 305–310. Available from: https://doi.org/10.1016/j.agee.2006.07.016

Mauro, R.P., Anastasi, U., Lombardo, S., Pandino, G., Pesce, R., Restuccia, A. et al. (2015) Cover crops for managing weeds, soil chemical fertility and nutritional status of organically grown orange orchard in Sicily. *Italian Journal of Agronomy*, 10(2), 101–104. Available from: https://doi.org/10.4081/ija.2015.641

Melander, B., Munier-Jolain, N., Charles, R., Wirth, J., Schwarz, J., van der Weide, R. et al. (2013) European perspectives on the adoption of non-chemical weed management in reduced-tillage systems for arable crops. *Weed Technology*, 27(1), 231–240. Available from: https://doi.org/10.1614/wt-d-12-00066.1

Melander, B., Nørremark, M. & Kristensen, E.F. (2013) Combining mechanical rhizome removal and cover crops for *Elytrigia repens* control in organic barley systems. *Weed Research*, 53(6), 461–469. Available from: https://doi.org/10.1111/wre.12042

van der Meulen, A. & Chauhan, B.S. (2017) A review of weed management in wheat using crop competition. *Crop Protection*, 95, 38–44. Available from: https://doi.org/10.1016/j.cropro.2016.08.004

Miñarro, M. (2012) Weed communities in apple orchards under organic and conventional fertilization and tree-row management. *Crop Protection*, 39, 89–96. Available from: https://doi.org/10.1016/j.cropro.2012.04.002

Miville, D. & Leroux, G.D. (2018) Rolled winter rye-hairy vetch cover crops for weed control in no-till pumpkin. *Weed Technology*, 32(3), 251–259. Available from: https://doi.org/10.1017/wet.2018.9

Montanaro, G., Xiloyannis, C., Nuzzo, V. & Dichio, B. (2017) Orchard management, soil organic carbon and ecosystem services in Mediterranean fruit tree crops. *Scientia Horticulturae*, 217, 92–101. Available from: https://doi.org/10.1016/j.scienta.2017.01.012

Morselli, N., Puglia, M., Pedrazzi, S., Muscio, A., Tartarini, P. & Allesina, G. (2022) Energy, environmental and feasibility evaluation of tractor-mounted biomass gasifier for flame weeding. *Sustainable Energy Technologies and Assessments*, 50, 101823. Available from: https://doi.org/10.1016/j.seta.2021.101823

Moss, S.R., Perryman, S.A.M. & Tatnell, L.V. (2007) Managing herbicide-resistant blackgrass (*Alopecurus myosuroides*): theory and practice. *Weed Technology*, 21(2), 300–309. Available from: https://doi.org/10.1614/wt-06-087.1

Navarro-Miró, D., Blanco-Moreno, J.M., Ciaccia, C., Chamorro, L., Testani, E., Kristensen, H.L. et al. (2019) Agroecological service crops managed with roller crimper reduce weed density and weed species richness in organic vegetable systems across Europe. *Agronomy for Sustainable Development*, 39(6), 1–13. Available from: https://doi.org/10.1007/s13593-019-0597-8

Olsen, J., Kristensen, L., Weiner, J. & Griepentrog, H.W. (2005) Increased density and spatial uniformity increase weed suppression by spring wheat. *Weed Research*, 45(4), 316–321. Available from: https://doi.org/10.1111/j.1365-3180.2005.00456.x

Peruzzi, A., Gagliardi, L., Fontanelli, M., Frasconi, C., Raffaelli, M. & Sportelli, M. (2023) Continuous mowing for *Erigeron canadensis* L. Control in vineyards. *Agronomy*, 13(2), 409. Available from: https://doi.org/10.3390/agronomy13020409

Ranaldo, M., Carlesi, S., Costanzo, A. & Bàrberi, P. (2020) Functional diversity of cover crop mixtures enhances biomass yield and weed suppression in a Mediterranean agroecosystem. *Weed Research*, 60(1), 96–108. Available from: https://doi.org/10.1111/wre.12388

Rasmussen, J., Azim, S. & Nielsen, J. (2021) Pre-harvest weed mapping of *Cirsium arvense* L. based on free satellite imagery – the importance of weed aggregation and image resolution. *European Journal of Agronomy*, 130, 126373. Available from: https://doi.org/10.1016/j.eja.2021.126373

Reicosky, D.C. & Archer, D.W. (2007) Moldboard plow tillage depth and short-term carbon dioxide release. *Soil and Tillage Research*, 94(1), 109–121. Available from: https://doi.org/10.1016/j.still.2006.07.004

Restuccia, A., Scavo, A., Lombardo, S., Pandino, G., Fontanazza, S., Anastasi, U. et al. (2020) Long-term effect of cover crops on species abundance and diversity of weed flora. *Plants*, 9(11), 1506. Available from: https://doi.org/10.3390/plants9111506

