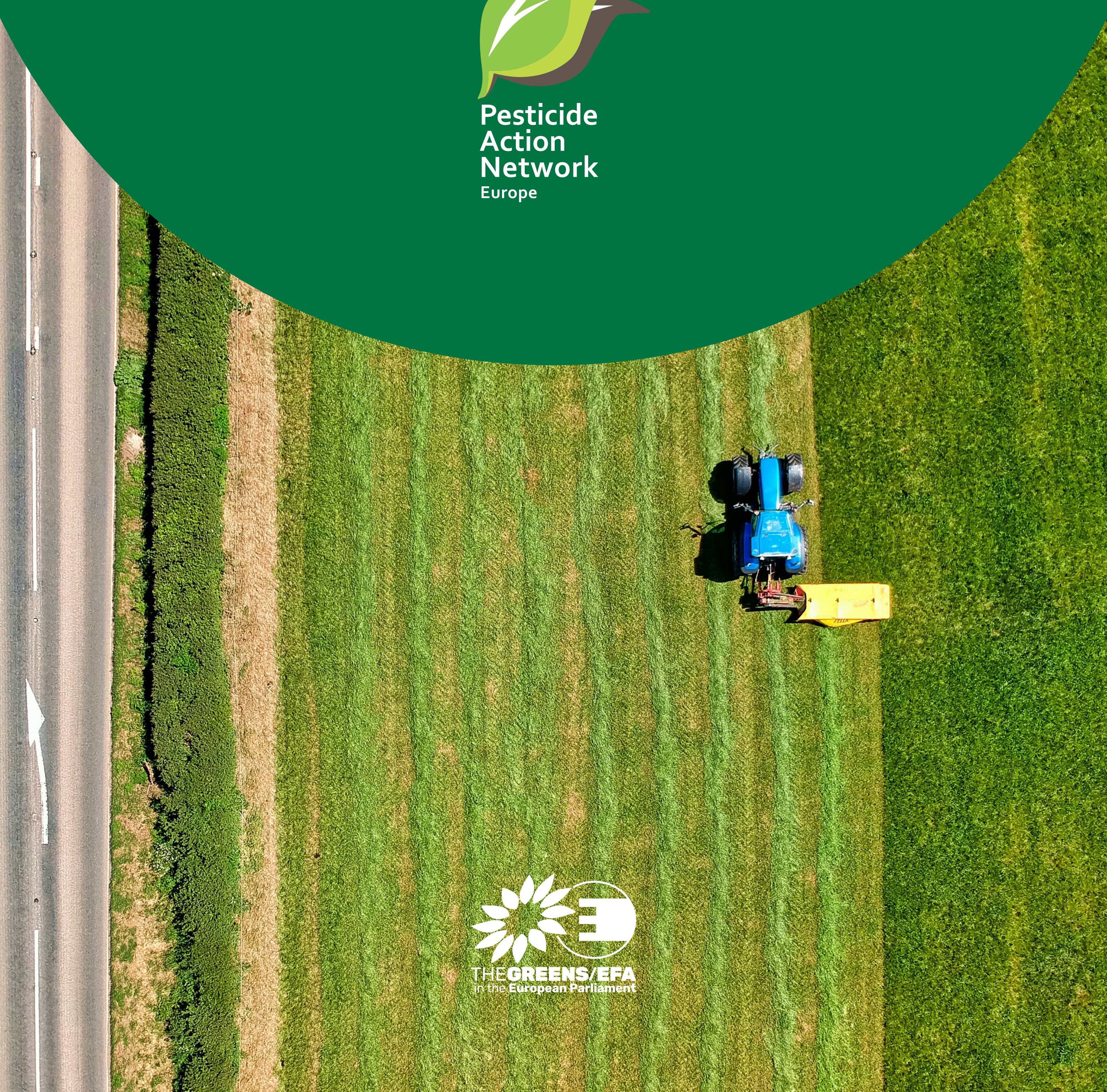
WEED MANAGEMENT: ALTERNATIVES TO THE USE OF GLYPHOSATE

Pesticide
Action
Network
Europe



THE GREENS/EFA
in the European Parliament

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1. **INTRODUCTION**

While the use of synthetic pesticides in agriculture has helped to increase food production, this has occurred at great cost to the environment, natural resources, and human health. The 2017 United Nations (UN) report of the Special Rapporteur on the Right to Food highlights the adverse impact of pesticide use on human rights, human health (workers, their families, bystanders, residents, and consumers), and the environment. The report also reveals that intensive agriculture based on pesticide use has not contributed to reducing world hunger[1].

Herbicides are used in agriculture and horticulture to combat weeds that, above certain thresholds, compete with crops and pasture for nutrients, water, and sunlight resulting in reduced crop and livestock yield and quality, which in turn reduces profitability. The next most widespread use is for no-till and reduced tillage systems where herbicides, principally those based on glyphosate, are used to kill all vegetation, both post-harvest and also before crop and pasture establishment. A third use is to ripen and desiccate grain and seed crops before harvest. Non-agricultural uses include the management of invasive plant species, assisting the management of public areas, for aesthetics or reducing hazards (e.g., sidewalks, pavements, and railways), or for weed control in private gardens.

There is a widespread belief that herbicides are safe for human health and have little impact on the environment. Based on this belief, mainstream agricultural systems are now almost completely dependent on the use of pesticides, particularly herbicides. Many farmers have abandoned several equally effective, non-chemical weed management methods. As a result, tonnes of herbicides, particularly glyphosate products, are applied every day to fields and their surroundings, which can put human health at risk and negatively impacts biological processes and ecosystem functioning. Herbicide use with a zero tolerance approach to weeds is a major driver of farmland biodiversity decline; this includes loss of beneficial species which could otherwise combat pests. Farmers and growers have become dependent on pesticides and herbicides while many non-chemical alternatives have been lost from the collective memory, so producers end up trapped on a pesticide treadmill.

Herbicides can have a wide range of non-target impacts including direct toxic effects on non-target species, including soil organisms, invertebrates, and vertebrates, as well as ecosystem-level effects. But there are also important effects resulting from the intended aim of reducing weeds, which are vitally important food and ecological resources for the other species that inhabit farmland, such as insects and birds. Therefore, there are direct and indirect effects of herbicide use on farm ecosystems that result in the large declines observed in what were once widespread and vitally important farmland species of public concern, including wildflowers, insects[2], and birds[3].

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1 United Nations, 2017. Report of the Special Rapporteur on the right to food.
http://ap.ohchr.org/documents/dpage_e.aspx?si=A/HRC/34/48

2 Hallmann CA, Sorg M, Jongejans E, Siepel H, Hofland N, Schwan H, *et al.* (2017) More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS ONE 12(10): e0185809.
https://doi.org/10.1371/journal.pone.0185809

3 http://vigienature.mnhn.fr/page/produire-des-indicateurs-partir-des-indices-des-especes-habitat,
https://www.independent.co.uk/environment/europe-bird-population-countryside-reduced-pesticides-france-wildlife-cnrs-a8267246.html

Not only do the use of herbicides and pesticides have many negative impacts, but they are also increasingly failing to work due to evolved resistance, i.e., weeds evolve mechanisms that make them resistant to regularly-used herbicides, such that the herbicides no longer kill the weeds. In December 2022, there were 515 "unique resistance cases", i.e., weed species populations resistant to one herbicide (in 267 species), a large increase from less than ten cases in 1970[4]. Of those, over 100 species are resistant to two herbicide modes of action, and more than 50 species are resistant to three modes of action. Weeds have evolved resistance to 21 of the 31 known herbicide modes of action and 165 different herbicides. As a result, the number of glyphosate-resistant weed species now stands at 56.

Several new European Union (EU) policies demand an urgent reduction of pesticide use in Europe. Glyphosate is by far the most widely used active ingredient of herbicides in Europe. In the EU Green Deal announced in June 2022, *"the European Commission adopted a proposal to restore damaged ecosystems and restore Europe's nature from agricultural land and seas to forests and urban environments, by 2050. As a part of this, the Commission proposes to reduce the use and risk of chemical pesticides, as well as the use of the more hazardous pesticides, by 50% by 2030."* [5] The EU Biodiversity and Farm To Fork strategies[6] had earlier specified the two pesticide reduction targets in May 2020. However, at the current rate of use of herbicides, the EU pesticide reduction targets cannot be fulfilled. That is why we need alternatives to the current use of herbicides and particularly the most used, glyphosate.

European citizens are also demanding a radical reduction of pesticide use. In 2022, the European Citizens' Initiative (ECI) Save Bees and Farmers passed the milestone of 1 million valid signatures[7]. The ECI calls for phasing out the use of synthetic pesticides: by 2030, says the call, the use of synthetic pesticides should be gradually reduced by 80% in EU agriculture; and by 2035, agriculture in the entire Union should be working without synthetic pesticides. Earlier, in 2017, another successful ECI called to ban glyphosate, reform the EU pesticide approval process, and set mandatory targets to reduce pesticide use in the EU; it was officially handed into the European Commission with a total of 1,320,517 signatures collected from all across the EU[8].

This report outlines the wide range of non-chemical alternatives to herbicides that are already available and used by organic farmers and those practising integrated weed management (IWM). It highlights the critical need for mainstream farmers and growers to make much wider use of these tools, and the need to expand and improve current non-chemical tools, while also developing novel approaches. Using glyphosate-based herbicides as a reference, the current analysis presents a wide variety of weed management approaches that achieve highly effective weed control without the use of herbicides.

By integrating physical, mechanical, biological, and ecological agricultural practices with the broad knowledge acquired on the biological and ecological characteristics of crop plants and weeds, farmers can successfully manage weeds without herbicides, while maintaining yields,

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[4] Heap, I. The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/

[5] https://ec.europa.eu/eip/agriculture/en/news/green-deal-halving-pesticide-use-2030

[6] https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/farm-fork-targets-progress_en

[7] https://www.pan-europe.info/press-releases/2022/11/1-million-eu-citizens-tell-eu-commission-end-war-against-nature

[8] http://ec.europa.eu/citizens-initiative/public/initiatives/successful/details/2017/000002

avoiding building resistance in weed species, protecting soil health and biodiversity, and minimising erosion.

This report also covers topics such as the use of glyphosate in the EU and globally, general pesticide sales in the EU, and the impacts of glyphosate on soil and environment. Finally, it presents a list of suggestions for the transition towards glyphosate-free and pesticide-free weed management practices. The report draws upon several biological and agronomic principles, such as the “many small hammers” approach to weed management and the IWM hierarchy. In terms of soil, it explains the “living roots all year round” approach and most importantly for IWM, it redefines the concept of a weed by introducing the category of Aliae Plantae (other plants) which are not harmful to the crop but are rather benign to it or even beneficial to the agro-ecosystem. Widespread understanding this could be a game-changer, as farmers would no longer spend time, effort and money in eradicating aliae plantae for no benefit.

Finally, the IWM regime for dealing with docks (*Rumex spp.*) in pasture has been developed in to a new annex, and the 8 main uses of glyphosate and chemical and non-chemical alternatives to them have been summarised in a table, also in annex.

2. **WHAT IS GLYPHOSATE?**

The herbicide active ingredient glyphosate (N-(phosphonomethyl)-glycine) and its formulations are the most widely used herbicides, both globally and in the EU. Glyphosate was first synthesised in 1950 by a pharmaceutical company, but when research demonstrated the significant phytotoxicity of glyphosate in 1971, Monsanto patented it as an herbicide active ingredient. The first formulations of glyphosate were introduced into the US market in 1974 under the trade name Roundup™[9]. Due to the exceptionally broad spectrum and non-selective effects (lethal effects on every vascular plant), and the fact that it is systemic (it is transported through the plants' vascular system), Roundup formulations rapidly became popular in chemical agriculture. In the 1990s, the usage of Roundup expanded further with the development and planting of glyphosate-resistant genetically modified (GM) crops ("Roundup Ready" GM glyphosate-resistant soybean, followed by Roundup Ready maize and cotton). The cultivation of GM crops allows the post-emergence application of glyphosate-based formulations (two or three applications in a season), resulting in death of all plants except those resistant to glyphosate but also an increased chemical load on our environment. Neither the identification of the water-polluting properties of glyphosate nor the appearance of resistant weeds have slowed the market success of glyphosate-based formulations; in fact, the global market for glyphosate is continuously growing[10]. Roundup/glyphosate-based herbicides are also the foundation of chemical no-till agriculture and are used on millions of hectares globally for that use alone.

Glyphosate inhibits the shikimic acid metabolic pathway in plants by blocking the action of the enzyme 5-enol-pyruvyl-shikimic acid-3-phosphate or EPSP, which has a key role in the synthesis of amino acids (e.g. tryptophan and tyrosine) and other nutrients essential for the plant; triggering a cascade of reactions, the result is premature ageing and necrotic alterations of the entire plant, followed by rapid plant death (Holländer & Amrhein, 1980). The metabolic pathway inhibited by glyphosate occurs in every vascular plant, therefore the death of both terrestrial and aquatic plants can be caused by glyphosate (Boocock & Coggins, 1983). As a secondary effect, glyphosate can alter the endophytic and rhizosphere microbiome of plants (van Bruggen *et al.*, 2021), which can weaken defence of the plants via decreased antimicrobial production against pathogen attacks and increased exudation of pathogen-attractive amino acids and carbohydrates from the plants (Kremer & Means, 2009). Furthermore, the shikimate pathway is also found in microorganisms including bacteria and fungi, not only in plants (Duke, 2018). Indeed, glyphosate was patented in 2010 by Monsanto as an antimicrobial agent against certain pathogenic infections[11]. Due to the differing sensitivity of various microorganisms to glyphosate, the microbial composition of environmental elements (e.g. soil, surface waters, plant surfaces) can be impacted (van Bruggen *et al.*, 2018). Additionally, glyphosate can interact with gut microbiota of animals including humans and adversely affect their beneficial

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[9] Patent number US 3799758 A. N-phosphonomethyl-glycine phytotoxicant compositions.
[10] Benbrook, C.M. Trends in glyphosate herbicide use in the United States and globally. https://doi.org/10.1186/s12302-016-0070-0
[11] Patent number US 7771736 B2. Glyphosate formulations and their use for the inhibition of 5-enolpyruvylshikimate-3-phosphate synthase.

intestinal bacteria, resulting in dysbiosis, or imbalance of the composition of gut microbiota (Rueda-Ruzafa *et al.*, 2019; Hu *et al.*, 2021).

Since Monsanto's patent on glyphosate expired in 2000, many other pesticide manufacturers started producing glyphosate-based herbicide products. According to the European Glyphosate Task Force, a consortium of companies that produce glyphosate-based products, glyphosate is now marketed by more than 40 companies and over 300 herbicide products containing glyphosate are currently registered in Europe[12].

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[12] Glyphosate Task Force (industry consortium) https://www.europarl.europa.eu/RegData/etudes/BRIE/2018/614691/EPRS_BRI(2018)614691_EN.pdf

3. USES AND SALES OF GLYPHOSATE IN THE EUROPEAN UNION

3.1. USES OF GLYPHOSATE

Glyphosate is a broad-spectrum, non-selective, systemic herbicide, a crop desiccant, and to a lesser extent a plant growth regulator. Glyphosate-based herbicides (i.e., formulations containing glyphosate as an active ingredient, together with other chemicals) are non-selective, meaning they effectively kill or suppress all types of vascular plants (including grasses, perennials, vines, shrubs, and trees) when applied to green foliage. Glyphosate has been reported to be effective against more than 100 annual broadleaf weeds and grass species, and more than 60 perennial weed species (Dill *et al.*, 2010). A representative summary of its uses in the EU is given in **Table 1**. Additionally, the eight main uses of glyphosate in the EU and the possible alternatives are summarised in **Annex 1** (according to various experts' opinions edited by Hans Muilerman).

In conventional chemical agriculture, glyphosate-based herbicides are applied before crops are sown, to kill weeds to facilitate crop establishment. They are also used in chemical no-till farming to clear the land of weeds and previous crops, as a replacement for tillage/cultivation. Glyphosate is also used as a pre-emergent herbicide between sowing and crop emergence to kill weed seedlings that have been stimulated to germinate by tillage. In glyphosate-resistant crops (most of which are created by genetic engineering/genetic modification (GM)), the herbicide is used post crop emergence to kill the weeds but leave the crop unharmed. Glyphosate-based herbicides are also used to clear the ground beneath perennial crops such as fruit trees and grape vines.

Another use of glyphosate-based herbicides is as a crop desiccant on cereals and grains, to facilitate harvest. It is applied close to harvest to accelerate the ripening process and dry the seeds while the crop dies. Post-harvest, glyphosate is used to kill the remains of the crop plants and any weeds present. The use of glyphosate as a pre-harvest desiccant has become a common practice, particularly in regions where humidity levels are higher. However, since this use leaves the highest amount of glyphosate residues in the seeds and grains, some Member States have strict rules on this use (**Box 1**[13]). The cultivation of glyphosate-resistant GM crops and desiccation in agricultural practice allows the post-emergence use of glyphosate. Consequently, the adverse effects of glyphosate must be assessed in both non-GM and GM-cultivated areas, and the resulting picture is of growing glyphosate consumption everywhere, independent of the strict regulation of GM cultivation.

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[13] DG SANTE official website
https://ec.europa.eu/food/sites/food/files/plant/docs/pesticides_faq_glyphosate_20170719_final.pdf

Table 1. Representative uses of glyphosate registered in the EU (EFSA glyphosate peer review, 2015)

Crops/plant species	Growth and stage	Weeds controlled	Application rate of product l/ha (min-max)	Application rate of active ingredient kg/ha (min-max)
All*	Pre-planting of crops	Emerged annual, perennial and biennial weeds	1-6	0.36-2.16
All*	Post-planting pre-emergence of crops	Emerged annual, perennial and biennial weeds	1-3	0.36-1.08
Cereals (pre-harvest) wheat, rye, triticale, barley, oats [a]	Crop maturity < 30% grain moisture	Emerged annual, perennial and biennial weeds	2-6	0.72-2.16
Oilseeds (pre-harvest) rapeseed, mustard seed, linseed [b]	Crop maturity < 30% grain moisture	Emerged annual, perennial and biennial weeds	2-6	0.72-2.16
Orchard crops, vines, including citrus, tree nuts, olive trees	Post-emergence of weeds	Emerged annual, perennial and biennial weeds	2-8	0.72-2.88

* Crops including but not restricted to: root and tuber vegetables, bulb vegetables, stem vegetables, field vegetables (fruiting vegetables, brassica vegetables, leaf vegetables and fresh herbs, legume vegetables), pulses, oil seeds, potatoes, cereals, and sugar- and fodder beet; before planting fruit crops, ornamentals, trees, nursery plants etc.
[a] Minimum pre-harvest interval (crops cannot be harvested before) = 7 days
[b] Minimum pre-harvest interval (crops cannot be harvested before) = 14 days

Share of the area (in thousand hectares) of annual and perennial crops treated with glyphosate in the Member States of the EU plus Norway, Serbia, Switzerland, and Turkey (Antier *et al.*, 2020a) is presented in **Figures 1 and 2**.

All the registered uses of glyphosate in the EU can be found in the glyphosate risk assessment peer review report of the European Food Safety Authority (EFSA) (EFSA, 2015) and a summary is given in **Table 1**. In the EU, the maximum amount of glyphosate that can be applied is 4.32 kg of active ingredient per hectare in any 12-month period, which corresponds to approximately 12 litres of herbicide product (EFSA, 2015).

On a global scale, about 50% of glyphosate products used in agriculture are used on glyphosate-resistant GM crops, including maize, cotton, soya beans, oilseed, and sugar beet. The whole point of these crops is to use glyphosate-based herbicides exclusively for weed control. The significant spread of glyphosate use has been connected to glyphosate-resistant GM crops (e.g., glyphosate-resistant soybean, cotton, and maize) (Baylis, 2000; Dill *et al.*, 2010). According to the U.S. Department of Agriculture, GM herbicide-resistant crops now account for about 56% of global use of glyphosate (Modor Intelligence, 2022), and approximately 80% of cultivated GM crops belong to herbicide-resistant varieties (Bonny, 2011).

Figure 1. Share of the acreage (in thousand hectares) of annual crops treated with glyphosate in the Member States of the EU plus Norway, Serbia, Switzerland, and Turkey according to ENDURE Survey, 2019 (Antier *et al.*, 2020a)

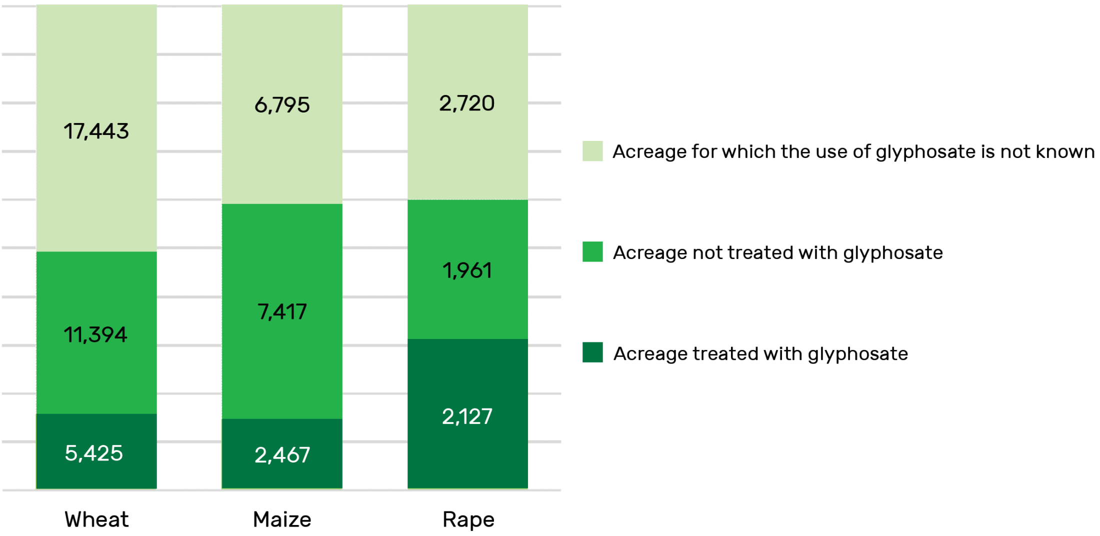
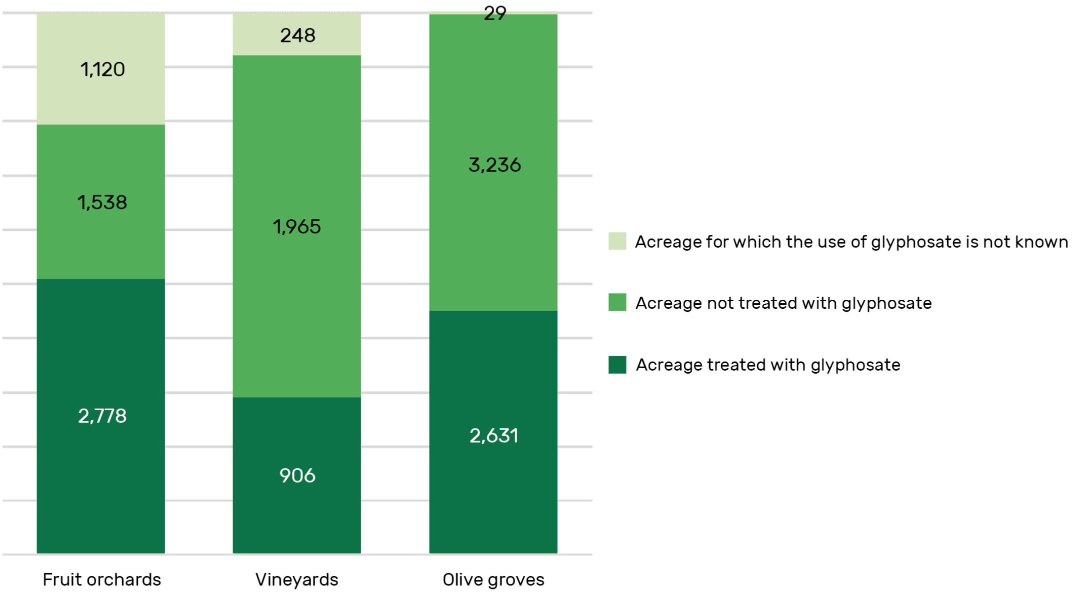


Figure 2. Share of the acreage (in thousand hectares) of perennial crops treated with glyphosate in the Member States of the EU plus Norway, Serbia, Switzerland, and Turkey according to ENDURE Survey, 2019 (Antier *et al.*, 2020a)



However, the EU has strict regulations regarding the planting of GM crops and 19 EU countries have excluded themselves from the geographical scope of the GM applications already authorised or in the process of authorisation[14]. The Member States that cultivate GM crops

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[14] https://ec.europa.eu/food/plant/gmo/authorisation/cultivation/geographical_scope_en

are the Czech Republic, Spain, Slovakia, Romania, and Portugal[15]. The total area dedicated to GM crops in Europe is approximately 130,000 ha, which is just below 0.1% of EU agricultural land. 95% of that land growing GM crops is in Spain[16] (124,227 ha in 2017). Currently, there is only one GM crop authorised for cultivation in the EU, the maize variety MON 810; although the crop is not glyphosate-resistant, glyphosate would be used before crop emergence and as a desiccant pre-harvest, like other crops grown in industrial-scale monocultures.

