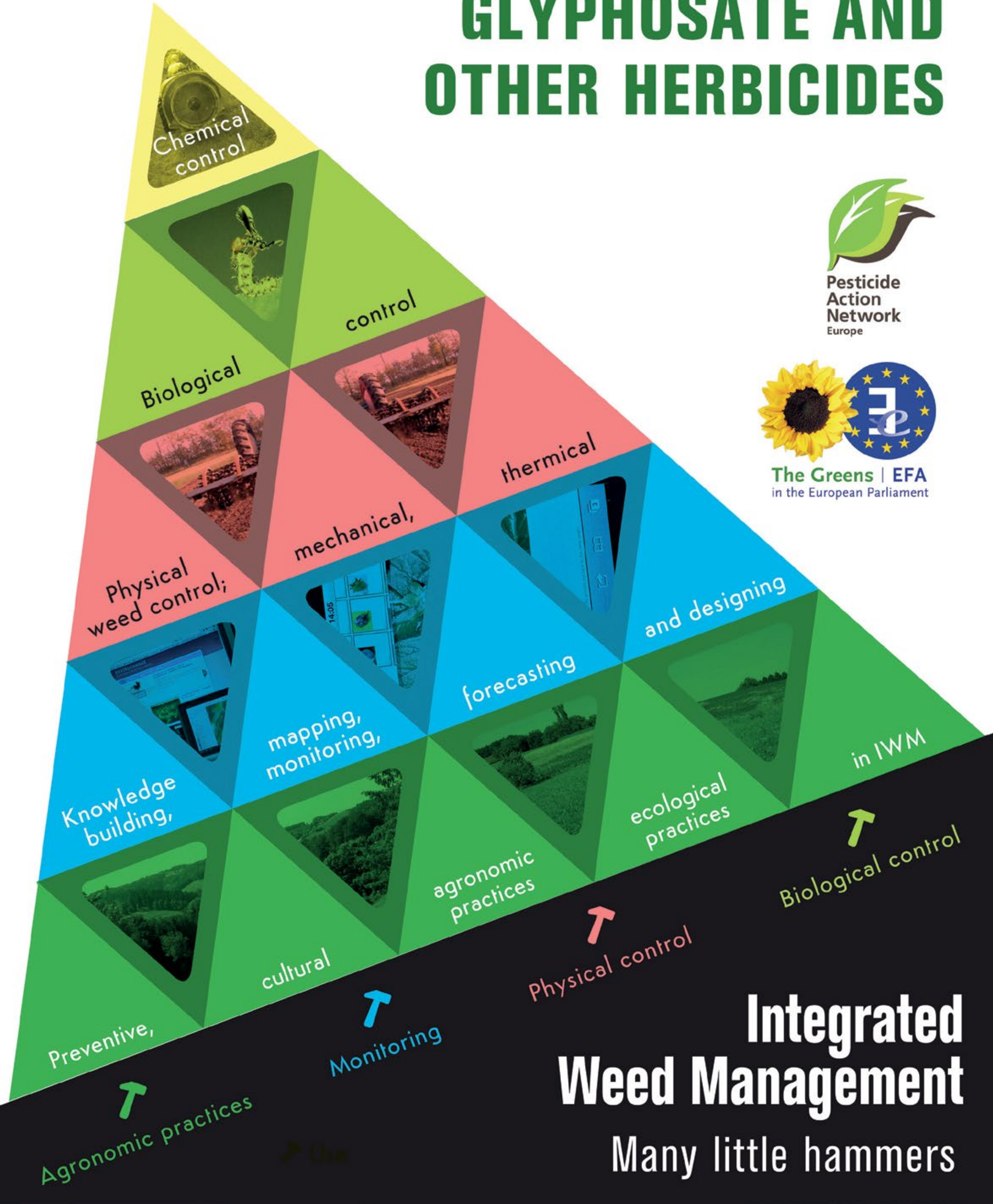
ALTERNATIVE METHODS IN WEED MANAGEMENT TO THE USE OF GLYPHOSATE AND OTHER HERBICIDES



Pesticide Action Network Europe

The Greens | EFA in the European Parliament

Integrated Weed Management

Many little hammers

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01 Introduction

While the use of synthetic pesticides in agriculture has helped to increase food production, this has not occurred without great costs to the environment, natural resources and human health. The 2017 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 reduce world hunger[1].

Herbicides are used in agriculture and horticulture to combat weeds that 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 glyphosate, are used to kill all vegetation, post harvest, and also pre-crop and pasture establishment. It is also used to ripen and desiccate grain and seed crops prior to harvest. Non-agricultural uses include the management of invasive plant species, to assist the management of public areas, for aesthetics or reduce 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, specifically herbicides. Many farmers have abandoned a number of equally effective, non-chemical weed management methods. As a result, every day tonnes of herbicides are applied to fields and their surroundings, which can put human health at risk and also negatively impacts on biological processes and ecosystem functioning that can combat damaging weeds and other 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 on a pesticide treadmill they cannot get off.

Herbicides can have a wide range of non-target im-

[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

pacts 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. So there are direct and indirect effects of broad-spectrum 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].

Not only do the use of herbicides and pesticides have many negative impacts, they are increasingly failing to work due to evolved resistance, i.e., weeds evolve mechanisms that make them resistant and/or tolerant to regularly-used herbicides, such that the herbicides no longer kill the weeds. In 2018, there were nearly 500 'unique resistance cases', i.e., weed species resistant to one herbicide, from less than ten cases in 1970[4]. Of those, over 100 species are resistant to two herbicide modes of action, 50 plus species are resistant to three modes of action, all the way through to one species that is resistant to 11 modes of action. As a result of this over-use, the number of glyphosate resistant weeds now stands at 42[4]. It is increasingly clear, that beside the negative impacts of herbicides on the environment and health, they are failing at an ever-increasing rate as a technology, meaning that farmers and growers may well be forced to use non-chemical weed management as the herbicides cease to function.