Riemens, M., Sønderskov, M., Moonen, A.C., Storkey, J. & Kudsk, P. (2022) An integrated weed management framework: a pan-European perspective. *European Journal of Agronomy*, 133, 126433. Available from: https://doi.org/10.1016/j.eja.2021.126443

Ringselle, B., Bertholtz, E., Magnuski, E., Brandsæter, L.O., Mangerud, K. & Bergkvist, G. (2018) Rhizome fragmentation by vertical disks reduces *Elymus repens* growth and benefits Italian ryegrass-white clover crops. *Frontiers in Plant Science*, 8, 1178. Available from: https://doi.org/10.3389/fpls.2017.02243

Ringselle, B., de Cauwer, B., Salonen, J. & Soukup, J. (2020) A review of non-chemical management of couch grass (*Elymus repens*). *Agronomy*, 10, 1178. Available from: https://doi.org/10.3390/agronomy10081178

Ringselle, B., Brandsæter, L.O., Mangerud, K. & Bergkvist, G. (2023) Vertical rhizome disking to reduce *Elymus repens* (quackgrass) abundance in grass-clover leys. *Crop Protection*, 172, 106301. Available from: https://doi.org/10.1016/j.cropro.2023.106301

Rosario-Lebron, A., Leslie, A.W., Yurchak, V.L., Chen, G. & Hooks, C.R.R. (2019) Can winter cover crop termination practices impact weed suppression, soil moisture, and yield in no-till soybean [Glycine max (L.) Merr.]? *Crop Protection*, 116, 132–141. Available from: https://doi.org/10.1016/j.cropro.2018.10.020

Sardana, V., Mahajan, G., Jabran, K. & Chauhan, B.S. (2017) Role of competition in managing weeds: an introduction to the special issue. *Crop Protection*, 95, 1–7. Available from: https://doi.org/10.1016/j.cropro.2016.09.011

Scavo, A., Restuccia, A., Abbate, C., Lombardo, S., Fontanazza, S., Pandino, G. et al. (2021) *Trifolium subterraneum* cover cropping enhances soil fertility and weed seedbank dynamics in a Mediterranean apricot orchard. *Agronomy for Sustainable Development*, 41(6), 1–16. Available from: https://doi.org/10.1007/s13593-021-00721-z

Schreier, H., Bish, M. & Bradley, K.W. (2022) The impact of electrocution treatments on weed control and weed seed viability in soybean. *Weed Technology*, 36(4), 481–489. Available from: https://doi.org/10.1017/wet.2022.56

Schwartz-Lazaro, L.M., Gage, K.L. & Chauhan, B.S. (2021) Editorial: weed biology and ecology in agroecosystems. *Frontiers in Agronomy*, 3, 730074. Available from: https://doi.org/10.3389/fagro.2021.730074

Seavers, G.P. & Wright, K.J. (1999) Crop canopy development and structure influence weed suppression. *Weed Research*, 39(4), 319–328. Available from: https://doi.org/10.1046/j.1365-3180.1999.00148.x

Sharma, G., Shrestha, S., Kunwar, S. & Tseng, T.M. (2021) Crop diversification for improved weed management: a review. *Agriculture (Switzerland)*, 11, 461. Available from: https://doi.org/10.3390/agriculture11050461

Shrestha, A., Kaan Kurtural, S., Fidelibus, M.W., Dervishian, G. & Konduru, S. (2013) Efficacy and cost of cultivators, steam, or an organic herbicide for weed control in organic vineyards in the San Joaquin Valley of California. *HortTechnology*, 23(1), 99–108. Available from: https://doi.org/10.21273/horttech.23.1.99

Soriano, M.A., Álvarez, S., Landa, B.B. & Gómez, J.A. (2014) Soil properties in organic olive orchards following different weed management in a rolling landscape of Andalusia, Spain. *Renewable Agriculture and Food Systems*, 29(1), 83–91. Available from: https://doi.org/10.1017/S1742170512000361

Sportelli, M., Frasconi, C., Gagliardi, L., Fontanelli, M., Raffaelli, M., Sbrana, M. et al. (2023) Testing of roller-crimper-and-undercutting-blade-equipped prototype for plants termination. *AgriEngineering*, 5(1), 182–192. Available from: https://doi.org/10.3390/agriengineering5010013

Stefanelli, D., Zoppolo, R.J., Perry, R.L. & Weibel, F. (2009) Organic orchard floor management systems for apple effect on rootstock performance in the midwestern United States. *HortScience*, 44(2), 263–267. Available from: https://doi.org/10.21273/hortsci.44.2.263

Storkey, J. & Neve, P. (2018) What good is weed diversity? *Weed Research*, 58(4), 239–243. Available from: https://doi.org/10.1111/wre.12310

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., Van der Heijden, M., Liebman, M. et al. (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, 6, eaba1715. Available from: https://doi.org/10.1126/sciadv.aba1715

Teasdale, J.R., Brandsæter, L.O., Calegari, A. & Skora Neto, F. (2007) Cover crops and weed management. In: Upadhyaya, M.K. & Blackshaw, R.E. (Eds.) *Non-chemical weed management. Principles, concepts, and technology*. Cambridge, MA: CABI, pp. 49–64.