Box 1. Glyphosate: Different desiccation practices along Member States

Agricultural practices for which glyphosate-based herbicides are approved vary across EU Member States. According to the EU's Directorate General for Health and Food Safety (DG SANTE), some Member States have rules for when glyphosate can be used, and some stipulate how much can be used for different purposes. A report made by the Danish Environment Protection Agency on the use of glyphosate explains:

"The EU Member States differ to some extent with regard to approval of specific applications of glyphosate use:

- *In Denmark, glyphosate products can be used for pre-harvest weed control and desiccation (harvest aid) until 10 days before harvest.*
- *In Austria, the use of glyphosate for desiccation (harvest aid) in cereal crops was banned in 2013; while its use for weed control is still permitted.*
- *In Germany, the use of glyphosate for harvest aid is not banned as such but it is not considered good agricultural practice.*
- *Sweden is in a similar situation: no glyphosate products approved for this particular use are available on the market.*

The European Crop Protection Association (ECPA, the industry lobby association of pesticide producers) adds: *"In several north-western European countries, glyphosate can be applied before crop harvest for weed control, to enhance ripening on non-determinate crops to reduce crop losses, and to help manage determinate crops in wet seasons. Different countries have different recommendations for crops but the common factor is that the bulk grain sample must have dried to a maximum of 30% moisture content. The climate in southern Europe is such that few weeds remain green at the time of harvest, and crops typically ripen fully, so pre-harvest use of glyphosate is not normally recommended."*

There are no official data on the overall amount of glyphosate used for agricultural or non-agricultural purposes across the EU. Based on U.S. global official and industry data, Benbrook (2016) gives an overall picture of the agricultural and non-agricultural use of glyphosate presented in **Figure 3**.

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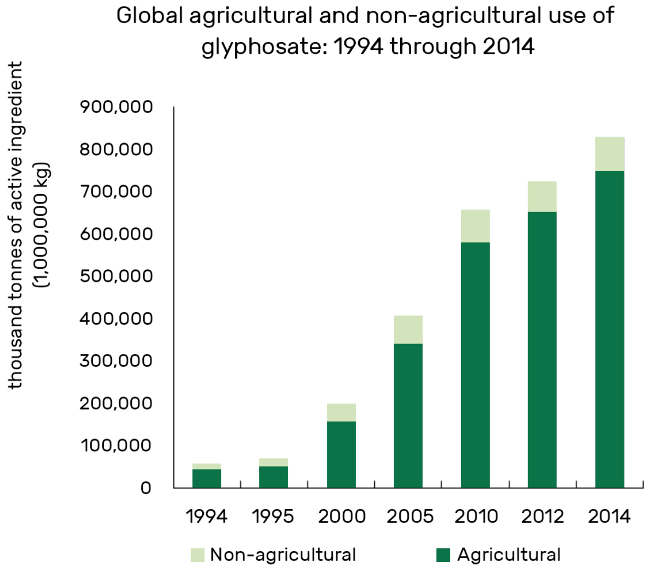
[15] European Parliamentary Research Service (EPRS) - PE 545.708, author: Tarja Laaninen, https://www.europarl.europa.eu/EPRS/EPRS-AaG-545708-Member-State-bans-on-GMOs-FINAL.pdf, https://royalsociety.org/topics-policy/projects/gm-plants/what-gm-crops-are-currently-being-grown-and-where/

[16] https://www.infogm.org/-Qui-cultive-des-OGM-dans-les-monde-Et-ou-

These data also reveal that global use of glyphosate has increased almost 15 times in the last 10 years. Glyphosate is still the leading herbicide active substance, and it is the global market leader; global use of glyphosate reached 826 million kg in 2014 (Benbrook, 2016), and the annual consumption was expected to reach over 1 billion tons in 2017 (Transparency Market Research, 2016).

Figure 3. Global agricultural and non-agricultural uses of glyphosate (adapted from Benbrook 2016)



For the EU, public data on pesticide use is sparse and often limited by considerations of commercial sensitivity, although some data are collected by the Member States. Annual sales data are available from EUROSTAT, which are used as a proxy for use/application. But the obligation for farmers to keep records of pesticide use[17] has not been used to generate datasets on the application of pesticides; that will only take place in 2026 for certain crop groups and from 2028 for all crops[18]. In Germany, a survey of arable farmers in 2009, by the University of Göttingen, found glyphosate was applied to approximately 4.3 million hectares of arable land (39% of the total arable area surveyed), and that application of glyphosate was about 4,197 tonnes of active ingredient (Steinmann *et al.*, 2012). In the UK, glyphosate-based herbicides were the most used of all herbicides in arable crops and were used on 2,812,366 hectares in 2020, with 2,557 tonnes of "active substance" applied (Ridley *et al.*, 2020).

The estimated average use of glyphosate in 2017 by the agricultural sector, per hectare of utilised agricultural area in conventional agriculture in the Member States of the EU, plus Norway, Serbia, Switzerland, and Turkey, is presented in **Figure 4**. Furthermore, the relative dominance of glyphosate-based herbicides can be seen in **Figure 5**, which shows the average use of all herbicides (both glyphosate-based and other herbicides) in 2017 in the agricultural sector per hectare in the Member States of the EU, plus Norway, Switzerland, and Turkey (Antier *et al.*, 2020a).

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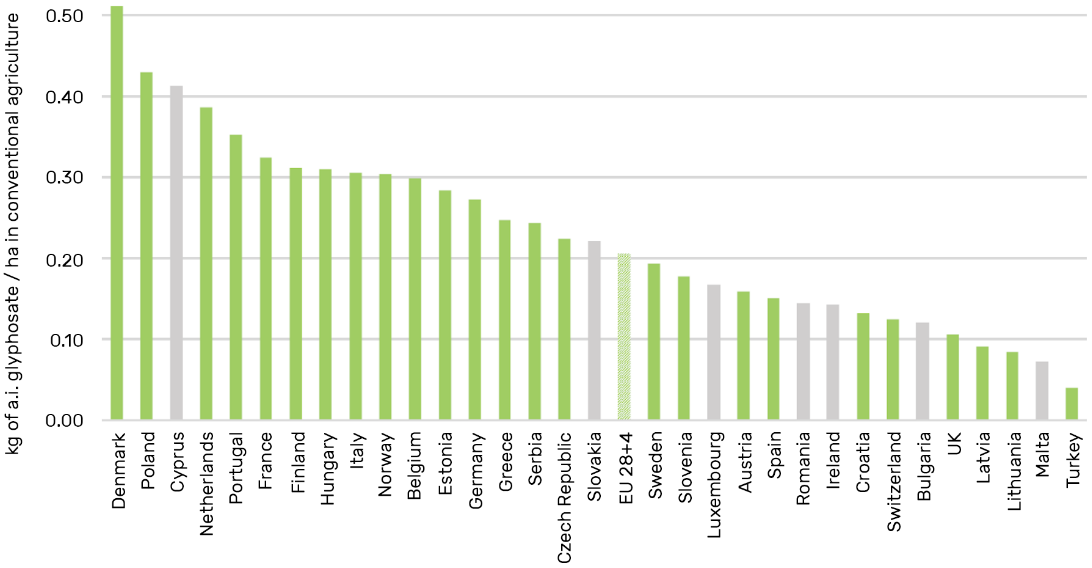
[17] Article 67 of Regulation (EC) 1107/2009 concerning the placing of plant protection products on the market https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009R1107

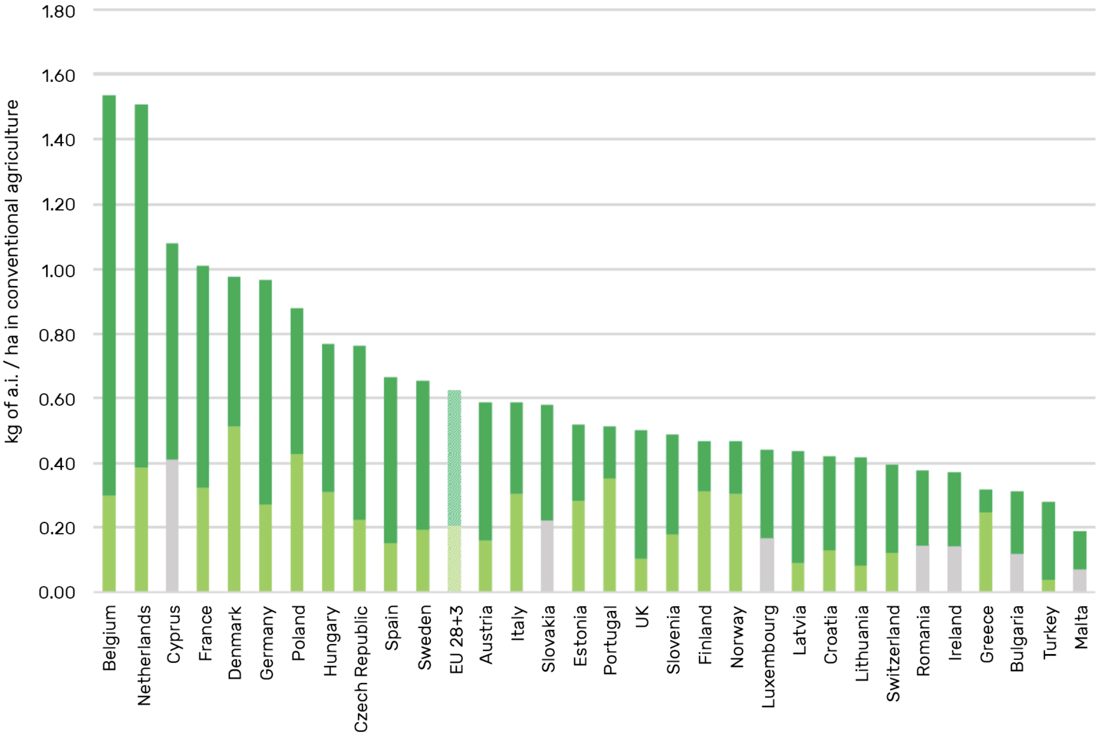
[18] Under the regulation (EU) 2022/2379 on statistics on agricultural inputs and outputs (SAIO), this farm level data on pesticide applications will be collected electronically by the Member States, who will transmit it to the European Commission, who will publish it via EUROSTAT. https://eur-lex.europa.eu/eli/reg/2022/2379/oj

Figure 4. Estimated average use of glyphosate in 2017 by the agricultural sector, per hectare of utilised agricultural area in EU Member States plus Norway, Serbia, Switzerland, and Turkey (EU 28+4) according to ENDURE Survey, 2019 (Antier *et al.*, 2020a)*



(*green: data obtained from ENDURE Survey, grey: estimated data)

Figure 5. The average use of glyphosate and other herbicides in the agricultural sector per hectare in the EU Member States plus Norway, Switzerland, and Turkey (EU 28+3) in 2017 according to the ENDURE Survey, 2019 (Antier *et al.*, 2020a)*



(*grey: estimated values, no exact data were reported in the survey)

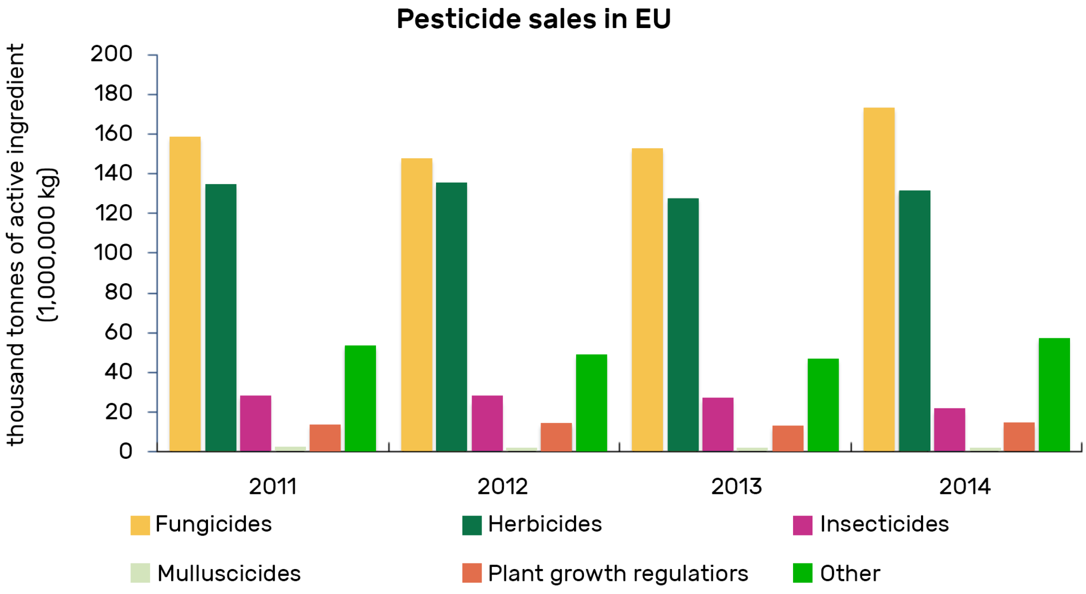
3.2. SALES OF GLYPHOSATE AND OTHER HERBICIDES IN THE EU

According to the global organisation Transparency Market Research, Europe held around 16.6% of the global glyphosate market in 2012[19], and in 2017, glyphosate represented 33% of the total herbicide market in the EU (Antier *et al.*, 2020b). The global glyphosate market was estimated at about 4438.5 million USD in 2020 (ReportLinker, 2021).

It is hard to find detailed data published by the EU institutions on the use of individual herbicide products, while detailed sales data per product are often hidden under the pretext of commercial sensitivity. So, it is currently very difficult to find out how much glyphosate-based herbicides are being used in EU countries. However, the statistical office of the EU, Eurostat (part of the European Commission) provides statistics for the sales of pesticides in the EU Member states[20], which are presented below.

Figure 6 shows the summary of pesticide sales in Europe between 2011-2020. A total of 387,078 tonnes of pesticides were sold in 2020 (Eurostat). Based on the data provided by Eurostat, herbicides are the second most widely sold category of pesticides, closely behind fungicides. In 2020, 136,177 tonnes of herbicides were sold, accounting for 35% of all pesticide sales.

Figure 6. Pesticide sales in Europe according to data provided by Eurostat between 2011-2020



Looking at pesticide sales at the country level, for some countries, herbicides are the most widely sold pesticide product category (**Figure 7**). For example, in 2020, more herbicides than fungicides were sold in 17 European countries: Bulgaria, the Czech Republic, Denmark, Estonia,

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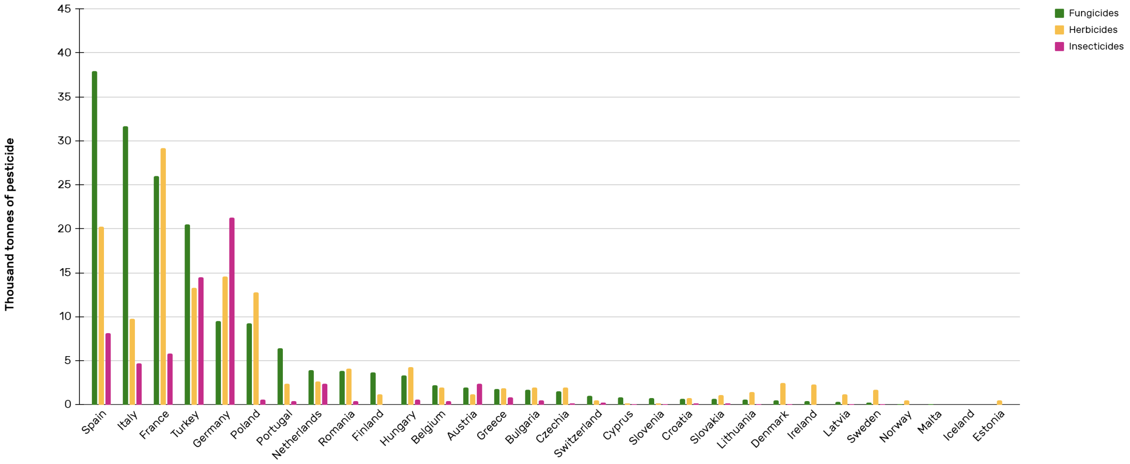
[19] https://www.transparencymarketresearch.com/glyphosate-market.html

[20] https://ec.europa.eu/eurostat/databrowser/view/TAI02/default/table?lang=en&category=agr.aei.aei_pes

Germany, Greece, Hungary, Iceland, Ireland, Latvia, Lithuania, Norway, Poland, Romania, Slovakia, and Sweden.

Figure 7. Sales of herbicides, fungicides and insecticides across the European countries in 2020 according to the dataset of Eurostat



France, Germany, Spain, Poland, and the United Kingdom are the countries with the highest herbicide sales in Europe (**Figure 8**). Together, these five countries on average across all years had sales of 84,757 tonnes of herbicides, which is 60% of Europe's entire herbicide sales. It is worth noting that Spain is the country where most glyphosate-resistant crops are grown in the EU, and it also has the EU's second largest area of agricultural land after France. Overall herbicide sales changed little during 2011-2020, with the exceptions of Denmark, Germany, and Romania, where there was a reduction in sales, and Spain where sales increased from 13,834 tonnes in 2011 to 20,199 tonnes in 2020 (**Figure 8**). The market of herbicides including glyphosate between 2013 and 2017 is shown in **Figure 9** in six European countries (Antier *et al.*, 2020a).

Figure 8. Sales of herbicides across European countries in 2011-2020 according to Eurostat

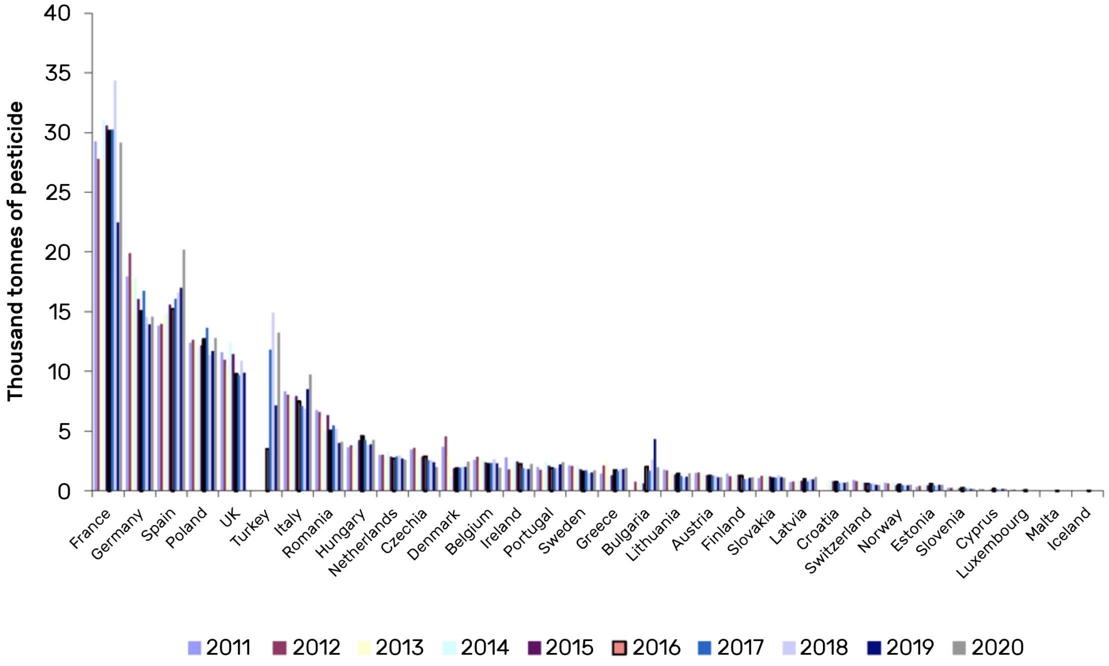
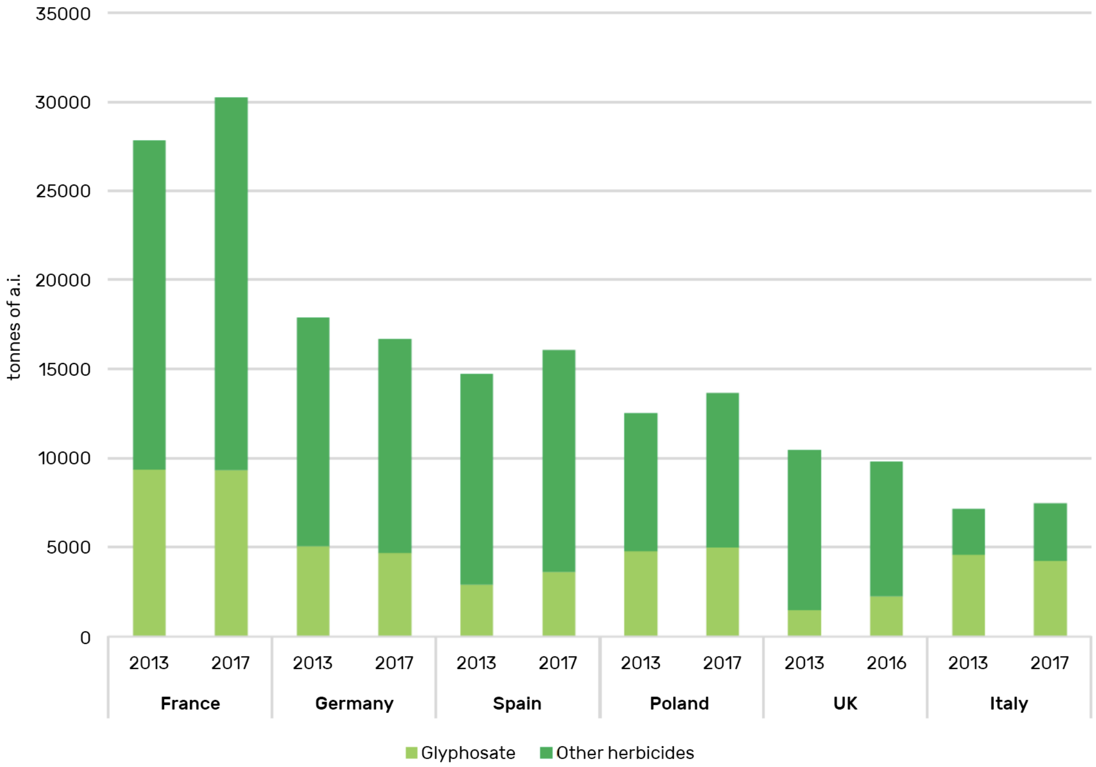


Figure 9. The market of herbicides with a focus on glyphosate between 2013 and 2017 in six different European countries according to ENDURE Survey, 2019 (Antier *et al.*, 2020a)



4. **IMPACT OF GLYPHOSATE ON ECOSYSTEMS**

Due to the continuous increase of glyphosate usage there is glyphosate contamination in a range of different environmental areas e.g., soils, sediments, and surface waters. During chemical plant protection, glyphosate-based formulations are generally directly sprayed onto crop fields, and a significant part is taken up by plants or enters into the soil layers, where glyphosate can be transported by surface water runoff, reach groundwater via infiltration, adsorb to soil particles, or can be assimilated into living organisms. In addition to climatic conditions (e.g., intensity and frequency of rainfall) and the timing and frequency of glyphosate treatments (Hébert *et al.*, 2019), the environmental fate of glyphosate and its additives highly depends on various abiotic (e.g., pH, soil composition and structure, mineral content, hydrological conditions) and biotic (e.g., microbial composition and activity) factors in terrestrial and aquatic habitats (Mamy *et al.*, 2016; Grandcoin *et al.*, 2017; Hébert *et al.*, 2019).

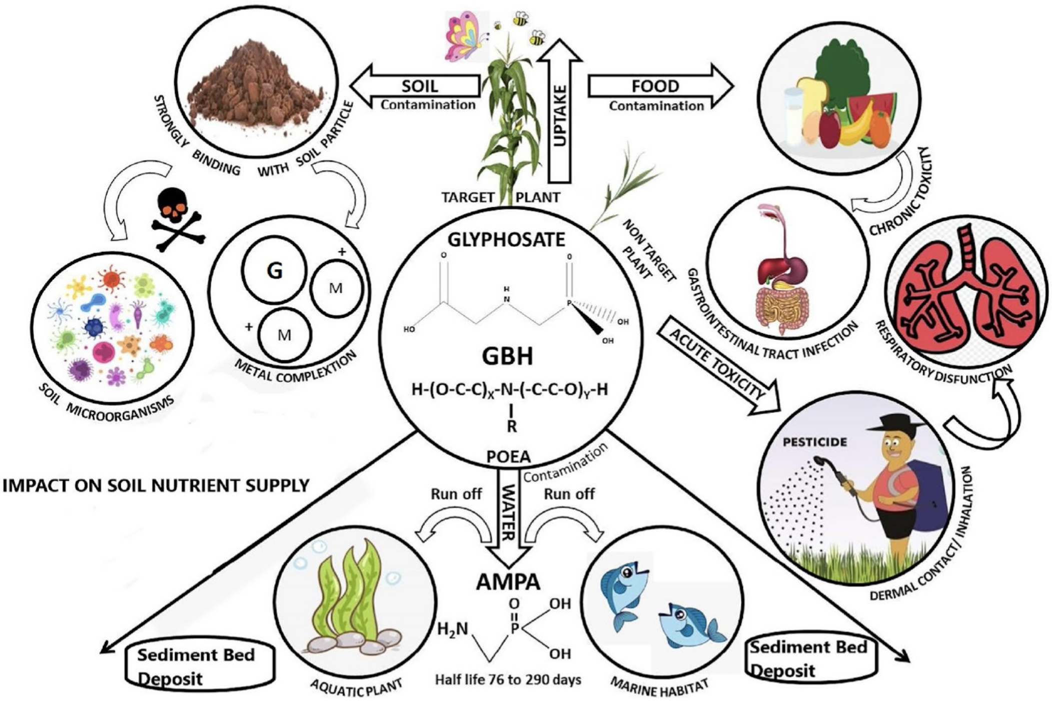
Due to the extensive use of glyphosate, the occurrence of glyphosate as a ubiquitous contaminant in various environmental elements (especially in aquatic ecosystems) is a globally observed phenomenon. Although variability of detected and reported glyphosate residue levels can be high (Székács & Darvas, 2018), glyphosate contamination can reach up to 5200 µg/l in surface waters (Edwards *et al.*, 1980). Moreover, the frequency and the magnitude of detected residue levels are highly dependent on e.g., application rates, hydrological conditions, and rainfall intensity (Coupe *et al.*, 2012). AMPA is the main metabolite of glyphosate and its mobility is higher compared to the parent compound (Duke & Powles, 2008), thus AMPA is also often detected in environmental samples. Therefore, the potentially toxic effects of metabolites on the ecosystem ought to be an important part of environmental risk assessment. The use of glyphosate-based formulations for desiccation and weed management in glyphosate-resistant GM crop cultivations allows also the post-emergence use of glyphosate, thus the environmental risk connected to glyphosate must be evaluated in non-GM and GM-cultivated areas as well.