Thomsen, M.G., Brandsæter, L.O. & Fykse, H. (2011) Sensitivity of *Cirsium arvense* to simulated tillage and competition. *Acta Agriculturae Scandinavica Section B Soil and Plant Science*, 61, 693–700. Available from: https://doi.org/10.1080/09064710.2010.543142

Thomsen, M.G., Mangerud, K., Riley, H. & Brandsæter, L.O. (2015) Method, timing and duration of bare fallow for the control of Cirsium arvense and other creeping perennials. *Crop Protection*, 77, 31–37. Available from: https://doi.org/10.1016/j.cropro.2015.05.020

Travlos, I.S., Kontopoulou, C.-K., Kanatas, P.J., Panagopoulou, M. & Bilalis, D.J. (2017) Cover crops against herbicide-resistant invasive weeds. *Scientific Papers. Series A. Agronomy*, LX, 425–429.

Valencia-Gredilla, F., Royo-Esnal, A., Juárez-Escario, A. & Recasens, J. (2020) Different ground vegetation cover management systems to manage *Cynodon dactylon* in an irrigated vineyard. *Agronomy*, 10(6). Available from: https://doi.org/10.3390/agronomy10060908

Van Eerd, L.L., Chahal, I., Peng, Y. & Awrey, J.C. (2023) Influence of cover crops at the four spheres: a review of ecosystem services, potential barriers, and future directions for North America. *Science of the Total Environment*, 858, 159990. Available from: https://doi.org/10.1016/j.scitotenv.2022.159990

Volakakis, N., Kabourakis, E.M., Rempelos, L., Kiritsakis, A. & Leifert, C. (2022) Effect of different cover crops on suppression of the weed *Oxalis pes-caprae* L., soil nutrient availability, and the performance of table olive trees 'Kalamon' cv. In Crete, Greece. *Agronomy*, 12(10), 2523. Available from: https://doi.org/10.3390/agronomy12102523

Walsh, M.J. & Powles, S.B. (2022) Harvest weed seed control: impact on weed management in Australian grain production systems and potential role in global cropping systems. *Crop and Pasture Science*, 73, 313–324. Available from: https://doi.org/10.1071/CP21647

Walsh, M., Ouzman, J., Newman, P., Powles, S. & Llewellyn, R. (2017) High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. *Weed Technology*, 31(3), 341–347. Available from: https://doi.org/10.1017/wet.2017.9

Walsh, M.J., Squires, C.C., Coleman, G.R.Y., Widderick, M.J., McKiernan, A.B., Chauhan, B.S. et al. (2020) Tillage based, site-specific weed control for conservation cropping systems. *Weed Technology*, 34(5), 704–710. Available from: https://doi.org/10.1017/wet.2020.34

Weigel, M.M., Andert, S. & Gerowitt, B. (2023) Monitoring patch expansion amends to evaluate the effects of non-chemical control on the creeping perennial *Cirsium arvense* (L.) Scop. in a spring wheat crop. *Agronomy*, 13(6), 1474. Available from: https://doi.org/10.3390/agronomy13061474

Weisberger, D., Nichols, V. & Liebman, M. (2019) Does diversifying crop rotations suppress weeds? A meta-analysis. *PLoS One*, 14(7), e0219847. Available from: https://doi.org/10.1371/journal.pone.0219847

Westerman, P., Hofman, A., Vet, L. & van der Werf, W. (2003) Relative importance of vertebrates and invertebrates in epigeaic weed seed predation in organic cereal fields. *Agriculture, Ecosystems & Environment*, 95, 417–425. Available from: https://doi.org/10.1016/S0167-8809(02)00224-4

Woodburn, A.T. (2000) Glyphosate: production, pricing and use worldwide. *Pest Management Science*, 56, 309–312. Available from: https://doi.org/10.1002/(SICI)1526-4998(200004)56:4<309::AID-PS143>3.0.CO;2-C

Wynn, S. & Webb, E. (2022) Impact assessment of the loss of glyphosate within the EU: a literature review. *Environmental Sciences Europe*, 34, 91. Available from: https://doi.org/10.1186/s12302-022-00667-3

Żelazny, W.R. & Licznar-Małańczuk, M. (2018) Soil quality and tree status in a twelve-year-old apple orchard under three mulch-based floor management systems. *Soil and Tillage Research*, 180, 250–258. Available from: https://doi.org/10.1016/j.still.2018.03.010

Zhang, S., Huang, G., Zhang, Y., Lv, X., Wan, K., Liang, J. et al. (2023) Sustained productivity and agronomic potential of perennial rice. *Nature Sustainability*, 6(1), 28–38. Available from: https://doi.org/10.1038/s41893-022-00997-3

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