Glyphosate-based formulations contain various additives including formulating agents, besides the active ingredient, in order to improve the efficacy and bioavailability of the formulation by increasing the solubility, adsorption, and uptake of the active ingredient (Foy, 1987). The different additives (e.g. formulating agents) used in the formulation of the active ingredients were classified as inactive components in terms of the main biological effect (as a herbicide) of the plant production products. Therefore, the authorisation of additives required simplified risk assessments compared to the active ingredients (Fishel, 2020; US EPA, 2022). Although, in recent years, several scientific reports and studies have proved the high toxicity of individual formulating agents, including POEA (a mixture of polyethoxylated tallow amines) used in glyphosate-based formulations. It was also found that the combined toxicity of the active ingredient and additives, taken together in the formulations, was higher than the toxicity of glyphosate alone (Mesnage *et al.*, 2019). Due to unequivocal scientific evidence, the use of POEA in glyphosate-based formulations has been banned (European Commission, 2016).

Therefore, the evaluation of the combined toxicity of active ingredients and additives is of utmost importance, while most active ingredients enter into various ecosystems as a mixture of different components.

Pesticide residues including the residues of glyphosate-based formulations can interact with the abiotic and biotic elements of the ecosystem, and may have adverse effects on living organisms (Figure 10). Risks related to the ecotoxicity of glyphosate are mainly linked to the increased level of glyphosate usage and residues. Different terrestrial and aquatic non-target organisms are exposed to the adverse effects of glyphosate-based pesticides, but significant differences can be observed in the sensitivity of different species. Co-exposure to glyphosate and to formulating additives often leads to additive or synergistic toxic effects. Based on the scientific literature, glyphosate, its formulations, and also the formulating agents can induce a broad range of ecotoxicological effects (e.g., lethal/sub-lethal effects, morphological and biochemical changes) on terrestrial and aquatic organisms exposed to them (Sesin *et al.*, 2020; Lanzarin *et al.*, 2021; Zaller *et al.*, 2021).

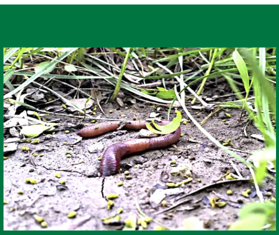
Figure 10. Environmental contamination and risk from glyphosate-based herbicides (Gandhi *et al.*, 2021)



The broad-spectrum glyphosate and glyphosate-based herbicides have both direct and indirect impacts on ecosystems and the environment. Direct effects include glyphosate causing harm in a wide range of species, including birds, fish, frogs, snails, insects, and soil microbes (Watts *et al.*, 2016). Direct effects such as the unprecedented elimination of weeds and wildflowers from crop fields, has indirect/knock-on effects on agro-ecosystems (e.g., reduction in plant diversity and biomass) (Watts *et al.*, 2016). Farmland biodiversity and ecosystem functions, such as pest control by their natural predators, pollination services by insects and functional soil structure, are increasingly jeopardised by the near-complete elimination of not only weeds but all wild plants from agricultural fields and adjacent land, in addition to direct toxic effects on many species (Box 2). The ecological disturbance and disruption of such ecosystem services is one of the difficulties conventional farmers face when transitioning to ecologically friendly agricultural systems (Schütte, 2003).

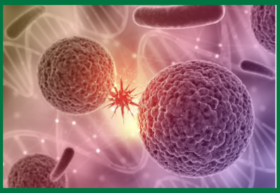
Several studies show that the composition and abundance of microbial communities in the soil are affected by glyphosate-based formulations (e.g., impacts on the abundance of rhizosphere-associated bacterial communities and arbuscular mycorrhizal fungi) (Druille *et al.*, 2013; Newman *et al.*, 2016; Zaller *et al.*, 2017; Helander *et al.*, 2018.). This indicates the possible long-term effect of glyphosate on the nutrient status of the rhizosphere, as these communities protect their plant symbionts and facilitate nutrient and water uptake by the plant roots and rely on plant root exudates of sugars and proteins to feed them. Other examples of disturbance in soil communities following the application of glyphosate formulations are an increase in the colonisation of specific *Fusarium* species (plant pathogens) on roots, which may result in increased production of mycotoxins, also increasing food safety risks (Zobiole *et al.*, 2011). The disturbance of beneficial soil bacteria (e.g., Pseudomonas and Bacillus species) was also demonstrated; this is important because certain bacterial species have an important role in the making soil minerals available to plants and suppressing pathogens (e.g., pathogenic fungi) (Yu *et al.*, 2015; Aristilde *et al.*, 2017).

Box 2. Examples from the scientific literature on how glyphosate use affects ecosystem services



Earthworms: Also called "ecosystem engineers", they shred and redistribute organic material in soil, increase soil penetrability for roots through their movement, and consequently improve overall soil fertility. Glyphosate-based herbicides affect the reproduction of earthworms and cause a dramatic decline in their population[1].

Soil microbial communities: These form the basis of ecosystem services such as plant residues and litter decomposition, organic matter mineralization, carbon and nitrogen cycling among others[2]. Certain fungi and bacteria facilitate nutrient uptake in plant roots. Repeated applications of glyphosate alter the microbial community of certain soils[3], increase soil pathogens[4] and affect plant nutrient uptake[5].



Pollinators: Honey bees, bumble bees, butterflies and other insects, play a key role in the pollination of the plants, and have a key role in the pollination of crops in agriculture to produce, seeds or fruits. As glyphosate is a broad spectrum herbicide, it reduces the number of flowering plants that are a food source for the pollinators but it may also impact honey bees following long-term exposure[6].

Plant defence: Plants have their own defence system to respond to infections by synthesising and exerting specific substances to reach the site of infection (e.g. antimicrobial phytoalexins). Glyphosate acts on the pathway that many of these plant-defences are produced, making the crops more susceptible to pathogens and diseases[7].

[1] Gaupp-Berghausen *et al.* 2015; [2] Delgado-Baquerizo *et al.* 2016; [3] Lancaster *et al.* 2010; [4] Kremer and Means, 2009; [5] Zaller *et al.* 2014; [6] Herbert *et al.* 2014; [7] Johal and Huber, 2009.

The potential toxicity of glyphosate-based formulations has been evaluated on various terrestrial test organisms. Results show higher toxicity in the presence of POEA, abnormal cellular respiration and lipid metabolism, oxidative stress, and altered physiological mechanisms (e.g., moulting) on the springtail *Folmosia candida* (Simoes *et al.*, 2018); accumulation of glyphosate and its metabolite (AMPA) in snail tissues (Druart *et al.*, 2011); and altered plant metabolome in Arabidopsis thaliana (Ke *et al.*, 2022) which may affect plant resilience (Saikkonen *et al.*, 2020). Glyphosate residues in soil may have direct or indirect effects on the phytohormone homeostasis of plants (Fuchs *et al.*, 2022) which can have consequences for ecosystems including plant-microbe and plant-insect dynamics, e.g., interfering with plant resistance and the attraction of beneficial insects (Fuchs *et al.*, 2021). Glyphosate residues in soil can result in reduced body mass and altered activity of earthworms (Zaller *et al.*, 2014; Pochron *et al.*, 2020): based on a study, earthworms that were not exposed to Roundup Alphée improved the performance of tomato plants and increased levels of Vitamin C and ß-carotene in the fruits, while in the presence of exposed earthworms, tomato plants were unable to set fruit (Owagboriaye *et al.*, 2020).

Aquatic organisms are highly exposed to glyphosate as a water pollutant; indeed, their exposure is unavoidable in water, especially if they inhabit sink habitats where agricultural pollutants accumulate. The adverse effects on natural freshwater bacterial and zooplankton communities can be observed even at very low glyphosate concentrations, indicating the possibility of diversity loss (da Costa *et al.*, 2021). Toxic effects of glyphosate and its formulations were identified on algae cells (e.g., disruption of thylakoids and mitochondria, morphological changes) (Iummato *et al.*, 2019), and phytoplankton communities. On the other hand, at lower concentrations, glyphosate may serve as a source of nutrients and phosphate for the benthic microbial and algae communities resulting in induced biomass growth (Qiu *et al.*, 2013). The ecotoxicity of glyphosate and its formulations on various aquatic organisms was determined, with remarkable differences being observed in the sensitivity of different organisms, even taxonomically close species, despite similar feeding strategies and lifestyles (e.g., crustaceans) (Reno *et al.*, 2018). Exposing mollusc species to glyphosate-based herbicide has both lethal effects (e.g., mortality) and sub-lethal effects (e.g., on reproduction, altered hormone levels) (Reddy *et al.*, 2018); while in several aquatic invertebrate and fish species, enzyme activities changed upon exposure (Sandrini *et al.*, 2013; Iummato *et al.*, 2018). Exposure to glyphosate-based formulations caused an increase in the level of reactive oxygen species (ROS), genotoxicity, reproductive effects, as well as developmental and behavioural effects, primarily in fish (Fiorino *et al.*, 2018; Lanzarin *et al.*, 2021). In addition, the harmful effects of glyphosate on amphibians (e.g., cytotoxicity, genotoxicity) have recently become a major focus of research and results of scientific studies indicate the extreme sensitivity of amphibians compared to the other vertebrate species (Bach *et al.*, 2016).

Several scientific studies have indicated the potential risks of glyphosate to other wildlife such as birds, reptiles and beneficial arthropods such as pollinators (Ruuskanen *et al.*, 2020; Graffigna *et al.*, 2021). Toxic effects of glyphosate on honeybees including behavioural and developmental effects, as well as altered growth, metabolic processes, reproductive success and immune defence are also indicated by several studies (Graffigna *et al.*, 2021; Tan *et al.*, 2022).

As a consequence of the high levels glyphosate usage, the occurrence of its residues and metabolites in the environment can result in the contamination of drinking water and food products, where the quantity of the residues may exceed the allowed safety limits. Human exposure via drinking water and food consumption has been associated with several toxic effects and diseases (Tabrez *et al.*, 2014), while the presence of glyphosate was proven in foodstuffs/beverages (e.g., bread, honey, beer[21], wine[22], agricultural products) (Rubio *et al.*, 2014; Bou-Mitri *et al.*, 2022), as well as in biological samples (e.g., urine[23], breast milk) (Grau, 2021; Camiccia *et al.*, 2022). Serious health concerns have been raised, especially about cancers, human pregnancy and birth defects[24] among agricultural workers and consumers (Acquavella *et al.*, 2004), in several cases the conflict resulted in litigation, where compensation was awarded to the affected farmers[25].

However, there is no uniform legal opinion about the effects of glyphosate on human health, while the U.S. Environmental Protection Agency (US EPA) classified glyphosate as a compound "probably not carcinogenic to humans"; their opinion agrees with the standpoint of the EFSA and the European Chemicals Agency (ECHA), that glyphosate is unlikely to be a carcinogen in humans. In contrast, the International Agency for Research on Cancer (IARC) at the World Health Organisation (WHO), has graded glyphosate as "probably carcinogenic to humans" (2A) (Székács & Darvas, 2018). Furthermore, scientists have challenged the ECHA classification[26] after examining the 11 animal studies provided by pesticide companies.

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[21] https://www.stern.de/gesundheit/gesundheitsnews/bier--pestizid-glyphosat-in-14-deutschen-bieren-gefunden-6716556.html/

[22] https://d3n8a8pro7vhmx.cloudfront.net/yesmaam/pages/680/attachments/original/1458848651/3-24-16_GlyphosateContaminationinWineReport_(1).pdf?1458848651

[23] http://www.urinale.org/wp-content/uploads/2016/03/PK-Text-Handout.pdf

[24] https://docs.iza.org/dp12164.pdf, https://ehjournal.biomedcentral.com/articles/10.1186/s12940-018-0367-0

[25] https://www.agri-pulse.com/articles/16445-glyphosate-a-timeline-of-a-pesticides-rise-and-legal-cases, https://www.centerforfoodsafety.org/press-releases/6051/legal-settlements-awarded-to-cancer-patients-and-farmers-harmed-by-monsanto-herbicides

[26] https://www.env-health.org/scientific-evidence-of-glyphosate-link-to-cancer-dismissed-in-ongoing-eu-assessment-new-report-reveals/

5. **WEED MANAGEMENT WITHOUT GLYPHOSATE**

Weed management is one of the dominant challenges in agriculture, particularly in arable and vegetable cropping systems. Failure to manage weeds can result in complete crop loss, particularly, if no or insufficient weed management is undertaken for several years, allowing the "weed seed bank" (weed seeds in the soil) to build up, with proportional increases in the number of weeds in subsequent years. Farmers' efforts in managing weeds are reflected in EU herbicide sales, which account for 35% of all pesticide sales (**Figure 6**).

Yet in order to reduce the environmental and human impacts of herbicides, there is a clear need to reduce and eventually eliminate herbicides and other pesticides. The solution is to invest in sustainable agricultural systems that can reverse the damage caused by herbicides and pesticides and create an ecologically and economically viable agricultural production model.

This section, together with the examples given in **Annexes 1, 2, and 3**, shows that it is possible to reduce or even eliminate the use of herbicides in agriculture. Organic farmers are prohibited from using synthetic pesticides, including herbicides, and have been successfully farming without them for over seventy years. But it is not just organic farmers who have been farming without herbicides: increasing numbers of conventional farmers are reducing or stopping using herbicides. Many non-chemical weed management methods already exist that any farmer can adopt, which allows them to reduce and then eliminate herbicide use. Even challenging issues, like the use of glyphosate in "conservation tillage" that minimises tillage, and in particular avoids ploughing, can be resolved without herbicide use (**Box 3**) (TILMAN-ORG, 2016).

Electrothermal weeders are starting to demonstrate their potential to be a direct replacement for glyphosate and other herbicides such as paraquat in no-tillage (NT) and reduced-tillage (RT) systems (see Section 5.5.2). If this potential is realised, then electrothermal techniques could revolutionise NT and RT. It would mean NT could be used in organic and other farming systems where glyphosate and other herbicides are prohibited. It would also allow existing herbicide-dependent no-tillage systems to become herbicide free.

Box 3. Herbicide-free conservation tillage

No-tillage and reduced-tillage

No-tillage (NT, also called zero-tillage and direct drilling) is a technique for growing crops and pasture without disturbing the soil through tillage. This is achieved by using seed drills specifically designed to plant seeds in un-tilled soil. The aim is to minimise the negative impacts of tillage on soil health, such as soil aggregation, earthworms, and mycorrhizal fungi. However, NT systems are currently dependent on glyphosate, and other herbicides such as paraquat, to manage weeds and other vegetation (such as killing crop plants after harvest). Glyphosate herbicides are referred to as "chemical ploughing" because they are a direct replacement for the plough and other forms of tillage. Ideally, there would be a way of gaining the benefits of NT but without using glyphosate herbicides.

One option is **reduced-tillage** (RT, also called conservation-tillage, and minimum-tillage (min-till). RT abstains from full-depth ploughing (also called conventional-tillage, and inversion tillage), rather it uses shallow tillage that only disturbs the top five to fifteen centimetres of the soil, principally through non-inversion techniques, or, occasionally shallow ploughing. Research has shown that RT compared with full tillage, can not only manage weeds effectively but also causes less soil disturbance, and has a lower impact on soil biology (TILMAN-ORG, 2016). Therefore, when combined with other agronomic practices, such as growing subsidiary crops, e.g., green manures, RT can effectively manage weeds and crop residues that overcome the need to use herbicides.

5.1. "LIVING ROOTS YEAR ROUND" – THE IMPACT OF WEED MANAGEMENT ON SOIL HEALTH

There is a fundamental interaction between weed management as a whole, not just herbicides and soil health (James & Merfield, 2021). As soil health is essential to so many other issues in agriculture, such as the provision of ecosystem services, ensuring good soil health is vital to many outcomes in agriculture. However, in the last decade soil science has undergone a paradigm shift in its understanding of how soil organic matter (SOM) is formed and thus the drivers of soil health (Cotrufo *et al.*, 2022).

The old paradigm was that plant and animal residues (such as leaves, manure, compost) deposited on the soil surface or tilled into the soil, were then broken down by organisms such as worms, and then microbes such as bacteria, with tough materials like lignin ending up as "humus" which could last for centuries to millennia.

The new paradigm is that it is the exudates from living plant roots that drive SOM formation. Between 10% to 40% of the photosynthates, and therefore the energy that plants capture from the sun, are pushed out of their roots in the form of simple carbohydrates, lipids, and proteins to feed the microbes that live in a mutualistic symbiosis around the roots – an area called the "rhizosphere". The microbes return the favour by providing water, nutrients, and protection from diseases for example. The plants also change the types of exudates to favour specific microbes when they need their particular help. And different plant species have different exudates that favour different microbes. It is thus vital to have a diversity of plants to maximise the diversity of microbes, in order to optimise soil health.

The microbes also transform and put some of the exudates inside the mineral soil particles where it is highly protected. This organic matter is called mineral-associated organic matter (MAOM) and it can last for centuries to millennia. So the old paradigm is subsumed as part of the new paradigm, in that the surface residues are still broken down by the likes of worms and bacteria, but they only last for years to a few decades, not centuries to millennia as was previously thought. This is now called particulate organic matter (POM).

Thus, it is a diversity of living plant roots that are the primary drivers of soil biology, SOM formation, and thus soil health, not crop residues, compost, manure etc. Hence the mantra "Living roots year round".

The implication for weed management is that the core objective of weed management – reducing the diversity and biomass of plants – works directly against the need to maximise the diversity and biomass of living plants to maximise soil health. Therefore, all forms of weed management, chemical and non-chemical, must only reduce plant diversity and biomass to the absolute minimum level required for successful crop production. A new definition of weeds has recently been published that addresses this very issue.

5.2. REDEFINING WEEDS FOR THE POST-HERBICIDE ERA

Called "Redefining weeds for the post-herbicide era" (Merfield, 2022) the paper is published in "Weed Research", the world's leading weed science journal. The paper first notes that weeds are not a scientific concept: there is, for example, no botanical category of "weeds". Weeds are entirely value judgments about the "goodness" or "badness" of particular plants (NB plants, not plant species). It then defines weeds as:

A plant, or population of plants,
in a specific time and place,
causing **significant harm**,
either immediately or in the longer term,
based on a holistic analysis of both their positive and negative attributes.

The common definition of a weed is a "plant growing where it is not wanted"; the value judgement within it is "not wanted". The paper argues that this is far too low a bar now we understand the multiple harms caused by weed management (not just herbicide use) and thus creates a much higher bar of 'significant harm'. It also requires that plants are only defined as weeds in a specific place and time to counter the common belief that particular plant species e.g., fat hen (*Chenopodium album*) are always weeds, i.e., the statement "fat hen is a weed" is complete nonsense without the context of where the fat hen plant is. The requirement that the harm caused by weeds may be in the future is to address the issue that the plants may not be causing harm now; but, if left to themselves, they will create harm in the future (e.g., become invasive, set lots of seeds, get really big). Therefore, it is more efficient to manage them now when it is easy than in the future when it is hard. The final line notes that all plants have both positive and negative benefits (provide ecosystem services vs. compete with crops) and that both positives and negatives need to be weighed up before deciding if a plant is a weed.

The definition thus eliminates the idea that all non-crop plants are weeds. This means there are now three types of plant in a field: the crop, the true weeds, and everything else – "other plants" or as the paper calls them "aliae plantae". Aliae plantae are non-crop plants that are on balance not causing significant harm and can therefore just be left alone.

This definition can be seen at work where a farmer uses herbicides to kill plant species in their crops and the same farmer is subsidised to sow the same plant species as wildflower strips, because those species are considered useful and fulfil beneficial agro-ecological functions e.g., supporting pollinators and predators of pests. Therefore, there is a need to more intelligently manage non-crop plant flora, both within crops and in non-cropped areas. For example, deliberately leaving aliae plantae among crops has been shown to provide multiple ecosystem services while maintaining yield (Adeux *et al.*, 2019). Aliae plantae contribute to sustaining crop yields through their roles in supporting beneficial biodiversity and soil fertility (Jordan & Vatovec, 2004; Ziska & Dukes, 2018). Aliae plantae offer a habitat for mycorrhizal fungi, they cover bare soil after harvest, keeping beneficial soil microorganism communities alive through their root exudates of sugars and proteins. In addition, they provide habitats for beneficial insects, which are vital for pest management, and the pollen and nectar they produce help to maintain the populations of pollinators. The aim should not therefore be to completely eradicate all non-crop plants, as they play an important ecological role that is useful for farmers and the wider environment. Rather than a zero-tolerance, low biodiversity approach, a balance between crop and non-crop vegetation, therefore, needs to be struck, between limiting damaging weeds to maintain yields and allowing aliae plantae to support vital ecosystem services. As economic damage is caused only when weed infestation by a minority of species reaches above a certain threshold, a successful weed management approach should take into consideration the biological and ecological characteristics of weeds and non-crop flora, and use various agricultural practices to reach that balance. The key framework to achieve this balance is “integrated weed management” (IWM).

5.3. INTEGRATED WEED MANAGEMENT

The core of sustainable weed management is to integrate a wide range of different methods to manage weeds, each one adapted to the type of weed and type of crop and usually applied in combination, at specific times during the life cycle of the crop. This approach is the basis of integrated weed management (IWM), where techniques such as rotations, mechanical weeding, biological control, and active monitoring are used to achieve optimum weed management and healthy, quality crops with good yields. The compilation of all the available techniques can be seen as a pyramid, where each layer provides a list of methods that can be applied for weed management, and where chemical control is used only as a last resort only if all other methods have failed **(Figure 11**). This is often also called the “many little hammers” approach (Liebman & Gallandt, 1997). The metaphor has even been extended to say that by using “many little hammers”, a farmer can keep on top of weeds without resorting to the chemical “wrecking ball” of synthetic herbicides. This helps create a higher biodiversity system where beneficial ecosystem processes are allowed to function. While synthetic herbicides are part of the IWM approach/weed management pyramid, their use is not covered in this report, as its focus is on non-herbicide weed management.

The practices of weed management can be divided into four parts:
(the IWM pyramid; see **Figure 11**):

- preventive and cultural agronomic practices;
- monitoring – observation and identification of weeds, assessment of potential value or harm;
- physical control;
- biological control.

It is vital to integrate as many methods into non-chemical weed management because one method is rarely enough to manage all weeds at all times in all crops. Indeed, even with herbicide-based weed management, a range of different types of herbicide modes of action are required to achieve sufficient weed management across the whole farm.

Figure 11. The Integrated Weed Management pyramid: building from bottom to top

The foundation of the weed management pyramid is preventative measures, typically system-level or whole-farm techniques such as rotations, particularly those that include both arable cropping and livestock. Good hygiene practices, for example, ensure that harvesting equipment does not move weed seeds from one field or farm to another. Next comes monitoring - walking the fields to determine what weeds are present. Then using the farmer's or grower's knowledge of weeds to decide if any weed management actions are required. These decisions can be supported by tools such as modelling and forecasting, and by good record keeping, so the producer knows how weeds are changing over time on their farms. Building on a base of sound information, the producer can decide what physical and biological weed management interventions are required, and only when these options have been exhausted should chemical control, especially with synthetic herbicides, be considered. **Figure 12** illustrates an example of an IWM approach for vineyards.

Figure 12. Integrated Weed Management approach plan in vineyards

Making a weed plan in vineyards:

- **Correct identification of weeds**

- know what you are dealing with;

- **some understanding of weed ecology**

- know why the weeds grow where they do and how they get there;

- **appropriate vineyard design**

- e.g.: choice of irrigation system can influence weed development and weed management approaches;

- **choice of appropriate management methods**

- use effective techniques that minimise negative impacts on the vineyard environment (eg. soil);

- **monitoring**

- know where weeds are a problem and how effective the control strategies have been.

Source: David Madge Vineyard agroecology http://agroecology.berkeley.edu/

IWMPRAISE: Integrated Weed Management: PRActical Implementation and Solutions for Europe

Considerable progress is being made in IWM in the EU. The IWMPRAISE (Integrated Weed Management: PRActical Implementation and Solutions for Europe) project consists of 37 partners from eight different European countries and includes 11 leading universities and research institutes within the area of weed management, 14 companies and industrial partners, 12 advisory services and end-user organisations (Riemens *et al.*, 2022)[27]. They have developed an IWM framework that consists of five pillars:

- diverse cropping systems;
- cultivar choice and establishment;
- field and soil management;
- direct control;
- monitoring and evaluation (**Figure 13**).

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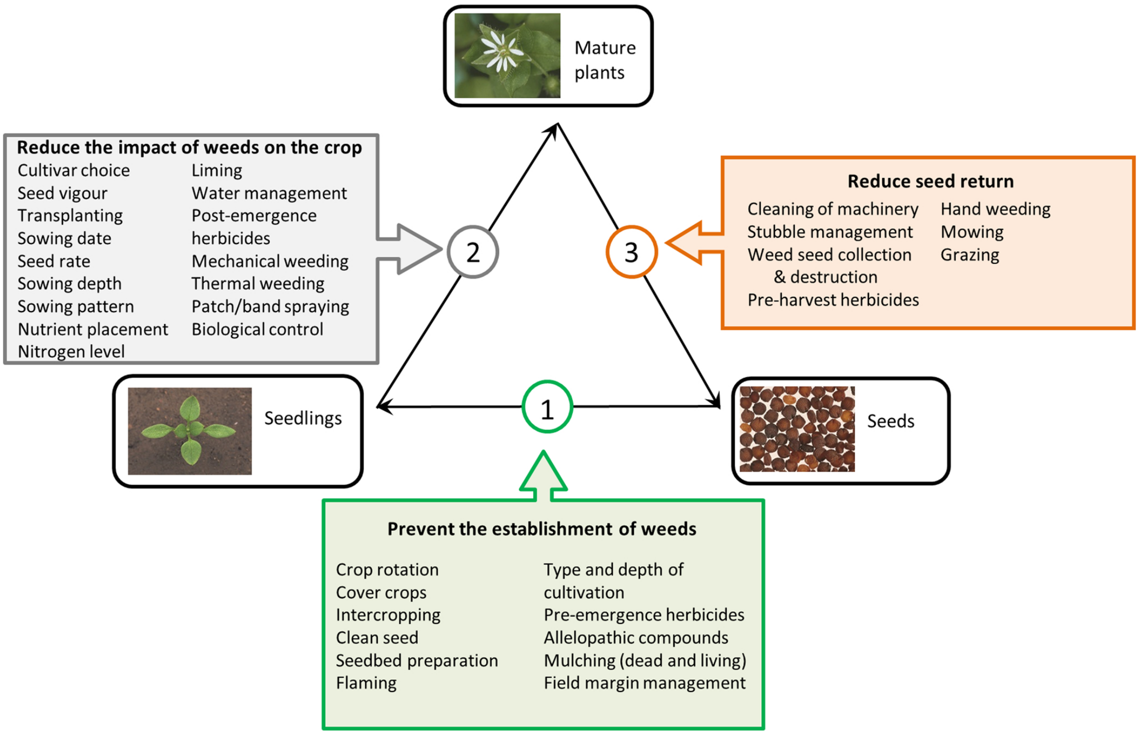
[27] https://iwmpraise.eu/

The first four are management pillars and they each have a range of individual "tactics" that are combined and used synergistically, i.e., as per the many little hammers concept (Liebman & Gallandt, 1997). The cross-cutting pillar of monitoring and evaluation includes activities, such as weed scouting, the use of decision support systems (DSS), and high-tech sensing technologies, to ensure that management tactics are only used when necessary, but also that weed infestations don't go undetected and become problematic. The weed management tactics are also focused on three stages of a weed's lifecycle: seeds, seedlings, and mature plants (**Figure 14**).

Figure 13. Framework for the planning and design of holistic IWM strategies that require combinations of individual management tools appropriately selected from each of the five pillars of IWM: diverse cropping systems, cultivar choice and establishment, field and soil management, direct control and the cross-cutting pillar monitoring and evaluation (Riemens *et al.*, 2022).

Figure 14. Weed control tactics are mentioned where they are expected to have maximum effect on weed survival. Weed control tactics affecting weed survival at different stages of their life cycle. (Riemens *et al.*, 2022)



The IWM framework has also been designed to be part of an "integrated crop management" system, so that weed management is not isolated from other components of the farm system, such as nutrient, pest, and disease management, so all crop management aspects are fully integrated, i.e., to be part of an agroecological approach.

5.4. PREVENTIVE AND CULTURAL WEED MANAGEMENT

The term "cultural control" or "cultural" agronomic practices refers to any method used to maintain field conditions so that weeds are less likely to become established and/or increase in number, or to strengthen the crops and facilitate them in competing with the weeds. Cultural weed control includes a wide range of practices such as rotations, subsidiary crops, management of soil quality (e.g., avoiding compaction), tillage (surface working vs. deeper ploughing), fertiliser/nutrient management and application (e.g., banding of nutrients), crop species and cultivars (e.g., choosing more ecologically competitive ones), crop establishment techniques (e.g., row spacing and drilling depth), through to harvest and post-harvest techniques (e.g., undersowing crops, leaving the "weed seed rain"[28] on the soil surface to be predated), etc.

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[28] The shedding of seeds from the parent plant onto the soil. Many individual annual plants can produce thousands, even tens of thousands of seeds.

All these cultural techniques are preventative – they are not about controlling weeds that have already become established, but rather they prevent the weeds from establishing in the first place. As in many other aspects of farming, prevention is much better than cure. It is often much more effective and cost-efficient than interventional techniques to kill already established weeds.

Box 4. Farmers' tips to beginners

Farmers' tips to beginners:

- Prevention is always better than cure – Make sure you have a clear plan and whole-farm approach to weed control, to minimise the amount of weeds in the crop that need to be controlled.
- "One year's seeding: seven years weeding" – This old farming adage points out that it is much easier to manage weeds by preventing them from seeding in the first place (stopping the weed seed rain), rather than controlling the weeds that result from shed seeds.
- Leave less open soil for colonisation by weeds - cover crops, undersowing, living mulches, and narrower row spacing can all be used to reduce the space available for the establishment of weed seedlings.

5.4.1. CROP ROTATIONS

Rotations are one of the oldest and most effective cultural controls to manage weeds. Just before the dawn of the herbicide era, Clyde E. Leighty wrote in the 1938 Yearbook of Agriculture: *"Rotation of crops … is the most effective means yet devised for keeping land free of weeds. No other method of weed control, mechanical, chemical, or biological, is so economical or so easily practiced as a well-arranged sequence of tillage and cropping."* However, the benefits of rotations are much wider than weed management (Snapp *et al.*, 2005). They are even more valuable for pest and disease management, particularly soil borne pests and diseases. They are also vital for maintaining soil quality, by diversifying plant species and maximising living roots year round. Moreover, where leguminous plants are grown in rotation as crops or as green manures, they boost soil nitrogen reserves, due to nitrogen-fixing bacteria that form a mutualistic symbiosis with the legumes. Indeed, farming without rotations is all but impossible without recourse to artificial nitrogen fertilisers, pesticides, and herbicides to replace the multitude of benefits that rotations bring to agriculture.

Rotations manage weeds by introducing temporal diversity to fields, changing from season to season. For any given crop, there are weed species (and pests and diseases) that grow and reproduce particularly well or at least are not suppressed as much. If the same crop is grown year after year in the same field, then the populations of those weeds will increase year-on-year until they become unmanageable. By rotating crops, weeds that thrive in one crop will be suppressed by other crops, such that one set of weed species never dominates and becomes problematic. Therefore, rotating between crops with contrasting conditions for weeds will have the greatest effect. In particular, rotating between annual crops, such as cereals and vegetables, and pasture with livestock is very effective because exceptionally few weed species can thrive in both cropping and pasture systems. Rotating between spring and autumn sowed crops in arable systems is also highly effective.

5.4.2. SUBSIDIARY CROPS (COVER CROPS)

Subsidiary crops, also called non-cash crops and cover crops are grown for benefits other than direct cash profit. The term "subsidiary" is used in the meaning of "service" or "support". Subsidiary crops which include nitrogen-fixing species are called green manures. Subsidiary cropping is a huge topic in itself (Sustainable Agriculture Network, 2007). There are many reasons to grow subsidiary crops. One of the main reasons is to increase soil health and organic matter, which increases the retention and availability of nutrients to the following cash crop. Weed management is another key reason to grow subsidiary crops.

For example, subsidiary crops can be used to allow a flush of weed seed to germinate which is then out-competed by the subsidiary crop, and which is terminated before the weeds set seed, thereby depleting the weed seed bank. For particularly problematic weeds such as the Californian thistle (*Cirsium arvense*), highly competitive subsidiary crops called "smother crops" such as rye (*Secale cereale*) and vetch (*Vicia species*) mixtures will compete so strongly with the thistle, both for light and soil nutrient resources, that they can crowd out and eradicate the thistle within one or two growing seasons.

5.4.3. INTERCROPPING AND UNDER-SOWING

Intercropping, also known as polyculture, mixed-cropping, or co-cultivation, is a method that involves growing two or more plants simultaneously in the same field so that the properties of each plant facilitate the growth of the other. Benefits of intercropping include legumes supplying nitrogen to non-legumes in a mixture, suppression of weed germination and growth, suppression of insect pests and plant diseases, and an overall increase in productivity. Suppression of weed germination is typically due to the crop foliage shading the soil, but it can also be through allelopathy, where the crop puts out allelochemicals that directly inhibit seed germination. Suppression of weed growth can be due to both aboveground competition for light and belowground competition for water and nutrients, as well as allelopathy and more complex interactions, such as those involving mycorrhizal fungi (Hirst, 2017). For example, legume-maize mixtures are a classic intercrop for protein-rich livestock forage, with the benefit of the legume directly supplying the maize with nitrogen (Nurk *et al.*, 2017).

Under-sowing involves seeding one or more subsidiary crops underneath the main cash crop, typically with the sowing of the subsidiary crop delayed for several weeks, to allow the cash crop to be sufficiently established that the subsidiary crop does not compete with it and reduce yield. When the cash crop is harvested, the subsidiary crop is released from the suppressive competition of the cash crop and grows rapidly, covering the soil and preventing germination and growth of weeds. This is a particularly valuable technique, as it eliminates the need to till the soil after the harvest of the cash crop because the under-sown crop is already developed. It is often used to establish pasture. This technique also reduces the time between the crops to zero, eliminating soil damage from tillage, and exposing bare soil, and it achieves a continuum of living roots so it is also better for soil biology. Farmers can win many weeks or even months of extra growth because the under-sown crop is already well rooted. At the same time, weed presence in the final under-sown crop is low, as they were crowded out in the preceding cash crop phase and suppressed during its growth. There are many highly successful cash crop/ under-sown crop combinations that have been researched and that are in widespread use, such as combinations of barley, wheat, maize, and soya using white clover, subterranean clover, and fenugreek as the under-sown plants (Ramseier & Crismaru, 2014).

5.4.4. CROP COMPETITION TO SUPPRESS WEEDS

For both pasture and arable crops, the competition that the crop exerts against the weeds can be a major contributor to successful weed management. Some vegetable crops can also be highly competitive against weeds, potatoes being the classic example. However, some are poor competitors throughout their life, e.g., onions. The competitiveness of crops can be improved through several approaches. For example, the breeding and use of more competitive cultivars, for example, ones that grow taller or have a horizontal canopy structure that shades the soil quicker (Andrew *et al.*, 2015). For allelopathic crops, where crops produce biochemicals that influence the growth, survival, development, and reproduction of other organisms., cultivars can vary significantly in the amount of allelochemicals they produce, and more strongly allelopathic cultivars can have a significant competitive edge. The density of sowing, which in arable crops can be increased two or even three times, can have a large effect. Using denser populations can result in significantly increased crop competition at the critical, early growth stages. For arable crops, altering sowing patterns, e.g., halving the row spacing or “double drilling” in a checkerboard pattern, can also increase crop competitiveness.

5.4.5. FALSE AND STALE SEEDBEDS

False and stale seedbeds are two related techniques based on three principles (Merfield, 2015). First, around 90% of the weed seed bank is dormant at any given time, but the 10% non-dormant seeds at the top of the soil profile will rapidly germinate given the right conditions. Second, tillage/cultivation is the most effective way to trigger weed seeds to germinate through a wide range of factors including increasing the amount of oxygen and nitrate, increasing temperature and diurnal temperature variation, as well as eliminating foliage shading the soil. Thirdly, and most critically, most seeds of crop weeds can only emerge from the topmost five centimetres of the soil, typically the top two centimetres. If the seeds are any deeper, their energy and nutrient reserves become exhausted before they reach the soil surface.

Both techniques need an optimum planting tilth (prepared soil surface), and the soil must be sufficiently moist for weed seeds to be able to germinate and emerge. Then, crop planting or sowing is delayed for one to three weeks to allow the non-dormant weed seeds to germinate and emerge.

In the false seedbed technique, the weed flush is killed by specialist tillage equipment that only tills the top two to four centimetres of the soil, while achieving a 100% weed kill. Tilling too deep (i.e., deeper than 4 cm), will bring up additional non-dormant seeds into the germination zone and infest the crop planted afterwards.

For stale seedbeds, the crop seeds are drilled into the soil among the emerging weeds, which are then killed with a flame, steam, or electrothermal weeder, 12 to 24 hours prior to crop emergence (Chen & Hooks, 2014; Merfield, 2015).

Both techniques are very powerful as they can rapidly deplete the weed seed bank that is able to emerge in the crop, and they effectively deal with both interrow and the more difficult to manage intrarow weeds. Because false seedbeds use inexpensive tillage as the weed management technique, both in terms of the capital and running costs, it is highly economic. Thus, using false seedbeds is an exceptionally valuable but highly underappreciated weed management technique.

5.5. IN-CROP WEED MANAGEMENT

Many farmers and growers new to non-chemical weed management erroneously think in a ‘herbicide mindset’ where nearly all weed management is focused on weeds growing in the crop. Following the many little hammers and weed management pyramid concepts, the majority, e.g., 90%, of non-chemical weed management should be achieved before the crop is planted, e.g., through the use of rotations, prevention of weed seed rain, nutrient management, false seedbeds, etc. Therefore, in-crop weed management should be viewed as the icing on the cake of non-chemical weed management, not the cake itself. Any farmer that believes non-chemical weed management starts at crop establishment is highly unlikely to be successful.

5.5.1. IN-CROP WEEDERS

Thanks to organic agriculture prohibiting the use of synthetic herbicides (and other pesticides) in the 1960s, there is now a vast range of weeding machinery that has been developed. This machinery is available for all farmers and growers to use for weed management. Indeed, there are so many different machines that it can be confusing for producers new to non-chemical weeding as to what weeders they need for the job. Just as herbicides have different "modes of action", so does weeding machinery. Understanding the different modes of action of the various types of weeder, and what they can and cannot do, allows farmers and growers to identify those weeders that are best suited for their needs. Additionally, like herbicides, one machine cannot do everything, so a toolbox of many little hammers in the form of a range of weeders is essential.

5.5.2. ELECTROTHERMAL WEEDERS – A DIRECT GLYPHOSATE REPLACEMENT

Electrothermal weeders (also called electrophysical and electric weeders) are a "back to the future" technology that was invented in the late 1800s (Diprose & Benson, 1984). However, it is only in the last decade that commercial machines have been developed, in part due to the increasing problems with herbicides.

Electrothermal weeders work by applying high-voltage electricity to the plants' foliage, which then instantly travels down the stem, into the roots, and out into the soil. The electricity heats the water inside the plant to boiling point turning it into steam, which causes the cells to burst, instantly killing the plant. This means electrothermal weeding has a systemic mode of action, like glyphosate, which is also applied to the foliage and translocates down the stem and into the roots. Electrothermal weeding has also a broader spectrum than glyphosate, as electrothermal weeding will kill all plants, while glyphosate only kills vascular plants. Many plant species are also naturally tolerant of glyphosate (i.e., glyphosate never effectively killed them) and there are now nearly 60 plant species with evolved resistance to glyphosate (Heap, 2022). Electrothermal weeding will kill all of these glyphosate-tolerant and resistant plants. The limitation of electrothermal weeding is the electricity does not reach all of the root systems, so, if plants can regrow from the undamaged roots or other underground parts, then the plants may be able to survive. Repeat treatments would then be required. Generally, it is only a few perennial plants that can regrow from underground organs; very few annual plants can survive either crop or weeds. This means that in many agricultural systems, electrothermal weeders can be a direct replacement for glyphosate, and many other herbicides as well.

For example, electrothermal weeding is being used:

- to kill all the vegetation in a field allowing direct-drilling without the use of glyphosate or tillage;
- to de-haulm potatoes and desiccate cereal crops to facilitate harvest;
- by robotic weeders to kill weeds at an individual plant level;

- to replace hoe blades in interrow hoes, killing the weeds without disturbing the soil or crop residues;

- to selectively kill tall weeds in pasture and crops based on the height difference between weeds and crops;

- to kill the weeds under and around the crop plants in perennial crops such as grapes and berries.

With an increasing range of applications and a growing amount of real-world experience, electrothermal weeding is proving to be a revolutionary technology and a direct substitute for glyphosate and many other herbicides.

This potential is stimulating an expanding range of research into electrothermal weeding, including dramatic reductions in the energy required to kill weeds. Recent research showed it was possible to kill plants with just a few Joules of energy, which means electrothermal weeding would use far less energy than herbicides if it can be scaled up (Bloomer *et al.*, 2022).

5.5.3. **WEEDING MACHINERY CLASSIFICATION**

In-crop weeders are classified into two main types: contiguous and incontiguous (**Figure 15**).

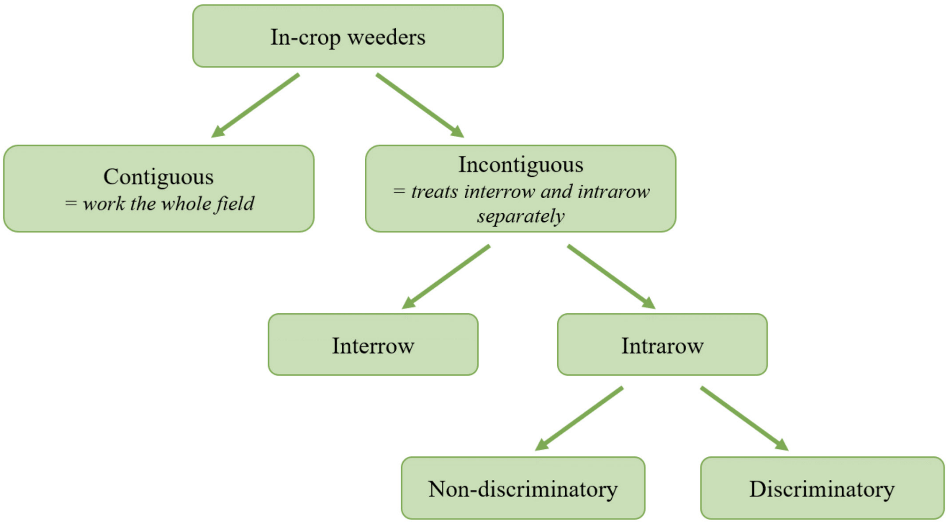
Contiguous weeders work the entire field surface and are also called “broad acre” weeders. Incontiguous weeders have gaps for the crop to pass through, so they treat the “interrow” (between the crop rows) and the “intrarow” (the crop row) differently. The interrow hoe is a classic example of this type of machine, where the interrow space is vigorously hoed while the crop row is untouched. However, modern incontiguous machines often also carry tools for weeding the intrarow, so the name “interrow hoe” is increasingly a misnomer.

Intrarow weeding tools and machines are in turn divided into two types: non-discriminatory weeders which apply the weeding action to crop and weeds alike, thus they are comparable to the contiguous weeders (see below for more detail), while the discriminatory weeders have a sensor to differentiate crop from weeds and then only apply the weeding technique to the weeds.

Contiguous weeders

As contiguous weeders weed the whole soil surface and both crop and weeds alike, the crop must be able to survive the weeding action while the weeds need to be susceptible to it. Contiguous weeders are somewhat analogous to selective herbicides that are applied to both weeds and crops, which kills the weeds while the crop survives. Contiguous weeders are mostly used in pasture and arable crops, especially those sown with row spacings less than 15 cm, although some can also be used in hardier vegetable crops.

Figure 15. In-crop weeder classification/hierarchy



Spring tine weeder

The spring tine weeder is the original contiguous weeder and the most versatile (**Figure 16**).

The working action of the spring tine weeder is very simple. It consists of a large number of lightly sprung, thin steel bars (tines), that are pulled through the soil surface (one to four centimetres deep). This pulls up, breaks, and buries small weedlings, especially dicotyledonous (broad leaf) weedlings. The crop survives because it typically has larger seeds, so is planted deeper in the soil (e.g., greater than 4 cm) and the young crop plant is larger and tougher than the weeds. Cereals, being monocotyledons, are particularly well suited to this weeding action as the upright thin leaves easily bend out of the way of the tines.

Figure 16. Spring tine weeder

The machine is highly flexible with several interacting adjustments which mean it can be set to barely 'tickle' the soil, allowing it to be used in comparatively delicate crops, all the way through to very aggressive settings that allow it to be used for final tillage passes. The weeders also come in a wide range of widths, from tractor width up to some 25 m wide, comparable in size to many agrichemical boom sprayers. The ability to work at speed (e.g., up to 15 km/h) means they have a substantial work rate. They can also be fitted with pneumatic seeders, allowing the broadcasting of seeds, which makes them an ideal tool for establishing pasture, subsidiary crops, and undersowing.

Spoon weeder/rotary hoe

The spoon weeder (called a rotary hoe in North America), is another well-established tool, especially in North America (**Figure 17**).

The spoon weeder consists of two rows of spoked wheels, with the ends of the spokes bent slightly backward and flattened into a spoon shape, hence the name. They work by picking up small cones of soil, which are thrown in the air, which then bury and break some weeds as they hit the ground. The amount of soil directly impacted by the tool is lower than the spring tine weeder which can cover all the field's surface, so the weed kill of the spoon weeder is generally lower. Its key advantages are that it can work in crop residue and harder-packed soils, which would defeat a spring tine weeder. In turn, it is defeated by stony soils as these blunt and wear out the spoons.

Figure 17. Rotary hoe or spoon weeder

Aerostar Rotation

The 'Aerostar Rotation' is a new machine produced only by Einböck (**Figure 18**).

It is a variation on the spring tine weeder's mode of action, in that it has vertical tines, but they are scuffed through the soil as they are mounted on angled wheels. This means it has a significantly more aggressive action than the spring tine weeder. Therefore, it should not be considered as an alternative to the spring tine weeder, rather, they are complementary tools, as the Aerostar Rotation will work in harder soils, and against larger weeds, than the spring tine weeder, but it may cause too much damage to softer crops.

Figure 18. Aerostar Rotation (photo: Einböck GmbH & CoKG.)

Combcut®

The Combcut® is an entirely novel weeding approach (**Figure 19**).

The Combcut® is based on a series of forward-pointing, dagger-like, knives that the crop slides between unharmed, but that cuts off the weeds. It is therefore almost exclusively for use in monocotyledonous crops and pasture against dicotyledonous weeds. It is also different from the other contiguous weeders and nearly all incontiguous weeders in that it is not soil-engaging, so is not impeded by wet and stony soils. It is also designed to be used later in the crop's life, unlike the other contiguous weeders that must be used against weeds when they are still very small, and generally within the first month of the crop's life. Combcut® is best used in the crop after the first month and up to the boot stage (the point when cereal crops put up a flower stem) when the weeds have thicker stems. After the boot stage, there is a risk of cutting the crop's flower stem, so then the weeder should be used to cut weeds off above the top of the crop. As it does not kill the weeds, the main effect is to set the weeds back so the crop can out compete them and to cut off flower/seed heads to prevent weed seed rain.

Figure 19. Combcut® (photo: Just Common Sense AB.)

Contiguous electrothermal weeders

Contiguous electrothermal weeders are used later in the crop's life, similar to Combcut®. They are used to kill weeds that stand taller than the crop, such as wild oats (*Avena fatua*) in cereals, ragwort (*Jacobaea vulgaris*) in the pasture, and fat hen (*Chenopodium album*) in vegetables. But, unlike Combcut® which only sets the weeds back, electrothermal weeders can completely kill the weeds.

Incontiguous weeders

Unlike contiguous weeders where there are five types of machine, the range of incontiguous weeders is larger. The dominant incontiguous weeder is the parallelogram hoe.

Parallelogram hoes

The design of parallelogram hoes has reached an optimum configuration. It is based on a tractor-mounted toolbar on which multiple parallelogram units are mounted. Each parallelogram has a tool frame onto which the weeding tools are clamped (**Figure 20**). This design permits very wide machines of up to 25 metres on a single toolbar, while allowing the weeding tools to be kept at a very accurate depth (± 1 cm) even in uneven fields. It is also highly customisable and there is a large range of weeding tools, both for interrow and intrarow weeding. The parallelogram hoe is therefore not so much a weeder itself, it is more of a platform on which to mount different weeding tools. This versatility is reflected in the fifty or more different manufacturers that make parallelogram hoes.

Figure 20. Parallelogram hoe

For the interrow, there is a wide range of hoe blade designs, most of which are based on a steel blade cutting horizontally through the soil. These come in four main types of design: duck or goose foot, A blade sweep, L blade hoe, and T hoe (**Figure 21**).

Figure 21. Interrow hoe blade designs, left to right: duck or goose foot, A blade sweep, L blade hoe, T hoe

To manage weeds in the intrarow there is an expanding range of non-discriminatory weeders for parallelogram hoes. The most effective of these is the "mini ridger" (**Figure 22**) which creates a small ridge of soil in the intrarow burying the weedlings while leaving the crop protruding. Research has found that if there is one centimetre of soil over the top of a plant (weed), regardless of how tall it is, it will be killed, and if two centimetres of a plant (crop) is left protruding from the soil ridge it will survive (Merfield, 2014; Merfield, 2018). This means that if the crop is a minimum of three centimetres higher than the weeds then mini-ridging is possible. This is often the case, both for quick growing large seeded arable crops and particularly transplanted vegetables.

Figure 22. Mini-ridger blades

A highly complementary tool to mini-ridgers is the finger weeder (**Figure 23**). These ground-driven, rotating tools, have a series of "fingers" that move the soil within the crop row, breaking, burying, and uprooting small weedlings. There is a wide range of designs to suit just about any crop, even trees, with the fingers being made from hard materials such as metal and plastic, though, to softer materials such as rubber. The finger weeder is an ideal companion to the mini-ridger. A ridge is first built up with the mini-ridger and then later the finger weedes are used to pull the ridge down. Thus, a weed kill is achieved both when building up the ridge and also when it is pulled down. This is similar to how potatoes grown on ridges are weeded, just at a much smaller scale.

Figure 23. Finger weeders

Other tools include torsion weeders which use sprung steel bars to break up the soil in the intrarow thereby breaking and uprooting weedlings. There are several tools based on thin vertical wires that rake through the intrarow, which are particularly valuable for upright, monocotyledonous crops such as maize, leeks and onions. These vertical wire weeders can be ground-driven using angled spoked wheels, like a miniature Aerostar Rotation wheel (**Figure 18**) as well as powered machines with many wires.

Horizontal axis brush hoe

Besides the mainstay of the parallelogram hoe, there are several other interrow hoe designs. The horizontal axis brush hoe is based on a large cylindrical brush, similar to those used on road sweepers, with gaps in the brush for the crop rows (**Figure 24**).

The hoe has a very aggressive weeding action, as the brush pulverises the top two to five centimetres of soil, macerating the weeds in the process. It achieves a high weed kill rate even in wet soils, stony soils, and against larger weeds that would challenge, and even stop, other interrow hoes working. It is therefore excellent for winter crops such as garlic. The downside is that when the soil is dry it can create a lot of dust, especially in clay and silt soils.

Figure 24. The horizontal axis brush hoe (left: mounted on a specialised tool-carrier tractor)

The basket weeder has a cylinder of wire cages instead of the brush hoe's brushes, with gaps for the crop rows (**Figure 25**). Unlike the brush hoe's single brush, which is powered by the tractor, the basket weeder has two rows of baskets with a differential chain drive between them which forces them to turn at different speeds so they cut and scuff through the soil, cutting and breaking the weedlings. The basket weeder is therefore mechanically much simpler and therefore less expensive than the brush hoe, making it ideal for smaller producers. It also does not produce the clouds of dust that the brush hoe does. However, it performs poorly in hard soil as it is not as effective at penetrating soil as the brush hoe and stones bend the bars, while the brush hoe can cope with the stoniest of soils.

Figure 25. Basket weeder

The final common interrow hoe design is the vertical axis powered tine weeder (**Figure 26**). This has small rotors with metal tines that spin around in the soil. It has an aggressive weeding action that can cut through hard-packed soil and can kill larger weeds. Their main disadvantage is their mechanical complexity makes adjusting row spacings difficult, and means they are expensive. And, while they can handle pebbly soil, stones tend to get caught between the tines and shields and may cause damage to the machine and crop.

Figure 26. Vertical axis powered tine weeder

Incontiguous weeder guidance

The key requirement of incontiguous weeders is that the crop rows need to fit through the gaps in the weeders if they are to survive, which means the weeders have to be accurately steered. Pre-computerisation, this was achieved by either having a person sitting on the hoe steering it independently of the tractor or using a specialised 'tool carrier' tractor where the weeder is mounted between the front and back wheels so the driver can see it and the crop (**Figure 24**). With a skilled operator these approaches could achieve highly accurate guidance, but the job requires high levels of continuous concentration which is hard on staff. There is also a limit to human reaction speeds and strength which restricts forward speed and machine size. Computerisation has created a revolution in weeder guidance and solved the guidance problem. There are two main approaches, computer vision systems and highly accurate global positioning systems (GPS).

Computer vision systems are based on digital cameras looking forward from the weeder at the crop rows. Sophisticated computer programs then determine where the crop row is and move the weeder to match. The GPS systems use real-time kinematic (RTK) technology which increases the metre-level accuracy of standard GPS to centimetre level accuracy. This is used to automatically steer the tractor, and in some cases both tractor and implement are independently steered, giving exceptional accuracy. With the GPS system, the crop must be drilled using GPS as the system is "blind" to the location of the crops, rather the GPS system only follows its pre-determined line, so the crops must be drilled or planted directly on the GPS line. In comparison, vision systems follow the actual crop row, so there must be sufficient crop plants visible for them to work. Both systems thus have pros and cons, and larger farming operations may well run both GPS and computer vision systems.

Computer vision systems have also created a further revolution by allowing discriminatory intrarow weeding.

Discriminatory intrarow weeding

Once computer vision systems could identify crop rows the logical progression was to identify individual crop plants and then have a hoe weed around each plant. These systems are mostly used in transplanted vegetables, as they have larger intrarow spacings between the individual plants. Leading edge machines, such as the "Robovator" can operate at speeds of up to 8 kph and working widths of up to 12 metres (**Figure 27**).

Figure 27. K.U.L.T Robovator (photo: K.U.L.T.)

Combining computer-guided interrow hoes and both computer vision-based discriminatory intrarow weeders and mechanically based non-discriminatory intrarow weeders, exceptional weed management, as good, if not better than herbicides, can be achieved over large crop areas.

Robotic weeders

The concept of robotic weeders has been around for almost as long as robots have. However, unlike factories where the environment is made to fit the robot, agricultural fields are exceptionally complex, unpredictable, and inhospitable environments for robots. However, in the last few years, robotic weeders have moved from very expensive research projects to robots that are economically and practically viable on-farm.

However, there are different types of robotic weeders (Merfield, 2023). The first type, called Level 1 is autonomous row followers. They use RTK GPS, computer vision, and other systems to follow crop rows, in both annual and perennial crops, or follow a pre-planned path. Therefore, they don't identify individual plants, only the crop row. Typically, these then have weeding tools mounted on them or sprayers, and the smaller ones such as the one in **Figure 28**, are also used for transport, e.g., taking produce from the fields to the packing shed.

Figure 28. Weeding robots

Level 2 robotic weeders can identify individual crop plants and weed around and between them. Therefore, this is another way of categorising the discriminatory intrarow weeders such as the K.U.L.T Robovator in **Figure 27**. Thus, some Level 2 robots are tractor-mounted and some are autonomous.

Level 3 robotic weeders identify every individual plant both crop and weeds and then individually kill the weed plants. This is the highest level of robotic weeder created to date and has been the most challenging level to achieve. Commercial Level 3 weeders have only been available in the last year or two.

Level 3 robotic weeders also open up the potential for a profound revolution in weed management. As discussed in Sections 5.1 and 5.2, many non-crop plants are not true weeds but rather aliae plantae that don't need to be killed. However, most existing weeding technologies, both herbicide and mechanical, cannot differentiate between true weeds and aliae plantae, so the aliae plantae are killed along with the weeds.

Level 4 robotic weeders would be able to determine if a non-crop plant is a true weed or an aliae plantae, based on both their species and populations, then kill the weed plants and leave the aliae plantae alone. Level 4 robotic weeders could thus undertake all weeding in both annual and perennial crops, throughout the life of the crop. Level 4 robotic weeders could in theory entirely replace all current in-crop weeding technologies, both herbicides and mechanical, while achieving fully ecological weed management. However, this is still only theoretical at present as no current robotic weeders have achieved Level 4 yet. The possibilities this opens up are however truly astounding (Merfield, 2023).

5.5.4. THERMAL WEEDING

Thermal weeding refers to weed management technologies that use heat or cold to manage weeds. Nearly every conceivable means of thermal weeding has been tried, including microwaves, liquid nitrogen, carbon dioxide snow, focused sunlight, etc., but the only ones that have proved practical, safe, and economical are flame, steam, and electrothermal. A common misconception with flame weeding is that the plants have to be burnt. The real aim is to boil the plants, i.e., the water inside the plant cells turns to steam causing the complete destruction of the plant tissues.

Stale seedbeds and bed flamers

The dominant form of thermal weeding is the use of flame weeders for the stale seedbed technique (see Section 5.4.5) to kill small weedlings, immediately prior to crop emergence. Due to high capital and running costs and often lower work rates, this technique is mostly reserved for higher-value crops such as vegetables. It is particularly valuable for slow-germinating crops that are poor weed competitors, such as carrots and onions. Flame weeders for implementing stale seedbeds typically consist of a shield or hood under which the flames are introduced, which keeps the heat close to the soil to maximise heat transfer and protect the flames from the wind (**Figure 29**).

Figure 29. A bed flame weeder for stale seedbeds

Selective flame weeding

The next most common use of thermal weeding is selective intrarow flame weeding in established annual row crops such as cotton, soybean, and maize. This is where the flames are directed at the base of the stem of well-established plants where they are rooted in the soil (**Figure 30**). The crop survives as the stems are tough enough that they can withstand the heat but the smaller weeds are either killed or defoliated which sets back their growth and allows the crop to be more competitive.

Figure 30. Selective, intrarow flame weeder working in sweetcorn

The same technique is also used in perennial crops (**Figure 31**). Steam is generally used in preference due to its much lower fire risk and more rapid heat transfer, due to the latent heat of condensation. It can operate better in windy and wet conditions and some machines can be used to weed over plastic and even paper without causing damage (Schonbeck, 2012).

Figure 31. Intrarow steaming for weed management in perennial crop

Another approach to intrarow weed management is used on specific direct-seeded crops at early growth stages. Called post-crop emergence bed flaming, it is based on some crop species being resistant to foliar thermal weeding, such as the monocotyledons e.g., onions and garlic, which have their growing points protected underground, and rosette-forming species such as carrots and beetroot. These crops can survive the loss of their foliage, while the susceptible weeds are killed. If it is done at early growth stages, the plants can compensate for the temporary loss of their leaves so yields are unaffected.

Reversing the concept of intrarow thermal weeding, in situations where managing interrow weeds using mechanical means is difficult, e.g., the soil is too wet, flaming can be used on the interrow weeds (**Figure 32**).

Electrothermal weeding

Electrothermal weeding is also being used for in-crop weed management. In the 1980s incontiguous weeders were setup with electrothermal electrodes to weed the interrow, and weeder manufacturers are again providing this technology. Electrothermal weeding is also a key weed-killing technology for Level 3 and Level 4 robotic weeders (see above).

Figure 32. Interrow flamer

Use of fossil fuels

One of the key concerns about the use of flame and steam weeding is the large amounts of fossil fuels used, mainly LPG (liquefied petroleum gas) and propane, which in the age of climate change is unacceptable (Bond *et al.*, 2003). Firstly, due to its high cost and lower work rates, the use of flame and steam is limited to high-value crops, such as vegetables and perennials, so it is not widely used, indeed it is a highly specialised technique, that is generally only used when no other options are available. Using the most energy-efficient designs of machines, e.g., with good shields/hoods is critical. And replacing LPG with biogas (methane) from anaerobic digesters running on farm-produced crop residues and animal manures would avoid the use of fossil fuels entirely.

A common concern with flame and steam weeding is harming soil biology. Due to the huge thermal mass of the soil, the weeders can only raise the temperature of the top few millimetres of soil by a few tens of degrees Celsius for a minute or two. Radiation from the sun on a hot day heats the soil to a much higher temperature, to a much greater depth, and for much longer, so is much more damaging to soil biology. Other farm activities, such as cultivation/tillage cause vastly greater damage to soil biology than flame and steam weeding ever could.

5.5.5. MULCHING

Covering or mulching the soil with biological or synthetic materials is a specialised technique limited to a few vegetable crops and in parks and gardens. There are two main types, particulate and sheet mulches. Particulate biological materials include wood/bark chips, compost, leaf litter, and other high-carbon materials. Most sheet mulches are made of plastics, mainly polythene, but there are an increasing number of paper and other biodegradable products available.

Sheet mulches work by creating a physical barrier to the weeds, and are typically light proof so killing the weeds by preventing them from photosynthesising, i.e., sheet mulches can kill established weeds. Sheet mulches also alter the soil environment and can inhibit weed seed germination.

Plastic mulches need to be disposed of once it has finished being used, but because they are contaminated with soil and plant material, many plastic recycling facilities will not accept them (Ngouajio *et al.*, 2008). In addition, due to the increasing evidence of the harm caused by microplastics, the use of plastic for sheet mulches needs to be reconsidered (Zhu *et al.*, 2019; Qi *et al.*, 2020; Xu *et al.*, 2020).

Particulate mulches work by changing the soil environment, such that weed seeds do not receive the environmental cues that tell them to germinate. Therefore, they need to be sufficiently thick, typically five centimetres at a minimum. Furthermore, they are rarely able to control established weeds, and creeping species such as white clover can spread rapidly through them due to the absence of competition. The key issues with particulate biological mulches is they decompose so need to be continually replenished, and due to the large volumes required, they can raise soil nutrient levels to excess, causing further problems such as nutrient pollution of waterways (Miles *et al.*, 2013).

5.6. DIRECT REDUCTION OF THE WEED SEEDBANK

There are also direct methods of reducing the soil weed seedbank, including soil solarisation (Cohen & Rubin, 2007), biofumigation (De Cauwer *et al.*, 2019) and anaerobic soil disinfestation (Lopes *et al.*, 2022). While these techniques are primarily aimed at soil borne pest and pathogen management they can also reduce weed seedbanks. However, they are often expensive in terms of the time required to implement them, especially as this is during the cropping season as well as the direct costs, such as laying plastic and drip irrigation. They can be harmful to soil health particularly biology due to intensive tillage and extended hot and anaerobic soil conditions. They are also considered to be a symptom of failure of the farm system as a whole to manage pests, pathogens and weeds. The need for their use should prompt a re-evaluation of the farm rotation and crop diversity to determine where improvements are required.

5.7. HARVEST WEED SEED CONTROL

Harvest weed seed control (HWSC) is where weed seeds are controlled as part of harvesting operations or soon after harvest. The technique is most applicable in arable crops and has been pioneered in Australia (Weed Smart, 2022), and there are several approaches. Most involve separating the chaff from the straw inside the combine harvester, as it is the chaff fraction that contains most of the weed seeds. One approach then uses a cage mill to grind up and kill the seeds in the chaff before spreading it back on the field. Another approach is "chaff carts" where the chaff and seeds are collected in a purpose-designed cart behind the combine harvester, which is then dumped in big piles. These are then eaten by livestock later in the season. Tramlining involves placing the chaff in the tractor wheelings. Having a thick layer of chaff suppresses weed seed germination and those that do emerge are driven over by machinery, killing or suppressing them. Further techniques involve bailing and selling the chaff off the farm or making narrow lines of chaff and burning it.

HWSM has proved incredibly effective in Australia and has been a vital tool to combat some of the world's worst herbicide-resistant weeds. It could prove to be equally a powerful tool in Europe.

5.8. BIOLOGICAL WEED CONTROL

Biological control involves using living organisms, such as insects, nematodes, bacteria, or fungi to reduce weed populations. There are three key biological control approaches:

- importation (classical) biocontrol, where an exotic biocontrol agent (BCA) is imported to control an exotic weed or pest;
- augmentative, which is subdivided into:
  - inundative where very large amounts of the BCA are applied to the weed or pest;
  - inoculative, where the BCA is inoculated and introduced into the weed or pests environment and multiplies to levels that control the weed or pest;
- conservation, where the environment is manipulated to benefit the weeds' or pests' naturally occurring BCA such that the BCA can then control the weed or pest.

Globally classical biological control has achieved some remarkable successes in completely solving apparently intractable weed problems, such as the elimination of prickly pear cactus (*Opuntia stricta* spp.) in Australia by the *Cactoblastis cactorum* moth's caterpillar. However, with Europe being part of the continental landmass of Eurasia, and also close to Africa, there is a large natural traffic of both weeds and their pests, such that the number of introduced exotic plants without their pests is low, compared to more isolated ecosystems, such as those of Hawaii, Australia, and New Zealand, where classical biocontrol of weeds and pests is a very valuable tool (Bond *et al.*, 2003). Classical biocontrol also has significant risks associated with it, as there are many examples from history where the introduced BCA has turned into a pest itself (Zimdahl, 2018). However, host specificity testing is now a well-developed science, and few modern introductions have had unforeseen effects. While the number of exotic pests and weeds in Europe is more limited, some, like Japanese knotweed (*Fallopia japonica*) are particularly problematic. These would be ideal candidates for classical biocontrol (as the prickly pear in Australia was). Much more funding for research is required in this area.

Inundative biocontrol typically involves applying a microorganism to the pest in large volumes often by spraying, though some inundative use of insects is also used. Inundative control for insect pests and plant diseases (biopesticides) is an increasingly valuable tool, moreover it is starting to replace agrichemicals as the pests and diseases develop resistance and social and legislative changes see their use restricted. A major advantage for insect and disease control is most microbial BCAs are highly specific and will only kill an individual pest species or narrow range of species, so that beneficial species are unharmed. However, for weeds, this specificity is a problem not a benefit, as any given crop or pasture will be infested with tens to hundreds of weed species, so, a separate BCA (bioherbicide) would be required for each weed species. If there were broad spectrum weed biocontrol agents, they would then likely kill crop plants and wild species as well. Finally, where inundative biocontrol agents for weeds have been identified, they have proven very challenging to turn into a reliably effective, and commercially viable product. Likewise, for inoculative biocontrol of weeds, finding a weed BCA that is suitable for such an approach has been a significant challenge (Lundkvist & Verwijst, 2011).

There also has been no conservation biocontrol of weeds, in the same fashion as for insect pests, where, for example, floral resources in the form of pollen and nectar are provided which boost the longevity and fecundity of an existing BCA such that it is then able to reduce the pest population below economic thresholds. However, cultural techniques such as rotations, choosing competitive cultivars, undersowing, etc., could from some perspectives be considered conservation biocontrol; however, that is somewhat outside the typical meaning.

5.9. WEED MANAGEMENT BY LIVESTOCK

Animal grazing is a traditional and highly valuable method for the biological management of weeds. While the use of animals for weed management is still widely practised in less intensive and traditional farming systems, its value has been lost from the larger scale intensive and specialised farm systems. However, with the decline in herbicides, the use of livestock in these systems will start to regain its importance. Moreover, mixed arable-livestock farming systems (vs. regional specialism) have other benefits in addition to weed control, such as diversifying incomes and rural economies, fertilisation from animal manure, closing nutrient cycling loops, etc.. Any domesticated livestock can be used, e.g., cattle, goats, sheep, horses, fowl, etc. (Popay & Field, 1996).

The most important use of livestock for weed management is part of a mixed rotation of pasture and crops. As discussed in Section 5.4.1, few arable cropping weeds can survive in pasture and likewise, pasture weeds seldom thrive in cropping systems. Cropping weeds are often highly palatable to stock, with names such as “fat hen”/lambsquarters (*Chenopodium album*) and “chickweed” (*Stellaria media*) illustrating the point.

Pigs (**Figure 33**) are very good at controlling the growth of weeds and grass, and cleaning up dropped fruit in orchards, and therefore are commonly used for vegetation management in organic orchard systems (Nunn *et al.*, 2007). "Weeder sheep" are becoming more popular due to their low cost compared to manual labour and their ubiquity. Sheep grazing can be beneficial in vineyards and orchards for eating weeds, managing pasture, and also leaf plucking in place of machines. If used later in the season sheep need to be prevented from eating the grapes; one way to do this is with nets which are also used to protect the grapes from birds (**Figure 34**).

Figure 33. Pig feeding on apples dropped during harvest

Figure 34. Sheep grazing in vineyards with a protective net

5.10. CERTIFIED ORGANIC HERBICIDES

Certified organic herbicides are made with ingredients extracted directly from plants, animals, or microbial synthesis, e.g., vinegar, as opposed to being produced synthetically. A range of materials for organic herbicides has been tried including plant oils such as pine, cypress, cedar, manuka, eucalyptus, red clover, clove, lemongrass, cinnamon, mint, rosemary, and sage. Allelopathic maize and mustard seed meals (ground grains/seeds), fatty acids derived from plant oils including pine, coconut, and rape seed oils, as well as concentrated organic acids including acetic acid, ammonium nonanoate (pelargonic acid), and citric acid are also used. As they are derived from biological sources, they are biodegradable and leave no residues. However, they are general biocides so they do not just kill weeds, and they may well also impact non-target species including soil biology. Thus, organic herbicides should be used as a last, not first resort.

Nevertheless, there is a need for more research to accelerate the development and implementation of effective organic-compliant herbicides that are environmentally safe and that help the producer meet increasing consumer demand for organic products.

5.11. CASE STUDY – THE PERENNIAL CREEPING WEED *ELYTRIGIA REPENS* (COUCH GRASS)

In northern European climates, managing the perennial creeping weed *Elytrigia repens* is a significant challenge for farmers. Hatcher & Melander (2003), presented a new concept whereby the underground creeping rhizomes of *E. repens* are mechanically dug up, then collected and removed from the field allowing for the immediate establishment of a barley crop with much lower populations of *E. repens* (**Figure 35**). They stated: "Four passes with a modified rotary cultivator, where each pass was followed by rhizome removal, reduced *E. repens* shoot growth in barley by 84% and 97%. Barley yield was only affected by treatments in the first season, where yield was negatively correlated with *E. repens* shoot biomass". While the authors commend the concept for having the potential to manage severe *E. repens* infestations, it was also acknowledged that more effective smother crops and less intensive methods of rhizome removal are still very much needed.

Figure 35. Integrated Weed Management approach for the weed *Elytrigia repens* (couch grass) in barley

Combining mechanical rhizome removal and cover crops for Elytrigia repens control in organic barley systems weed research volume 53, page 461-469
B. Melander, M. Nørremark & E.F. Christensen (2013)

Based on the scientific opinion of several experts, additional alternatives of glyphosate are presented in **Annex 1** (edited by Hans Muilerman).

6. ECONOMICS OF DISCONTINUING GLYPHOSATE USE

The pesticides industry and many farming organisations across the EU claim that a move away from glyphosate and other herbicides will be catastrophic for the EU farming sector because there are no alternatives. The previous chapters show that there are many highly effective alternatives to herbicides including glyphosate.

In this section we look at the economic costs of replacing an agricultural model based on the use of glyphosate herbicides with non-chemical means.

Apart from the evidence brought to the table by the pesticide industry, of which the quality and impartiality have been questioned[29], two recent studies provide insight into the costs of abandoning glyphosate:

- a study performed by Böcker *et al.*, (2017) on "Modelling the effect of a glyphosate ban on weed management in maize production"[30] develops a bio-economic model looking into replacing glyphosate used in pre-sowing applications with mechanical means, while replacing post-sowing uses of glyphosate with other herbicides. The report concludes: *"We find that a glyphosate ban has only small income effects. Our results show that selective herbicides are not used at higher levels, but glyphosate is substituted by mechanical practices leading to higher labour demand. Slight yield reduction due to less intensive pre-sowing strategies turns out as more profitable than maintaining current yield levels"*;

- a study from Antichi *et al.*, (2022) concludes the following statement: *"This study, for the first time, shows that targeted timing of roller-crimped hairy vetch in no-till sunflower can result in equal agronomic and economic performances as addition of glyphosate"*.

None of the studies describes any catastrophic impact on EU agriculture, but they highlight that it will involve a shift to agronomic and physical means, which can increase the workload in the fields. The study from the Julius Kühn Institute[31] is interesting as it estimates that the extra production costs per hectare to German farmers for ceasing application of glyphosate (and other herbicides) are:

- one mechanical weed treatment costs: 45.70 €/ha; and one tillage measure: 24.11 €/ha,

- stubble and pre-sowing treatments: 0 to 37 €/ha, while

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[29] PAN Europe is aware of the European Crop Protection Association's report "pesticides: with or without" as well as the report from Oxford Economics [https://croplifeeurope.eu/wp-content/uploads/2021/09/Oxford-Economics-Project-Presentation-final-results.pdf] but notes that findings in these reports are based on two controversial reports published by industry lobbies a decade ago: the Anderson report (2015, https://www.nfuonline.com/archive?treeid=37178) and the Humboldt report (2013). PAN Europe already showed the Humboldt report was made on incorrect assumptions: http://www.pan-europe.info/sites/pan-europe.info/files/public/resources/briefings/pan-europe-opinion-on-humboldt-report-2013.pdf

[30] http://ageconsearch.umn.edu/record/261982/files/Boecker_109.pdf

[31] https://www.researchgate.net/publication/306006079_Economic_assessment_of_alternatives_for_glyphosate_application_in_arable_farming

- cost-intensive drying of the harvest to replace the practice of desiccation by glyphosate herbicide (in combination with a substituted stubble and/or pre-sowing treatment) on average will lead to additional costs of about 50 to 100 €/ha.

Dr. Lorenzo Furlan (*Veneto Agricoltura*, Italy) states that the majority of herbicides can be replaced by non-chemical methods and that various machinery is available to replace most herbicide uses[32]. This is not "wishful thinking": many decades of organic farming which does not use herbicides show it is entirely possible to farm without glyphosate and other herbicides. According to Jesper Lund Larsen, health and environment officer at the Danish workers' union *3F*, some good alternative methods and techniques mean that the labour costs required to transition to the two systems outlined in the models above are relatively small[33].

In the economic calculations that producers make, there are costs of legal requirements for workers using pesticides, such as access to showers, and use of protective equipment (cleaning, replacement, training, etc.), which must be included in the overall costs.

However, in such cost calculations, the external costs of herbicides, such as the health impacts of pesticides on workers and bystanders, as well as the pollution of water resources resulting in damages to the environment, are often left out of cost-benefit analyses.

And while transitioning to farming on larger scales may well require different kinds of equipment, which could represent large investments, most machines are easy to scale up, so small inexpensive versions exist, and many cheaper solutions are available, for example:

- The increasing interest in low-impact farming, especially organics, has resulted in a wide range of weeding equipment being available. For example, many orchard and grape producers are using small under-vine/under-tree weeders, often produced locally.

- Many farmers operate machinery pools, which is a good way of spreading out costs, while others use contractors for specific tasks where the machinery is not used so often. Flexible management is the key, and these farmers do not need to bear all the costs of buying new machinery.

- Importantly, public funding can also fill in some cost gaps: the policy aims to accompany farmers in the transition towards a low input, sustainable agricultural model, and so public subsidies for non-chemical weeding equipment have been made available and should be taken up by national and regional administrations and widely promoted to farmers, including by farm advisory services. The EU's CAP (Common Agricultural Policy) already has provisions in the second pillar to accompany farmers on the transition to low input systems, including for farmers working in groups, but the Member States of the EU must first choose those options, then co-finance them, and then mainstream them.

In addition, moving to non-chemical weed management will require the farmer to re-learn some of the skills of their predecessors from the pre-herbicide era. This includes managing the farm as a whole system, using the many little hammers and weed management pyramid approaches.

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[32] https://www.venetoagricoltura.org/wp-content/uploads/2019/06/Conservation-Agriculture-150-ppi.pdf

[33] A personal communication to PAN Europe in 2017.

Any economic assessment must also consider other benefits of the transition: because the low input system based on alternatives to chemical pesticides builds functional biodiversity over time, both in the soil and on/around the fields, it brings with it other co-benefits that will increase farm resilience against not only other pests but also climatic fluctuations, while also allowing for a decrease in expenditure on costly herbicides and other inputs[34]. The costs of inaction is immense, so that they "hugely outweigh the costs related to the transition" as mentioned recently by the European Commission in their working document on drivers of food security. They illustrate that sticking with a model that continues degrading soil (costing the EU 50 billion Euro /year), continues collapsing ecosystem services (worth hundreds of billions of dollars, and where ecosystem services make up 21% of the total yield value), and that leaves farmers vulnerable to increasingly extreme and fluctuating climatic variations must be considered[35]. Because of the nature of alternative weed and pest management practices that are based on or compatible with agroecology, their adoption will also help to significantly reduce the severity of climate impacts on the farm system, therefore also the costs of climate disruption including loss of yield, so that there is an overall farm-level economic benefit in transitioning.

Another important consideration is pollination, which is decreasing in many high input systems with a negative impact on yields; pollinators contribute more than 14 billion Euro per year to the market value of EU crops[36]. Adopting alternative practices that do not impact negatively on pollinators and especially allow for food sources for them would optimise insect pollination of crops, helping assure yields and so contribute to compensate for the costs of transitioning.

Lastly, when considering the actual costs of pesticides to society that have recently been estimated in a few reports[37], the adoption of alternative practices can be seen as win-win.

6.1. USING THE COMMON AGRICULTURAL POLICY TO REDUCE PESTICIDE USE

Any economic consideration of a transition away from herbicide use must focus on the farmer and their production costs; therefore, the public payments EU farmers receive under the Common Agricultural Policy (CAP) must also be factored into the costing and their decision-making. Farmers are often taking a financial risk to change or adapt production systems, and it is the role of public policy to support them in that transition to more sustainable practices. This section will show how the CAP can be used to provide support, in the form of knowledge and funding.

Farm Advisory Systems, under AKIS, the Agricultural Knowledge & Innovation System

As part of the last two Common Agricultural Policy (CAP) reforms in 2013 and 2021, Member States were required to ensure that Farm Advisory Systems (FAS) under the CAP can advise

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[34] http://www.pan-europe.info/sites/pan-europe.info/files/public/resources/briefings/innovation-and-resource-efficiency-1.pdf

[35] European Commission: Drivers of food security, 04.01.2023 SWD(2023) 4 final, pgs 10-11, 31, 38-40, 68

[36] https://ipbes.net/assessment-reports/pollinators

[37] https://www.foodwatch.org/fileadmin/-INT/pesticides/2022-06-30_Pesticides_Report_foodwatch.pdf https://lebasic.com/en/pesticides-a-model-thats-costing-us-dearly/

farmers and growers on Integrated Pest Management (IPM), as called for in Article 55 of Regulation (EC) 1107/2009 on plant protection products and Article 14 of Directive 2009/128/EC on the sustainable use of pesticides.

The homepage of the European Commission's Agriculture and Rural Development department (DG AGRI)[38] states that a FAS advisor should act as a *"general practitioner, interlinking all different aspects of farming. He or She should explain to farmers not only the EU requirements but also their objectives, and the underlying policies".* However, while the potential of the FAS is huge in the development of independent advice, the current implementation remains very limited. Over the last decade only a few Member States[39] have made the FAS visible. However, even the Member States who do provide some form of advisory service only focus on how to apply pesticides "better", rather than promoting alternatives to the use of pesticides/herbicides.

Since the 2013 CAP reform[40], the scope of the EU-funded Farm Advisory Systems has covered economic, environmental and social dimensions, and specifically how to comply with good farming practices and conditionality rules (that all farmers should respect to receive full EU payment). Since 2013 CAP-funded FAS should assist farmers in implementing IPM as defined in the Sustainable Use of pesticides Directive (SUD). Since the CAP reform of 2021, advisors in the CAP-funded FAS must be independent from input providers[41].

European Innovation Partnerships (EIP) and the Agricultural Knowledge & Innovation System (AKIS)

AKIS is a new instrument in the new CAP post 2023 that aims to gather the knowledge acquisition and dissemination needed for the transition to sustainable agriculture[42]. EIPs have been in place since 2013, and continue in the new CAP from 2023 under the framework of the AKIS. The aim was to tap into the range of scientific and stakeholder organisations in the farming sector that have information on alternatives to the use of herbicides in agriculture[43] [44]. For example, the European Innovation Partnership (EIP-AGRI) financed work on alternatives to herbicides:

- Several focus groups studying topics of relevance such as "Organic farming – Optimising arable yields"[45].
- An Austrian project on "Organic Dock Control", testing whether docks can be controlled with the help of native clearwing moths, instead of using herbicides[46]. Field tests have been

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[38] https://ec.europa.eu/agriculture/direct-support/cross-compliance/farm-advisory-system_en

[39] Although the UK is no longer in the EU, it was a forerunner in provision of FAS when implementing the CAP: https://www.gov.uk/government/groups/farming-advice-service

[40] Regulation (EU) 1305/2013 recital 13 and article 15, also Regulation (EU) 1306/2013 recitals 10-12, articles 12-14, annexes I and II. Note from art.12 of Reg.1306/2013 that despite IPM being an obligation for all farmers according to the SUD and Reg.1107/2009 since 1st January 2014, IPM was not made compulsory for all farmers under the CAP i.e. covered under the CAP conditionality rules outlined in annex II of Reg.1306/2013, SMR 10. This anomaly still exists in the CAP agreed in 2021 (SMR 7 of annex III of CAP SPR Reg.2021/2115); the only obligation is for Member States to include it under FAS.

[41] https://onlinelibrary.wiley.com/doi/full/10.1111/1746-692X.12354

[42] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2021.435.01.0001.01.ENG; CAP Strategic Plans Regulation (EC) 2021/2115, recitals 50 and 85, & articles 3(9), 15, 78, 127

[43] IFOAM: http://farmknowledge.org/index.php/discussion-forum/weed-management

[44] Greenpeace: https://farmers2farmers.org

[45] https://ec.europa.eu/eip/agriculture/en/focus-groups/organic-farming-optimising-arable-yields

[46] https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/field_event_attachments/20160420-21_ws-legnaro-2016_ogs_represented_final_25042016.pdf

done and the results are now being spread through practical field trials on interested farms and in field workshops. Presentations are carried out in national and European workshops[47] and are available online[48].

- A French project studying "Zero herbicides in Mediterranean perennial crops" (vineyards and orchards, a new context for weed management)[49] for a four-year period ending in 2018.

- Over the last decade, PAN Europe has organised, together with the International Organisation for Biocontrol Control (IOBC), International Biocontrol Manufacturers' Association (IBMA), and Greenpeace Europe, eight symposia[50] in the European Parliament, inviting researchers, farmers, and companies to exchange information on experience in the uptake of alternatives to pesticides.

- Over the last years, testimonies have been collected from farmers explaining about their uptake of alternatives in vineyards and cereal crops[51].

- PAN Europe has been organising annual farm visits to a French perennial crop farmer (grapes and apples) applying integrated pest and weed management before converting to organic farming. They also organised a visit to an Italian research station to show the uptake of alternatives to pesticides in maize cultivation.

While the FAS, at the EU level, is yet to successfully implement provision of advice across the EU on integrated pest and weed management, it is essential that in the future it fulfils its mandate and provides advice independent of the vested interests of the chemical industry and builds on the many valuable initiatives that have developed so far.

For example, in the last CAP programming period, the French rural development programme offered financial compensation for growers of cereal (around 87 euros/ha), protein crops (around 85 euros/ha), orchards (90 euros/ha), and grape growing (96 euros/ha) for training on and implementing herbicide use reductions[52].

Pesticide reduction and IPM in the new CAP; CAP Strategic Plans Regulation (SPR)

The approach of the new CAP beyond 2023 is that EU Member States list how they will spend EU funds in their CAP strategic plans. "Results" indicators track assigned budgets, previously agreed between EU Commission and the member states; "impact" indicators will check much later at the end of the programming period after 2026, whether this money had any effect[53]. So, the farm area under measures reducing pesticide use (whether effective or not) or intending to make their use "sustainable" is tracked yearly at least. The areas would presumably include the following relevant payments:

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[47] https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/field_event_attachments/20160420-21_pres02_organic_dock_control_patrick_hann.pdf

[48] http://www.melesbio.at/ampferglasfluegler/

[49] https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/field_event_attachments/20160420-21_pres06_zero_herbicides_in_mediterranean_perennial_crops_xavier_delpuech.pdf

[50] https://www.pan-europe.info/events/annual-symposium

[51] http://www.low-impact-farming.info

[52] http://aisne.gouv.fr/content/download/11052/67154/file/DDT02-201407-01-D-T-EU_PHYTO_04.pdf

[53] Results indicator R.24 and impact indicator I.18 in annex I, CAP strategic plan regulation (EU) 2021/2115 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2021.435.01.0001.01.ENG

- Eco-schemes are new top-up payments additional to the basic area-based CAP payments, for voluntary actions that beyond the baseline of the conditionality rules that apply to all farmers. (Note that the most relevant conditionality rules are on crop rotation (GAEC 7) and Ecological Focus Areas (GAEC 8); and that EFAs are legislated as pesticide-free areas[54].) Eco-schemes can include IPM[55] and the European Commission already had in mind IPM, as well as precision farming which could be linked to IPM, for eco-schemes for a while[56]. They are fully-financed by the first pillar i.e. EU budget only; no co-financing by member states is needed. (Note that IPM does not appear in the list of conditionality rules that apply to all farmers[57], even if the SUD and the pesticide regulation 1107/2009 made IPM compulsory since January 2014.)

- In the second pillar (rural development), it has long been possible for member states to use agri-environment-climate measures[58] to pay farmers for "costs incurred, income forgone" due to transitioning to reduced pesticide use. They are co-financed between EU and the member states. It is important not to have their content overlapping with eco-schemes to avoid paying twice for the same thing. And like the eco-schemes, much relies on political will by the member state to provide the measure in the first place.

- In the market payments organised by sectoral producer organisations (POs), it is possible for farmers to access firstly fruit and vegetable payments and secondly wine payments for implementing IPM to reduce pesticide use[59]. However, these are essentially voluntary and depend on farmers being members of a PO in those sectors, which has to choose that IPM option from long lists of other options. So, the likelihood of uptake is very small, the expenditure is also small, measures are easily ignored by POs, while the programmes they undertake will not be checked by the member states or by the Commission (no content in reporting obligations).

It is also possible for member states to make available publicly-funded insurance for farmers for risk of yield or income shortfalls. Successful IPM measures are already are specifically linked to harvest insurance[60] so that farmers are exposed to less financial risk and feel more supported in pursuing pesticide reduction strategies; this should be mainstreamed.

Note that that area covered by CAP investment aid for pesticide reduction measures is not likely to be tracked. Also note that although buying animals for grazing weeds cannot be funded under the CAP investment aid[61], in principle member states could grant farmers investment aid for weeding machinery, also in groups. But first they should have specified this in their CAP Strategic Plans, which is by no means a given. Moreover, in principle it is possible for farmers

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[54] See annex III of CAP strategic plan regulation (EU) 2021/2115, Good Agricultural and Environmental Condition (GAEC) 7 on crop rotation in arable land, and GAEC 8 on Ecological Focus Areas: the great majority of these EFAs are productive (legumes, catch crops) , but pesticides cannot be used on them since 2017 as their objective is to increase biodiversity. The Commission introduced a derogation for these GAEC for 2022 and 2023 due to the war in Ukraine.

[55] article 31(4).f of CAP strategic plan regulation (EU) 2021/2115

[56] https://agriculture.ec.europa.eu/system/files/2021-01/factsheet-agri-practices-under-ecoscheme_en_0.pdf

[57] CAP strategic plan regulation (EU) 2021/2115, annex III, statutory management requirements SMR 7 and 8

[58] article 70 of the CAP strategic plan regulation (EU) 2021/2115

[59] Articles 49(1)(a)(viii) and 58(1)(a)(iv) of the CAP strategic plan regulation (EU) 2021/2115

[60] „Fondo Risemina Maize" developed in 2014 by a group of maize farmers in Veneto, Italy, covering 53.000 hectares, underwrites possible losses by linking IPM practices with insurance schemes, in this case mutual funds funded under article 76 of the strategic plan's regulation 2021/2115. In Furlan, Contiero *et al.* (2015), https://www.researchgate.net/publication/272823066_Mutual_funds_are_a_key_tool_for_IPM_implementation_a_case_study_of_soil_insecticides_in_maize_shows_the_way

[61] CAP SPR (EU) Reg.2021/2115, Article 73(3)d. Note machinery is not included in the negative list in para (3)

to work together in groups and access funds for shared equipment[62]; these may be linked to EIP project implementation. This cooperation remains very rare, small-scale and not multiplied, and farmers in the former Soviet member states still have a cultural sensitivity to working collectively.

The above examples demonstrate that there is considerable scope for support in the CAP for measures to cover the additional costs to adopt alternatives to herbicides as well as investment support for the required machinery. Although member states have had to stipulate their proposed spending on IPM in their CAP strategic plans, and even if most have likely not done so, it is always possible for those strategic plans to be revised[63], for example in line with a new focus on IPM given by the reform of the sustainable use of pesticides directive[64]. Therefore, the question as to why all Member States have not activated these measures to help farmers implement the transition away from dependence on glyphosate and other herbicides remains to be answered; but it is by no means too late to push for their inclusion.

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[62] Article 77 of the CAP strategic plan regulation (EU) 2021/2115

[63] Article 119 of the CAP strategic plan regulation (EU) 2021/2115

[64] The old sustainable use of pesticides directive „SUD" is proposed to become a regulation ("SUR") with a far greater emphasis on IPM https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52022PC0305

7. **POLICY RELEVANCE**

7.1. THE EU'S GREEN DEAL AND FARM TO FORK STRATEGY

The European Union announced its Green Deal in 2020 to tackle Climate change and environmental degradation in Europe and globally. As a part of the Green Deal adopted by the European Commission in 2022[65], targets were proposed in order to restore damaged ecosystems and restore Europe's nature, from agricultural land and seas, to forests and urban environments, by 2050. A key part of the proposal is to reduce the use and risk of chemical pesticides, especially cutting the use of the more hazardous pesticides, by 50% by 2030. EU Biodiversity and Farm to Fork strategies[66] had earlier specified the two pesticide reduction targets in 2020:

- ***Target 1*** *– 50% reduction in use and risk of chemical pesticides – This target will be measured based on: the quantities of active substances contained in the pesticides which are placed on the market (sold), and therefore used, in each Member State, and the hazard properties of these active substances*

- ***Target 2*** *– 50% reduction in the use of more hazardous pesticides – This will be measured using data on the quantities of more hazardous active substances, the so called „candidates for substitution"*[67]*, contained in the pesticides which are placed on the market (sold), and therefore used, in each Member State*

These Green Deal targets acted as a guiding principle throughout the mandate of the current European Commission: as we near the end of the mandate that began in 2020, efforts are now focussed on legislating for them. Their translation into EU law, by inserting the targets into the proposed revision of the Sustainable Use of Pesticides directive that would become a regulation, are being met with opposition from groups interested in maintaining the status quo.

7.2. THE EUROPEAN CITIZENS' INITIATIVE "SAVE BEES AND FARMERS"

European citizens supported even more ambitious pesticide phase out targets in 2022. The European Citizens' Initiative "Save Bees and Farmers", supported by over 1.2 million citizens[68],

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[65] Green Deal: Halving pesticide use by 2030. https://ec.europa.eu/eip/agriculture/en/news/green-deal-halving-pesticide-use-2030

[66] Farm to Fork targets - Progress - For both reduction targets, the trend is compared to a three-year baseline, comprising the average of 2015, 2016 and 2017. https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/farm-fork-targets-progress_en

[67] Candidates for substitution in accordance with Article 24 of Regulation (EC) No 1107/2009 and listed in Part E of the Annex to Implementing Regulation (EU) No 540/2011, or containing one or more active substances listed in the Annex to Implementing Regulation (EU) 2015/408.

[68] https://www.savebeesandfarmers.eu/eng

urged the Commission to take immediate action to restore biodiversity and protect citizens' health by rapidly eliminating the use of synthetic pesticides.

The formal demands of the "Save Bees and Farmers" European Citizens' Initiative[69] were:

- A phase-out of the use of synthetic pesticides: by 2030 the use of synthetic pesticides shall be gradually reduced by 80% in EU agriculture. By 2035, agriculture in the entire Union shall be working without synthetic pesticides.

- Measures to recover biodiversity: habitats shall be restored and agricultural areas shall become a vector of biodiversity recovery.

- Support for farmers: farmers must be supported in the necessary transition towards agroecology. Small, diverse, and sustainable farms shall be favoured, organic farming expanded, and research into pesticide-free and GMO-free agriculture will be supported.

7.3. THE EUROPEAN CITIZENS' INITIATIVE TO "BAN GLYPHOSATE AND PROTECT PEOPLE AND THE ENVIRONMENT FROM TOXIC PESTICIDES"

Citizens' awareness of glyphosate is illustrated by the sheer speed at which the #StopGlyphosate European Citizens' Initiative (ECI) fulfilled the requirements to be officially deemed successful: it reached the threshold one million signatures in only six months from its launch. The ECI to ban glyphosate, reform the EU pesticide approval process, and set mandatory targets to reduce pesticide use in the EU was officially handed into the European Commission on 3rd July 2017, with a total of 1,320,517 signatures collected from all across the EU[70]. This petition was presented to the European Commission in the autumn of 2017.

The ECI's three demands were: the ban of glyphosate, a reform of the EU pesticide approval process, and mandatory EU targets to reduce pesticide use. On 12th December 2017, the European Commission responded to the ECI[71], essentially rejecting the demands.

Instead of concrete actions and a proposal for a ban on glyphosate the Commission proposed to increase data transparency. Non-governmental organisations (NGOs) stated[72] that it is *"a misleading response to the ECI's demand that EU pesticide approvals be based only on fully published studies. Existing EU law already provides for the release of the studies, as confirmed by the European Court of Justice. EFSA has withheld data contrary to this ruling".*

The ECI demand for studies to be funded by industry but commissioned by regulators instead of the industry was also rejected. The Commission also rejected the ECI's demand to set EU-wide targets for pesticide reduction.

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[69] https://www.pan-europe.info/press-releases/2022/11/1-million-eu-citizens-tell-eu-commission-end-war-against-nature

[70] http://ec.europa.eu/citizens-initiative/public/initiatives/successful/details/2017/000002

[71] http://europa.eu/rapid/press-release_IP-17-5191_en.htm

[72] https://www.greenpeace.org/eu-unit/issues/nature-food/759/commission-rejects-demands-of-stopglyphosate-citizens-initiative/

7.4. RE-AUTHORISATION OF GLYPHOSATE

After a half-year debate, glyphosate was re-approved[73] with a slight majority by the Council Standing Committee on Plants, Animals, Food and Feed (SCoPAFF), made up of EU member states' representatives voting by qualified majority, in November 2017. A shorter 5 years authorisation (instead of the proposed 15 years) was granted until 15th December 2022. Scientists and NGOs criticised this decision since the IARC classified glyphosate as probably carcinogenic to human health[74]. An independent review by experts[75] on mutagenicity revealed that the 2017 EU decision on glyphosate's genotoxicity is based on a faulty and unreliable industry study.

On 10th May 2019, the European Commission appointed four Member States (France, Hungary, the Netherlands, and Sweden) as rapporteurs for the re-assessment of the compound – making up the Assessment Group on Glyphosate (AGG)[76]. In June 2021, the AGG submitted the draft renewal assessment report (dRAR) and Harmonised Classification and Labelling (CLH) report to the EFSA and the ECHA. They concluded[77] that, besides data gaps being identified, the classification of glyphosate as genotoxic, mutagenic, carcinogenic, or toxic for reproduction is not justified. The dRAR pointed out that regarding the behaviour of glyphosate in the environment *"several points still need to be clarified by the applicant during the peer review process"*. However, despite acknowledging there were significant data gaps, the AGG's dRAR concluded that: *"Based on the current assessment, the AGG considers that glyphosate does meet the approval criteria set in Regulation (EC) N° 1107/2009."*

On 10th May 2022, EFSA and ECHA announced that as the AGG delayed the delivery of the updated dRAR, in order to complete the peer review process there will be almost a year delay in delivering the EFSA Conclusion, which is expected in July 2023.

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ECHA's Committee for Risk Assessment (RAC) carried out the hazard assessment of glyphosate to conclude its hazard classification. The RAC made its proposal[78] in May 2022, regarding the classification of glyphosate according to the CLP Regulation. NGOs criticised[79] the RAC opinion as a denial of science and disrespect of EU laws, when the ECHA's RAC decided not to classify glyphosate either as a carcinogen nor as genotoxic, despite even stronger scientific evidence than the IARC classification in 2015. The RAC proposed to maintain the existing classification indicating glyphosate is toxic to aquatic life with long-lasting effects (Aquatic Chronic 2; H411). However, independent studies (Fiorino *et al.*, 2018; Zhang *et al.*, 2021) would justify a more severe classification of chronic toxicity to aquatic life (Category 1 Aquatic Chronic).

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[73] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R2324
[74] https://monographs.iarc.who.int/wp-content/uploads/2018/06/mono112-10.pdf
[75] https://s3.amazonaws.com/s3.sumofus.org/images/briefing_how_eu_glyphosate_genotoxic.pdf
[76] https://ec.europa.eu/food/plants/pesticides/approval-active-substances/renewal-approval/glyphosate/assessment-group_en
[77] https://food.ec.europa.eu/system/files/2021-06/pesticides_aas_agg_report_202106.pdf
[78] https://echa.europa.eu/documents/10162/882a2dc7-9e6f-b0ac-491a-ed3526b4018a
[79] https://www.pan-europe.info/press-releases/2022/05/glyphosate-echa-classification-denial-science-and-disrespect-eu-law

On the 14th of October 2022, the Commission proposal of the one-year extension of the current approval failed to get a qualified majority[80] in the SCoPAFF. Croatia, Luxembourg, and Malta voted against the proposal, while France, Germany, and Slovenia abstained. The European Commission appealed and a new vote by Member State representatives in the Appeal Committee took place on the 15th of November 2022. As no qualified majority was reached a second time[81], the Commission used its powers according to the provisions of the Treaty on the Functioning of the EU, to go ahead with the prolongation of the authorisation of glyphosate in December 2022.

EFSA is supposed to finalise its conclusions by July 2023. The conclusions must cover not only the active substance but one or more representative uses of at least one plant protection product containing that active substance. Based on EFSA's conclusion and the AGG's RAR, the European Commission will put forward a renewal report and a draft Regulation to the Member States, on whether the approval of glyphosate can be renewed, or not. The renewal report will be discussed in the SCoPAFF Committee and then the Member States will vote on the Commission's proposal – a final decision is expected in late 2023.

7.5. EU MEMBER STATES RESTRICTING USE OF GLYPHOSATE AND OTHER HERBICIDES

Although EU legislation allows for the authorisation of the active substance of each pesticide on the EU level (e.g. glyphosate), and for the approval of the final pesticide products (e.g. Round-up and others) by the EU member states, the following cases illustrate that some EU member states are pushing ahead based on pressure from their citizens.

Austria:

In July 2019, the Austrian parliament voted to ban all uses of glyphosate in Austria[82]. However the European Commission has blocked Austria from implementing a planned ban[83]. Later in 2021, the Austrian Parliament adopted a partial ban of glyphosate on so-called "sensitive" areas and for private use[84].

Luxembourg:

First EU country to decide about the ban on the use of glyphosate. A governmental decision declared that Luxembourg terminates the use of the substance glyphosate from 1st January 2021[85]. Bayer, the main producer of the substance, sued Luxembourg, arguing that the ban breached EU law. An administrative court ruled that the government's decision to ban glyphosate pesticides is unlawful[86].

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[80] https://www.euractiv.com/section/agriculture-food/news/temporary-extension-of-eu-glyphosate-approval-hits-roadblock/

[81] https://www.euractiv.com/section/agriculture-food/news/commission-to-temporarily-re-approve-glyphosate-without-member-states-go-ahead/

[82] https://orf.at/stories/3128905/

[83] https://geneticliteracyproject.org/2020/08/20/eu-blocks-austrias-planned-glyphosate-ban-rejecting-claim-that-weedkiller-harms-human-health/

[84] https://www.fas.usda.gov/data/austria-austrian-parliament-adopts-partial-ban-glyphosate

[85] https://gouvernement.lu/en/actualites/toutes_actualites/communiques/2020/01-janvier/16-interdiction-glyphosate.html

[86] https://today.rtl.lu/news/luxembourg/a/1947265.html

Germany:

In February 2021, the German Federal Cabinet approved the amendment of the Plant Protection Application Ordinance (PflSchAnwV) in order for immediate, significant restrictions on the use of plant protection products containing glyphosate and a complete “phasing out of glyphosate” by the end of 2023[87].

France:

After the decision in 2017 to re-approve the active substance, France was among several Member States who plan to phase out the use of glyphosate-based herbicides in agriculture once alternatives are identified[88]. The French government has pressed ahead to follow up on its decision to end the main uses of glyphosate within three years:

INRA (French National Institute for Agriculture), the French state institute for agronomic research, published a report in December 2017 on alternatives to glyphosate and its phase-out, which showed that many alternatives are already available[89].

The French government announced in July 2018 that it will establish a new resource centre for alternatives to pesticides by the end of 2018, merging research results from France’s „Ecophyto” programme[90], its extension services, the existing networks of regional chambers of agriculture, and state-funded plant & animal production institutes.

A 2022 law in France banned[91] the use of pesticides in sensitive sites where pesticide use can unnecessarily harm individuals or the wider public, including private residential properties, hotels and camping site, cemeteries, sport facilities. The ban applies throughout the country and extends the scope of a previous decree that restricted pesticide use on green spaces in public areas.

Denmark:

The Danish government has announced rules that come into force on 1st July 2018 banning the use of glyphosate on all post-emergence crops, to avoid residues in food in crops such as peas, barley, and other grains. The original idea was to prohibit its use 30 days before harvest, but this was extended, meaning glyphosate-based herbicides will only be used before crop emergence.

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[87] https://www.bmuv.de/themen/wasser-ressourcen-abfall/boden-und-altlasten/bodenschutz-und-altlasten-worum-geht-es/faq-plan-zum-glyphosat-ausstieg,
https://www.reuters.com/article/us-germany-farming-lawmaking-idUSKBN2AA1GF
https://www.euractiv.com/section/agriculture-food/news/temporary-extension-of-eu-glyphosate-approval-hits-roadblock/

[88] https://www.cultivateoregon.org/the_macron_government_of_france_is_offering_its_farmers_a_way_out_of_glyphosate_dependency_within_the_next_3_years

[89] https://hal.inrae.fr/hal-02790103

[90] https://agriculture.gouv.fr/encouraging-results-ecophyto-plan-reduction-pesticide-use

[91] https://beyondpesticides.org/dailynewsblog/2022/07/france-enacts-sweeping-restrictions-on-pesticide-use-in-public-and-private-landscaped-areas/

8. CONCLUSIONS

This report shows that, by combining and integrating the wide range of non-chemical weed management methods (e.g., preventive, cultural, and mechanical) with knowledge of the biological and ecological characteristics of weeds and crops, today's farmers and growers can successfully manage weeds without herbicides. All this while maintaining good yields, preventing the development of herbicide resistance, protecting soil biodiversity, reducing erosion, and reducing greenhouse emissions.

Non-chemical weed management has its challenges, but organic farmers and growers have clearly shown that they can be overcome. Compared to herbicides where there have been no new modes of action discovered since the 1980s, non-chemical weed management tools and techniques continue to expand, offering producers more and more options. It is necessary to continue to build on past successes, particularly to integrate the many tools (the many little hammers approach of IWM) into farming systems that can be scaled up and multiplied widely, and also to develop more machinery and knowledge, especially to tackle problematic weeds. Furthermore, results of scientific research must be effectively disseminated to farmers through efficient and effective partnerships, farm advisory services and peer-to-peer learning.

In many ways, farmers and growers have been leading the change and moving to more sustainable, non-chemical weed management systems, despite the lack of support, or even in the face of derision from some governments and scientists, with organic farming being the clearest example of this. It is therefore overdue for decision-makers and leaders at both the EU and Member State levels to provide the financial support that farmers and growers need to transition to sustainable farming systems including moving to non-chemical weed management and halting the use of herbicides and pesticides. In order to catalyse a change in the biodiversity collapse toward more sustainable farming systems, the role of public funds is essential: CAP funds especially should be targeted towards supporting farmers in this transition, both in terms of knowledge support and also by covering their financial risks when undertaking pesticide reduction measures. A multilevel approach is required, where farmers, distributors, policy-makers, citizens, and consumers are all informed on the negative impact of the use of herbicides and the available alternatives, and by adopting a long-term vision to work together to phase out the use of these harmful chemicals in agriculture.

We are not starting from zero: there are already knowledge and tools to replace herbicides. A number of farmers already apply them, while the CAP already foresees support for eco-schemes, agro-environmental measures, grants, and insurance to cover the additional costs of alternative approaches and investment support for the required mechanical tools. While research is still needed to develop combined approaches (IWM), in developing more specific weed-control machinery, and in collecting success-stories, slowly it is already happening within the EU research and innovation agenda.

However, to obtain a real transition towards a low impact system, it is essential that we all start to re-consider the concepts of weeds, with nuances between economically damaging levels of infestation and aliae plantae, harmless to crops but essential for biodiversity. Effective non-chemical weed management is impossible if you don't understand weeds /plants and how they interact with their environment.

In conclusion, the transition towards lower impact systems and less reliance on glyphosate-based herbicides, is possible: not only by replacing glyphosate with mechanical means or with other less harmful herbicides, but also re-discovering organic farming cycles and techniques, and working with nature. Key is following the guiding principles of the „many little hammers" approach (illustrated in Figure 12, Chapter 5) and so in this way applying all aspects of the IWM as mentioned in Chapter 5. All these elements taken together will over time increase farmers' resilience while allowing a decrease in reliance and expenditures for inputs[92].

However, if we are to see the Green Deal promise of 50% reduction of pesticide use become a reality, in order to avert the worst effects on biodiversity and ecosystem collapse, the new CAP, needs to be used smartly. Funding and effort must be re-directed in line with the proposal for the Sustainable Use of pesticides Regulation (SUR), to allow much more uptake of integrated pest management (IPM) and encouraging the use of non-chemical alternatives.

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[92] http://www.pan-europe.info/sites/pan-europe.info/files/public/resources/briefings/innovation-and-resource-efficiency-1.pdf

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ANNEX 1

The eight main uses of glyphosate in the EU and the possible non-chemical and chemical alternatives

A compilation of expert opinions (pers. com.) edited by Hans Muilerman (PAN Europe)

The eight main uses of glyphosate in the EU	Non-chemical alternative	Chemical alternative (not recommended by PAN Europe)	Remarks
1. Treatment to kill the cover crop (subsidiary crop or intercrop) – the practice of sowing plant seeds on a plot of land for soil cover until another crop is planted	Use winter-kill cover crops (like brassica and legume species that die ready for spring seeding). Standard rollers (e.g., Cambridge, Crosskill) increase the sensitivity of cover crop varieties to frost, which kills them. Numerous intervention methods are available to bury the cover crops (ploughing them in, rotating the soil; note additional benefits of incorporating green manure) and to kill the plants (burning, steaming, electrocution e.g., "Zasso"). Also, scalping tools (e.g., Actisol) to kill green manures in the spring (clover, alfalfa, *Phacelia spp.*), are composed of fins to dislocate the ground at depth. The organic sector uses a "crimper roller" machine that flattens the plants, including chisels to cut them. These alternatives also work in dry weather.		A ban can be put in place at the national level for this use: not a ban specific for glyphosate, but a ban on the chemical treatment of cover crops in general.

The eight main uses of glyphosate in the EU	Non-chemical alternative	Chemical alternative (not recommended by PAN Europe)	Remarks
2. Treatment of perennial weeds	Prevention: - clean equipment to avoid spreading weed seeds (after tillage, harvesting) - long rotation with winter crops (stifling crops) and spring crops (late-planting root crops) - sorting and sifting seed to remove weed seeds - composting manure in the field (soil reaches 45-50°C over 3-4 weeks) - monitor field borders (perennial weeds mainly enter from there) - don't leave bare areas of soil (use cover crops and/or under-sow secondary crops) - in-crop mechanical weeding (for perennial crops) - soil tillage during intercropping or shallow tillage can bring the perennating organs (e.g. tubers, rhizomes and corms) onto the soil surface where they desiccate - successive stubble removals (to remove weed seeds, ideally under drying conditions) - weeding by extraction with an inverted rotor (against thistles and *Rumex spp.*) - false seedbeds in spring and summer - root vegetable undercutter bar Cover crop cultivation is also an option, using crop types with a lot of biomass that will outcompete weeds both for light and water, exhausting them. Dense cover crops: Chinese radish, *Phacelia spp.*, Alexandria clover, brown mustard. Against thistles: - introduce alfalfa into the rotation for minimum 2 years (3 years if possible) - cover crops during intercultures are inefficient (or even increase weed pressure of thistles) - sowing crops that outcompete weeds into the rotation (hemp, rye, oats) In pastures, if nothing else works: terminating, growing an annual fodder crop, and then establishing new pasture. Electrothermal weeding should be game changing; both handheld and machine mounted.	Systemic herbicides: clethodim, dicamba etc.	Mechanical weeding might be repeated for an optimal effect.

The eight main uses of glyphosate in the EU	Non-chemical alternative	Chemical alternative (not recommended by PAN Europe)	Remarks
3. Stubble and pre-sowing treatments	Repeating different types of tillage (stubble tillage, rotary tillage, e.g. rotovator, or better, disk harrows) a few times. Numerous methods of mechanical weeding are available (e.g. machines applied in organic agriculture). Mechanical tillage is the alternative to glyphosate to destroy a previous crop before sowing another crop: - cultivator: a tool that allows the loosening of the soil, e.g., stubble cultivator - vibrocultivator: shallow soil cultivation with vibrating tines - harrow: a machine for shallow tillage of the soil. Tines scrape the soil and eliminate broadleaf weed seedlings. - plough: deep working of the soil.		Not all weeds have to be eradicated: a minority are harmful while a majority play a positive role in soil health. Integrated Weed Management should be followed, in which different management techniques (preventive, mechanical, biological, and monitoring) have their role. After harvest, the stubble is quickly decomposed, facilitated by tillage with stubble cultivators.
4. Desiccation: sunflower, oilseed rape, maize, wheat, barley	Electrothermal techniques or other alternatives to chemical pesticides.		Desiccation is out of scope of Reg. 1107/2009. This practice is already banned in member states like the Netherlands.
5. Inter- and intra-row weed control including in orchards/vineyards	- Mechanical harrows and (camera-guided) mechanical hoes ("Robocrop" of "Steketee IC-Weeder") are available. - A wide diversity of machines are applied in organic agriculture: "fingerweeders", "torso-weeders", "harrow-weeders", "vibrate-weeders", etc. - Tillage with weeders equipped with tree/vine/bush-detecting sensors (sometimes repetition needed). Sensors allow trees/vines to be approached very closely. Maintain vegetation rather than bare soil in between tree crops (with or without mowing): this limits weeds and is good against erosion. Interrows can also be grazed, especially when the crops are dormant, such as in winter; animal droppings also fertilise the soil. Intercropping: gaps between crop rows are filled by another crop that leaves no room for unwanted plants. Planting white clover, for example, between rows of maize is a good combination that keeps weeds down. The weeds are outcompeted and the soil is fertilised by nitrogen-fixing bacteria in clover nodules. Steaming and electrothermal weeding are additional options.	Several pesticides like diflufenican, chlorotoluron, flazasulfuron, pelargonic acid, etc.	Organic sector has decades of experience with these machines and techniques.

The eight main uses of glyphosate in the EU	Non-chemical alternative	Chemical alternative (not recommended by PAN Europe)	Remarks
6. Railway tracks and non-agricultural areas	Railways: steaming, UV radiation, and electrothermal weeding (between the tracks); by hand with a mower (path next to train tracks). "Green seeker" plant detection systems coupled with the focused light to kill the weeds are a good option. Non-agricultural areas: using plants to cover the soil (replaced with herbaceous vegetation left un-mown), steam, metal brushes (streets, pavements), flaming, and mowing. Golf courses: mowing, optimal treatment of grass. Level 3 robotic weeders for broadleaf species in the turf.	Pelargonic acid Although other chemical means exist, such as Flufenican, Flumioxazin, and Oxyfluorfen, others such as MCPA, 2,4-D, are far more hazardous than glyphosate.	Already implemented in several countries; several EU member states (Italy, Belgium, Netherlands) imposed a ban on use of pesticides in non-agricultural areas.
7. Control of specific plants (ragweed, bindweed, chivalry sorrel), including invasive species	Robots with cameras selectively detect these plants. Weeds with underground (problematic) roots can be cut by a "Rodweeder". In natural areas: why is intervention needed? Allow seral succession to play out. If intervention is still needed, for example for invasive species, it can be done by hand or mower, or using steam.		
8. Pasture "renewal"	Tillage, rotating, burning, etc. - Complete extraction and eradication of the weed roots using tooth stubble harrow and rhizome extractor, followed by reseeding with a seed mix that outcompetes the weeds. - rotate the grassland with a "cleaning crop" that inhibits or reduces weed presence. For thistles: - repeated mowing before flowering - electrothermal weeding and steaming.		It is possible to put a ban in place at the national level on the chemical treatment of pastures in general, not a ban specific for glyphosate. Note that properly pastured and grazed meadows do not leave room for unwanted weeds and therefore do not need to be restored. Note that pasture renewal involving tillage or ploughing up is not compatible with carbon sequestration or biodiversity goals. Renewal of permanent pasture also goes against current conditionality rules for all farmers under CAP and other CAP biodiversity measures, or future carbon farming payments.

ANNEX 2

Non-chemical management of docks *(Rumex spp.)*

By Dr. Charles Merfield, Head of the BHU Future Farming Centre

1. Introduction: when is a weed not a weed?

Docks, mainly the broad leaved dock (*Rumex obtusifolius*) and the curly dock (*Rumex crispus*) are common weeds in Europe, especially the cooler and wetter, higher latitudes. They are predominantly a weed of pasture, especially long-term pasture, because regular tillage/cultivation kills them so they don't survive in cropping systems. In the past they have been labelled as highly problematic weeds, even being listed in "noxious weed" legislation e.g., in the Republic of Ireland[1] and the United Kingdom[2]. However, this is considered a clear example of overestimating the negative impacts of particular weeds based on an outdated definition of weeds.

Fundamentally, a weed is a value judgement of the positive and negative attributes of any given individual and/or population of plants at a given point in time. Typically in agriculture, the value judgements are ultimately economic, i.e., does any particular plant or population of plants impact farm profitability. If the answer is no, the plant or population of plants are not weeds: they are "aliae plantae" (Merfield, 2022). In many cases, the economic impact of weeds has never been properly calculated, resulting in the view (as evidenced by noxious weed acts) that even one weed is too many and total eradication is required. This is a foolish view, especially where the weeds are in their native range and are impossible to eliminate. In addition, they do not necessarily negatively impact productivity within a certain range of cover: for example, according to studies in Ireland, pastures with 15% or less groundcover of docks will produce more total dry matter than the same pasture without docks (Courtney, 1985). Docks are palatable, unlike toxic weeds such as ragwort (*Jacobaea vulgaris*); dock foliage has higher potassium, zinc, magnesium, and tannin levels than grass; it has been found to prevent bloating of livestock; and young shoots of *R. crispus* have a good nutritive value for cattle (Courtney, 1972; Humphreys, 1995). So moderate populations of docks do not impact farm economics, and may even benefit livestock and thereby farm profits. Furthermore, such aliae plantae may be more resilient to drought - during the 2022 heatwave in Europe, most pasture turned brown as the grass died back but many weeds and aliae plantae remained green. Therefore, they should not be considered weeds, but rather natural components of farm ecosystems. However, it must be noted that large dock populations have clearly been shown to be detrimental (above the 15% groundcover referenced in Courtney (1985)), so they do need to be managed, but not exterminated.

Beyond farm profitability, the dock is a host for a wide range of other species in its native ranges, particularly insects. Even where they are exotic species, they potentially contribute to

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[1] https://www.agriculture.gov.ie/farmingsectors/crops/controlofnoxiousweeds/

[2] http://www.legislation.gov.uk/ukpga/Eliz2/7-8/54

biodiversity and ecosystem functions. For example, docks are a dominant food source for the green dock beetle (*Gastrophysa viridula*, **Figure 1**) and the seed is important to a range of seed-feeders including invertebrates such as beetles. The importance and benefits of weeds are being increasingly recognised (e.g., Gerowitt *et al.*, 2003; Marshall *et al.*, 2003; Blaix *et al.*, 2018; Storkey & Neve, 2018)[3] and so at an ecological level, the elimination of docks from farmland is undesirable.

The aim of managing docks and other weeds in modern farming should therefore be to maintain weeds below economically harmful thresholds, rather than aiming for their complete eradication.

2. Dock management

Non-chemical control of any weed or plant requires a systems-based or integrated approach. The metaphor of "many little hammers", coined by Liebman & Gallandt (1997), highlights that multiple tools are needed. To work out which tools will be effective and how to use them, it is essential to understand the biology and ecology of weeds.

> **Figure 1.** The green dock beetle (*Gastrophysa viridula*) Larvae skeletonising a leaf (left) adults (right)

2.1. *Key components of dock biology and ecology*

Docks are rosette-forming, herbaceous perennials, consisting of a crown (short, vertical, highly compressed underground true stem), with large fleshy storage tap roots (**Figure 2**).

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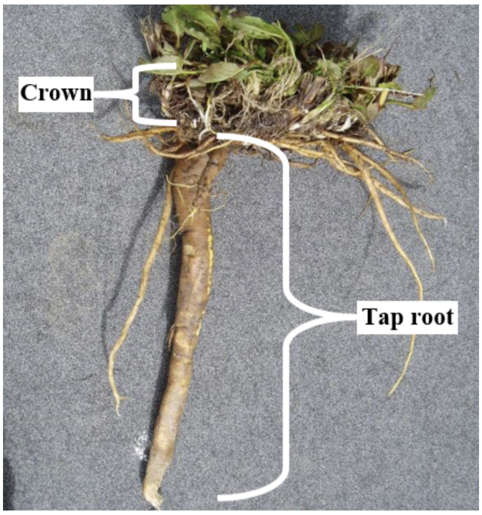
[3] http://www.arc2020.eu/unplanned-vegetation-is-important-aka-weeds-provide-for-needs/

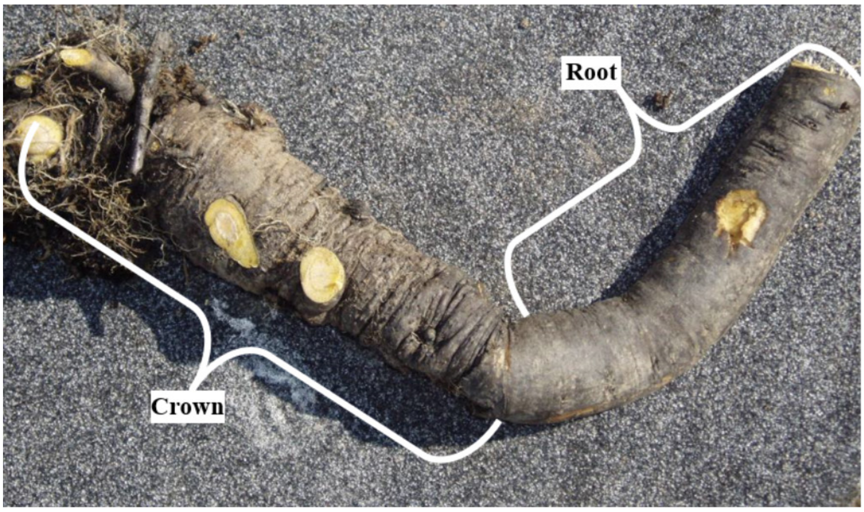
Figure 2. Dock plant showing regrowing leaves, the crown, the main large tap root and smaller roots sprouting from daughter crowns



Leaves and flower stems are produced from the crown. The main means of reproduction are via the large numbers of seeds that are produced, but docks can also produce clones via offshoots from the crown, though the number of new plants produced this way is insignificant, especially as the parent plants also tend to die off.

However, there is significant confusion both among land managers and scientists about the ability of docks to regenerate following disturbance, e.g., tillage/cultivation or digging them up. Only the buds (meristems) in the leaf axils of the true stem are able to dedifferentiate to produce roots. The true root is unable to dedifferentiate, so it cannot produce shoots. It is only the crown that can regenerate, as it is a true shoot. However, some people confuse the crown for true roots, not realising that the crown is a true shoot and not a root. This is probably due to the crown and root appearing quite similar in some plants (**Figure 3**), especially as the crown produces adventitious roots, so appearing root-like.

Figure 3. Section of dock showing the visual similarity between crown and root



As a comparison, docks are morphologically identical to rhubarb (*Rheum rhabarbarum*), another member of the Polygonaceae or buckwheat family. Rhubarb also only regenerates from the crown; this is why rhubarb is vegetatively multiplied by splitting the crown, not the root.

Docks tend to maintain a root to shoot ratio around 75% root: 25% shoot, with a higher root percentage over winter and a lower one when flowering. Removal of foliage causes the dock to withdraw its root reserves to re-establish its optimal root:shoot ratio, which takes about four weeks. Therefore defoliation at intervals of less than four weeks results in a reduction in plant size, as the root reserves are continually used to replace the foliage. In comparison, defoliation at intervals of greater than four weeks allows docks to accumulate carbohydrates in their roots, with a trend of increased rates of accumulation as the time intervals between defoliation increase. Therefore defoliation intervals greater than four weeks allow docks to become more competitive with pasture.

Dock seeds need light to germinate so they can only establish themselves on open soil, not under the cover of a good pasture sward. They also need sufficient diurnal temperature fluctuations to germinate, so are less likely to germinate in winter. Dock seedlings are weak competitors until they are about 40 to 50 days old, at which point the seedling root swells into a tap root. After this point, their competitive ability increases rapidly, becoming very high after six months of age.

2.2. *Pasture management*

Managing any pasture weed is mostly down to pasture management. Good pasture management is based on four key principles:

- healthy soil, based on optimum pH and nutrient levels, and good structure;
- a highly diverse sward, comprising multiple species of grass, legumes, and forbs;
- short duration rotational grazing with longer (taller) residuals (living plant foliage remaining after a grazing event);
- minimising soil compaction.

Healthy soil is the foundation of all farming. A soil with nutrient deficiencies or sub-optimal pH will not support optimum pasture growth, allowing weeds that can tolerate, or are even adapted to, sub-optimal conditions to out-compete the pasture. Good soil structure is vital for optimum root growth, allowing soils to hold onto moisture; on the other hand, compaction caused by farm vehicles or livestock can destroy soil structure, which prevents soil from draining freely. Observation of docks on farms shows that they often appear in wet and waterlogged areas of fields, though research on this is lacking. It is not clear if they prefer wet areas or are more tolerant of waterlogging than the pasture species, thus gaining a competitive advantage. Regardless, improving drainage through minimising compaction and improving soil aggregation are important to ensure good structure, optimum pasture growth, and minimal weeds.

The common view in farming since the Second World War has been that to maximise yield, the species or cultivar with the highest yield was identified and then grown in monoculture. This view is increasingly being challenged (Weigelt *et al.*, 2009; Sturludóttir *et al.*, 2014). From an ecological perspective, monocultures have many vacant ecological niches that are ripe for weeds to take advantage of. By having multiple species of each of the three key pasture functional groups: grasses, legumes, and forbs (e.g., plantain and chicory), the amount of vacant ecological space is significantly reduced, decreasing the space available for weeds. Further, different species grow at different times of the year, ensuring that the ecological niche is full all year round.

Likewise, having multiple species filling different ecological niches can produce higher yields than monocultures (Wendling *et al.*, 2017). From an animal's perspective, it is increasingly realised that although simplified pastures with only a few species provide sufficient dry matter for the animal, they fail to provide the diversity of diet the animals need to truly thrive and perform well (Beck & Gregorini, 2020).

The traditional grazing method, set stocking, spreads the animals around the farm so all pastures are being grazed most of the time. This creates the problem that the stock preferentially eats the most palatable species, grazing them out and leaving the unpalatable species, which allows them to prosper due to the reduced pasture competition. In addition, plants keep their root and shoots in balance, so when a plant is continually grazed, it only has a small root system; when coupled with a small amount of leaf, this means it can only grow slowly.

The alternative to set stocking is rotational grazing, which has the stock in large herds which only feed on one field or part of a field for a few days, or even just a few hours, before being moved on to the new pasture. It is also important not to graze the pasture too low (leave longer residuals), as this means there is only a small amount of leaf area to capture the sunlight that the plant needs to regrow, leading to slower regrowth. Also, for pasture species with above-ground buds (meristems), grazing them too low will exhaust them and they will die out. Rotational grazing with long residuals gives the pasture plants time to grow many leaves to capture sunlight and develop large root systems to capture water and nutrients. After they are grazed, they then have the resources in the large root system to quickly regrow new foliage in the absence of further grazing, thereby maximising forage production. This also means that pasture strongly competes with weeds. Further, with rotational grazing, livestock are less able to pick and choose what they eat, so they tend to eat everything, including the weeds, unless they are toxic or highly unpalatable. In such situations, most livestock will eat docks, thereby suppressing them.

After suboptimal nutrient levels, soil compaction is the second most important factor impacting pasture (and arable crop) productivity. It is not just large tractors that cause compaction: even small livestock such as sheep will cause compaction when the soil is too wet. It is therefore important to have strategies and systems in place to avoid having livestock on fields that are too wet and susceptible to compaction. However, docks are most problematic in the colder, wetter, higher latitudes where the soil can be wet for many months over winter. In many cases, livestock are already housed over winter because of this, but a renewed emphasis on compaction management at all times of year is required, e.g., having the resources to move animals to the sheds when there is heavy rain, even in summer.

2.3. *Mixed grazing*

Livestock species are well known for their varying acceptance of docks. Deer are the most tolerant, even liking docks, followed by goats and sheep, which will eat younger foliage; being browsers, goats like the woody flower spikes. These are followed by cattle who will eat docks, especially if hungry (**Figure 4**), while horses avoid docks as much as possible. Where practical, cross-grazing dock tolerating species with intolerant species can assist with keeping docks suppressed.

Figure 4. Beef finishers eating offered broad leaf docks plants while waiting to be moved to new pasture

2.4. *Mixed grazing*

Several alternative agriculture advocates claim soil nutrient levels are key drivers of weeds. However, there is exceptionally little research data to back up their claims, and the conceptual models of how nutrient levels drive weed populations have not even been formulated (e.g., does the weed have a higher requirement for specific nutrients, or can tolerate excess or deficient levels; what are the impacts on inter-species competition; is there an effect on seed quality, or germination, etc. ?) However, a significant amount of research on the impact of nutrients on docks in the pasture was undertaken by Dr. James Humphreys in the Republic of Ireland (Humphreys, 1995; Humphreys *et al.*, 1999).

The research clearly showed that potassium (K) is a key driver of dock persistence in the pasture because docks have a higher requirement for K than grasses, as it is used to drive the partitioning of carbohydrates between roots, leaves, and flowers. Where soil K levels are at or below optimum, grass will out-compete docks for K due to its highly competitive fibrous root system, thereby inducing K deficiency in the docks, stunting and making them less competitive. Once soil K levels are above the optimum, docks have free access to the excess K, because grass only takes up the amount of K it needs, so docks obtain all the excess K for themselves. Therefore, the higher soil K levels are above the optimum, the stronger and more persistent docks will become. Established docks are also highly competitive with pasture by shading it with their leaves, thus reinforcing the effect of high K levels.

The simple lesson from this is potassium levels must be kept at or below optimum. The standard cause of excess K levels on livestock farms is caused by the application of slurry and farmyard manure to the fields closest to animal housing. It is essential that soil nutrient tests are regularly undertaken (every three to five years), the nutrient content of each batch of manure is tested, and manure is only added in quantities where it will not bring any nutrient level above the optimum, particularly for nitrogen, phosphorus and potassium (NPK).

Humphreys also found a strong interaction between soil nitrogen (N) levels, defoliation frequency, and dock populations. At defoliation frequencies of less than four weeks, higher N levels favour grass; at defoliation frequencies of more than four weeks, higher N favours docks. So rotational grazing and harvest of conserved feed, e.g., silage, should be focused on a return period of a month or less (time between grazing/mowing events), especially during the main growing season, and nitrogen must never be over-applied, e.g., it is best in multiple small applications than single large applications.

2.5. *Silage and grazing fields*

Fields that are predominantly used for silage often have high dock levels. The key reason for this is not the return of large numbers of dock seeds in the slurry to silage fields, as it is commonly believed. This is because the first cut of silage occurs before seeds are set, so few seeds get into the main bulk of silage. Dock seeds are killed by the ensiling process due to low pH. Rumen digestion also kills a significant amount of seed, as does sitting in the slurry. So there are multiple reasons why slurry contains zero viable dock seeds.

The key reason silage fields have high dock populations is that they are typically close to the farmyard, so they are convenient sites for slurry applications; and as silage is being extracted from those fields, they have the highest need for nutrient replacement, so they often receive large amounts of slurry. The slurry is high in K, and (as discussed in Section 2.4) high K levels increase dock persistence. In addition, silage fields often have high levels of N which, coupled with infrequent cutting, also favours docks. Furthermore, silage cut close to the ground often results in bare exposed soil, which is what docks require to germinate. Therefore, silage fields are almost optimally managed for high dock populations.

The key solutions to this are to ensure N and K levels never exceed levels optimum through regular soil tests, e.g., every three years, and only applying slurry according to the results of those tests, and where possible to rotate grazing and silage fields, so that the shorter term rotational grazing (less than a month return time) starts wearing the docks out.

2.6. *The role of seed banks*

Much is made of the longevity of seeds, but many of these studies keep seeds in ideal conditions. In comparison, the soil is a highly hostile environment for seeds, being abrasive, chemically caustic, and teeming with living things from microbes to vertebrates that view seeds as a highly nutritious food source. Therefore, persistence in the soil is far less than the seeds' maximum potential longevity. It is therefore far more valuable to focus on the half-life of the weed seed bank which, compared to decades for longevity of individual seeds, can be as little as one year (Roberts & Feast, 1972; Gallandt, 2006; Gallandt *et al.*, 2010; Mirsky *et al.*, 2010).

Much is also made of the very large numbers of seeds that weeds such as docks can produce, with 60,000 seeds for broad-leaved dock being a commonly cited figure. However, like seed longevity, this is the maximum seed production under optimum conditions (e.g., in a large undisturbed plant). In a well-managed pasture, with frequent rotational grazing and strategic mowing to remove the flower stems post grazing, seed production will be a fraction of this, even zero. However, as few as 600 seeds per plant are required to maintain a seed bank of 12 million seeds; this may sound large but equates to 1,200 seeds per square metre, of which the vast majority (e.g., 90%) will be unable to germinate due to being too deep in the soil, dormant, etc. This leaves just 120 seeds per square metre able to establish themselves if conditions are right. This population is also tiny compared to arable weeds, such as fat hen (*Chenopodium album*) which can have 12,600 seeds per square metre (Rahman *et al.*, 2006). Humphreys (1995) concluded that because dock seeds need direct sunlight to germinate, in a well-managed pasture it would be highly unlikely for many docks to be able to establish themselves. Therefore, most docks in a pasture have been there since the establishment of the pasture. It is therefore considered that the dock seed bank is only truly relevant when pasture is newly established. However, no known research has studied the size and persistence of the dock seed bank in real pastures, which is a significant knowledge gap that needs addressing.

A core component of any non-chemical weed management strategy for controlling therophyte weeds (weeds that survive as seeds) is minimising weed seed rain, to reduce the size of the weed seed bank. Docks have a mixed strategy of being perennial, particularly the broad-leafed dock, and also producing a large amount of seed, which is their main form of reproduction and dispersal. Therefore, a vital long-term strategy is to minimise the weed seed rain from docks by stopping them from producing seeds e.g., by cutting or grazing off the flower stems. The best time to do this is when they have just started flowering because this results in the greatest loss to the plant. However, dock seed becomes viable very rapidly after flowering starts, with 15% viability six days after the end of the first flowering, rising to over 90% after 18 days. It is therefore essential not to leave cutting or grazing of flowering stems too long, otherwise viable seed will have set. When the flower stem is cut off, the plants will try to flower again, especially in warmer regions, so these secondary flushes of flower stalks also need controlling.

2.7. *Dock management at pasture establishment*

As the main route for docks into well-managed pasture is believed to be at the time of establishment, it is clearly a critical point for dock management. There are some well-established techniques to minimise docks becoming established in new pastures. The key is to get the pasture species established and to achieve ground cover as quickly as possible to suppress dock seed germination by intercepting light, and then to out-compete the docks while they are still young and uncompetitive.

As with pasture management in general, correct pH and nutrient levels are key to ensuring that pasture seedlings can thrive. A good seedbed is also critical. Where time allows, the use of false seedbeds is an exceptionally valuable technique (Merfield, 2015). It is important to only establish pasture at optimum times of the year, i.e., when the soil and weather are warm, not cold and wet, to ensure rapid growth. Having a large number of pasture species, especially legumes and forbs with large leaves that quickly cover and shade the soil, is particularly valuable. Higher seeding rates can also contribute to faster ground cover. Cattle slurry has also been shown to inhibit dock seed germination without affecting grass seed germination and this can be used to give the new pasture a competitive edge (Humphreys, 1995). However, it is not known what impact slurry has on legumes and forbs, so where diverse pastures are sown, slurry should not be applied post sowing, until more information is gained.

2.8. *Biological control*

Biological control comes in three forms:

- importation or classical;
- augmentation;
- conservation.

Importation involves importing a pest's natural enemies to a new locale where they do not occur naturally. Augmentation involves the supplemental release of natural enemies that already occur in a particular area, boosting the naturally occurring populations. This is further sub-divided into inoculative techniques, where a small starter population is released which reproduces and builds up its population, and inundative techniques, where very large numbers of an organism are released to swamp the pest. Conservation biocontrol aims to boost natural enemies that already exist in the environment, by making the environment more hospitable for them, for example for beneficial insects by providing nectar and pollen through the addition of flowering plants.

Importation of biological control of docks in Europe is difficult because they are in their native range. Importation biocontrol is best suited to exotic weeds that lack predators from their native range. Even then, success (defined as a reduction of the weed below economically damaging levels) is only achieved in 10% of cases.

Conservation biocontrol of docks is challenging, because docks already have a large number of species that attack them. So it is particularly hard to find an ecological manipulation that would significantly boost predators of docks to a sufficient number to meaningfully decrease dock populations.

Augmentation techniques, particularly inundative ones using microbes, have theoretical potential. There are species of pathogenic fungi that are specific to docks e.g., *Uromyces rumicis*. This type of specificity is very valuable as it means the microbe can be broadcast sprayed to kill docks without killing pasture species. But globally the development of mycoherbicides (fungi-based herbicides) has been very challenging and has mostly been focused on weeds in high-value cropping systems, due to the cost of the final products. Less than a handful have proved practical and economic, so developing one for docks in low-value pasture system is considered unlikely.

Inundative augmentation with invertebrate dock pests, e.g., fiery clearwing (*Pyropteron chrysidiformis*) or the green dock beetle has potential, but the challenges are considerable, including developing mass rearing systems and then scaling those up to commercial levels. Then distributing the live insects to farmers, getting them to lay sufficient eggs so the larvae kill or suppress enough docks to make an economic difference, all while keeping costs sufficiently low so that it is economically viable at the lower per hectare returns of livestock farming, are all considered exceptionally challenging.

2.9. *Physical control*

Livestock production has among the lowest gross margins of all types of farming (e.g., compared with arable and vegetable crops), and it often occurs on hilly land that is less or unsuited for machinery access, so often it is not financially viable to spend money on direct/ physical control techniques of docks. However, there are some situations where it is justified. For example, as most docks are believed to enter pasture during establishment, reducing dock numbers once the pasture is fully established, e.g., six months to a year after seeding, can pay dividends, especially if the pasture is kept for many years, as the benefits of removal accrue year on year.

2.9.1. *Direct dock plant removal*

The key to effective physical control of docks is that they can only regenerate from the crown (true shoot), not the true roots as discussed in Section 2.1. Typically, the crown only extends five centimetres below the soil surface, and rarely as deep as 10 cm, therefore as long as the crown is removed the root will eventually die. However, the ability of the crown to regenerate by producing new roots and shoots is prodigious, so the dug up crown must be prevented from re-establishing. In hot dry weather, especially if there is a good thickness of pasture to keep the crowns from having direct contact with the soil, they can just be left on the field to desiccate and die. In less than ideal drying conditions, the crowns may need to be taken off the field and destroyed, e.g., through composting or putting into slurry pits. The main tool for digging the crowns up is the ‘dock fork’ (**Figure 5**) which consists of two prongs and a pivot point to ensure a vertical clean lift and ease of use / good ergonomics.

Figure 5. Traditional dock fork (left), modern ergonomic design with interchangeable heads (right) (LazyDogTools.co.uk)

2.9.2. *Electrothermal weeding*

The other potential means of direct dock control is electrothermal weeding (Merfield, 2016). This technology was widely researched in the 1980s but lost out to herbicides, particularly application with weed wipers. It is now commercially available again due to the demise of herbicides. Its value lies in its systemic weed kill, due to the electricity flowing through the foliage and into the root system before dispersing into the soil. Where weeds are higher than the crop or pasture, the electricity can be selectively applied to the weeds based on the height difference. Therefore, electrothermal control has considerable potential for pasture weed management as a large majority of pasture weeds overtop the pasture, especially after grazing. Electrothermal weeding is thus both systemic and selective for tall pasture weeds.

The challenge for electrothermal control of docks is that the leaf petiole is very thin compared with the large mass of the crown, which is what needs to be destroyed to kill the dock as a whole. If the electricity is applied to the leaves, the petiole will be destroyed before sufficient electricity gets into the crown to kill it. It is thus likely that the electricity would have to be applied to the flower stalk to get sufficient energy into the crown. That may only work on younger plants with smaller crowns rather than old large docks. With hand-held electrothermal machines, it may be possible to directly apply the electricity to the crown itself. However, it is not clear if this would be more effective and efficient in terms of labour and costs than manual removal with a dock fork. More research is required.

2.9.3. *Other techniques*

A range of other techniques for direct dock control, such as thermal weeding using flame and steam, mechanised dock diggers, etc., have undergone trials. Flame and steam can only defoliate dock plants so are no more effective than grazing and mowing. They also require very large amounts of energy which makes them uneconomic. Mechanical approaches such as the "dock twirler" (Dierauer *et al.*, 2018) with its high capital cost, low agility, and thus slow work rate are considered unlikely to match a fit weeding gang using well-designed dock forks both for speed and cost.

2.9.4. Renewing pasture with high dock populations

Where dock populations are excessive, it is likely to be cheaper to terminate the pasture and re-establish it rather than try and remove the docks. Typically, shallow (5 to 10 cm), powered cultivation with a rotovator should be used initially to detach the crowns from the roots to minimise their reserves. The rotovator will also break the crowns up, again minimising the reserves of any one fragment that they can draw on to regrow. The crown fragments will vigorously regrow unless the soil and weather are particularly dry, so follow up tillage to stop the fragments re-rooting will be required.

One option is to bury the broken crowns as deep as possible with a plough. However, getting a good burial with a plough in ground that is already cultivated can be challenging.

An alternative is to use spring-tined cultivators and harrows to pull the crowns to the surface to stop them from re-rooting. It is best to avoid powered machinery as this will be more damaging to soil structure and is more likely to bury the crowns, effectively transplanting them.

The follow-up cultivations are utterly critical because if the crowns are not killed, the initial cultivation will create many more dock plants by dividing the crowns, just like for rhubarb.

Ploughing intact docks does not always guarantee success, because if the plants are large, they can send up shoots through a considerable depth of soil and re-establish themselves (**Figure 6**).

Figure 6. Dock plant that has been ploughed under, and then put up a shoot from the buried crown, that has then established a new crown and leaves. Note the elongated bamboo-like appearance of the shoot that grew to the surface and that adventitious roots are only produced from the nodes.

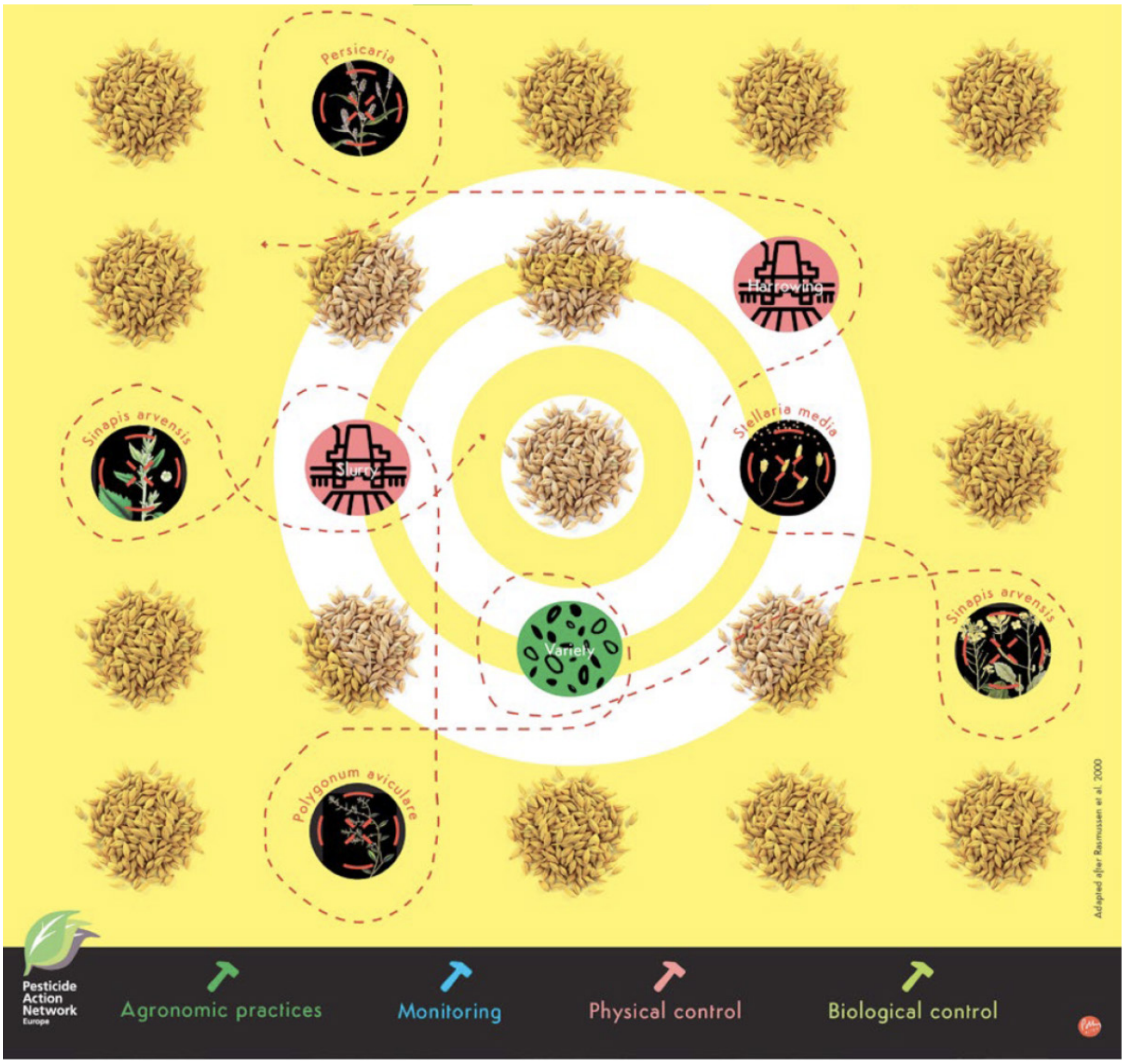
3. Conclusions

The zero-tolerance approach of the failed “war on weeds” must give way to a new focus on the economics of dock management, which tolerates a low population of docks, based on the knowledge that eliminating all dock plants is a waste of money, and they are an important part of the natural biodiversity of Europe, and that lower presence on pasture can be beneficial. Effective non-chemical dock management is based on a whole-system approach. First is understanding dock biology and ecology, particularly the role of the crown. A major part is good pasture management, though having a diverse sward that is grazed rotationally leaving longer residuals. It is important to rotate silage and grazed fields, and to ensure soil nutrients, pH, and structure are all optimal. Lastly, the weed seed rain must be minimised, and if docks do establish themselves in the new pasture, dock forks can be used to reduce their populations to acceptable levels.

ANNEX 3

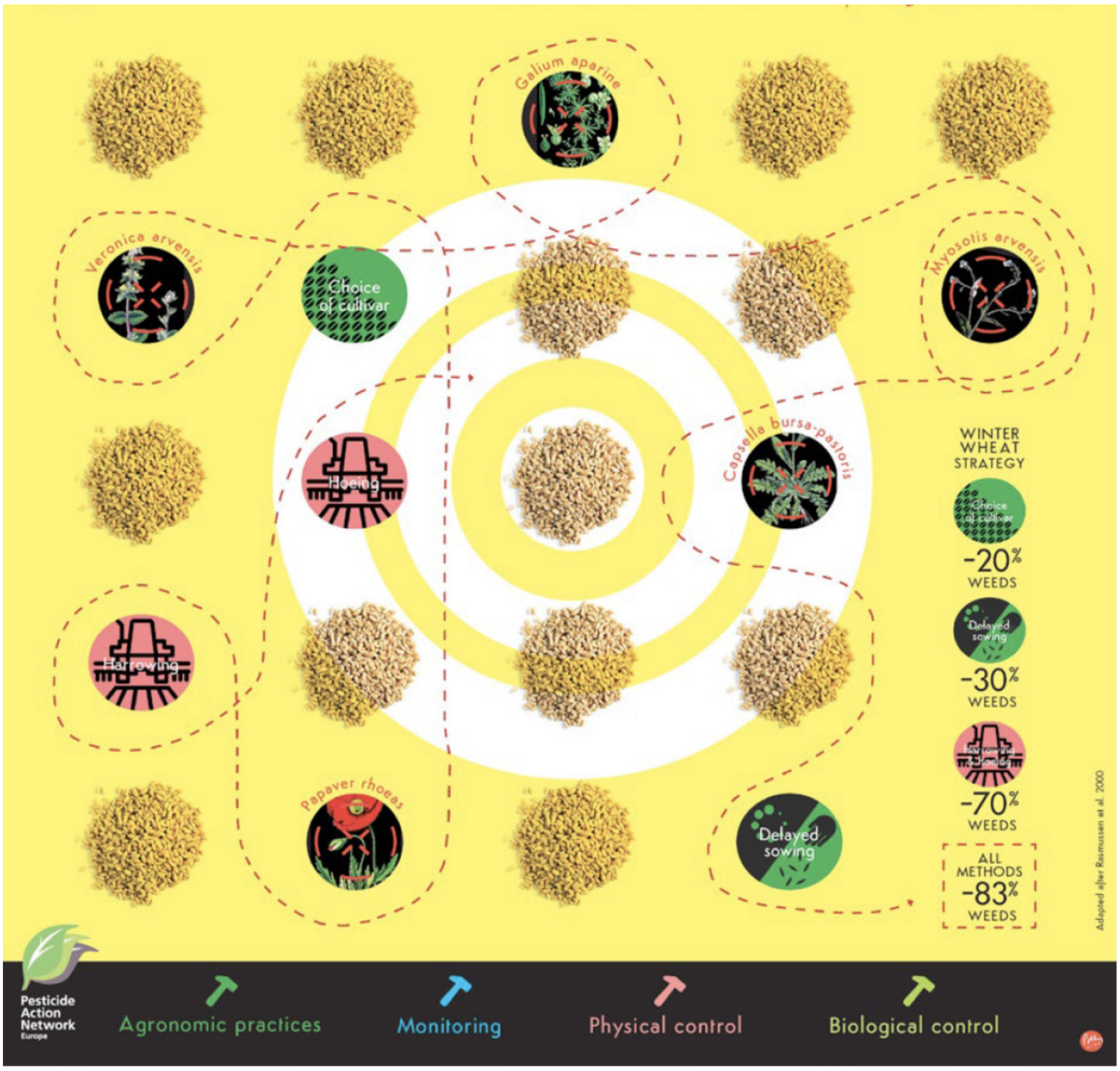
Illustration of the “many little hammers” approach in the fight against weeds

Figure 36. Integrated weed management for spring barley



Adapted after Rasmussen et al. 2000

Figure 37. Integrated weed management for winter wheat



Adapted after Rasmussen et al. 2000

OVERVIEW OF FIGURES

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