This report outlines the wide range of non-chemical alternatives to herbicides that are already available and used by groups such as organic farmers and those practicing 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 where current techniques are not effective enough. 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 or 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 high yields, 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, pesticide sales in the EU, and impacts of glyphosate on soil and environmental safety, as well as human health. Finally, it presents a list of suggestions on the transition towards a pesticide-free weed management practices.

This work was carried out in parallel with the project "Filming farmers across European Union on alternatives to herbicides, especially glyphosate", which was also commissioned by The Greens/EFA group in the European Parliament.

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[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://news.cnrs.fr/articles/where-have-all-the-farmland-birds-gone, https://phys.org/news/2018-03-bird-populations-french-countryside-collapsing.html, https://www.independent.co.uk/environment/europe-bird-population-countryside-reduced-pesticides-france-wildlife-cnrs-a8267246.html

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

02 Glyphosate

Glyphosate is the active ingredient of the world's - and the EU's - most widely used herbicide. The original formulation, manufactured by Monsanto, was sold under the trade name Roundup™. Roundup rapidly became popular with farmers due to it being exceptionally broad spectrum (kills all vascular plants) and systemic (travels through the plants vascular system) thus killing the entire plant, not just the foliage. In the 1990s, Roundup's usage expanded further with the development of Monsanto's "Roundup Ready" genetically modified (GM) glyphosate-tolerant soybean crops, followed by Roundup Ready maize and cotton crops. Roundup / glyphosate-based herbicides is also the foundation of no-till agriculture and is used on millions of hectares globally for that use alone.

The herbicide potential of glyphosate (N-(phosphonomethyl) glycine) was discovered by Monsanto in 1971 and was registered as an herbicide in 1974[5]. Glyphosate causes plant toxicity by blocking the action of an enzyme (5-enolpyruvylshikimate 3-phosphate or EPSP) with a key role in the synthesis of amino acids and other essential nutrients for the plant (through a cascade of reactions known as the shikimate pathway), resulting in plant starvation and eventually death (Holländer & Amrhein, 1980). This pathway is also found in microorganisms including bacteria and fungi as well as plants, but not in animals (Herrmann, 1995). For example, glyphosate was patented in 2010 by Monsanto as an anti-microbial agent against certain pathogenic infections[6].

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 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[7].

[5] Patent number US 3799758 A. N-phosphonomethyl-glycine phytotoxicant compositions.

[6] Patent number US 7771736 B2. Glyphosate formulations and their use for the inhibition of 5-enolpyruvylshikimate-3-phosphate synthase

[7] Glyphosate Task Force (industry consortium) website http://www.glyphosate.eu/history-glyphosate

03 Uses of glyphosate

Glyphosate is a broad spectrum, non-selective, systemic herbicide, crop desiccant and to a lesser extent plant growth regulator. Being non-selective, glyphosate-based herbicides (i.e. formulations containing glyphosate as an active ingredient together with other chemicals) effectively kill or suppress all types of 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 European Union is given in Table 1.

In conventional agriculture, glyphosate-based herbicides are applied before crops are sown to kill weeds to facilitate crop establishment. They are also used in no-till farming to clear the land of weeds and previous crops to as an alternative to 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 through tillage. In glyphosate-resistant crops (most of which are created by genetic engineering / genetic modification or GM), the herbicide is used post crop-emergence to kill the weeds but leaves the crop unharmed. Glyphosate-based herbicides are also used to clear the ground beneath perennial crops such as fruit trees and grape vines.

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

Crops/plant species	Growth & Stage	Pests 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 & biennial weeds	1-6	0.36-2.16
All*	Post-planting pre-emergence of crops	Emerged annual, perennial & 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 & biennial weeds	2-6	0.72-2.16
Oilseeds (pre-harvest) rapeseed, mustard seed, linseed[b]	Crop maturity < 30 % grain moisture	Emerged annual, perennial & biennial weeds	2-6	0.72-2.16
Orchard crops, vines, including citrus, tree nuts & olive trees	Post emergence of weeds	Emerged annual, perennial & biennial weeds	2-8	0.72-2.88

* Crops including but not restricted to: root & 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- & 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

Another use of glyphosate-based herbicides is as a crop desiccant on cereals and grains. It is applied close to harvest to accelerate the ripening process and dry the seeds while the crop dies, to facilitate harvest. 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 pesticide residues, some Member States have strict rules on this use (Box 1[8]).

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

Box 1. Glyphosate: Different desiccation practices along Member States

Glyphosate use practices vary across Member States. According to EU's Directorate General for Health and Food Safety DG SANTE some Member States have rules for when glyphosate can be used and some have rules on how much can be used for the 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 use for weed control is still permitted. In Germany, the use of glyphosate for harvest aid is not banned as such but is not considered good agricultural practice. Sweden is in the same is the situation: no glyphosate products approved for this particular use are available on the market."

European Crop Protection Association (ECPA) 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."*

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, 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 ha (4.32 kg/ha) 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 genetically engineered glyphosate resistant crops, including: maize, cotton, soya beans, oilseed, and sugar beet. The whole point of these crops is to use glyphosate-based herbicides for weed control. The European Union, however, has a strict regulation regarding the plantation 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[9]. The Member States that cultivate GM crops are the Czech Republic, Spain, Slovakia, Romania and Portugal[10]. Here we need to stress that the total area dedicated to GM crops in Europe is approximate-

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

[10] European Commission, Fact Sheet: Questions and Answers on EU's policies on GMOs (2015) http://europa.eu/rapid/press-release_MEMO-15-4778_en.htm

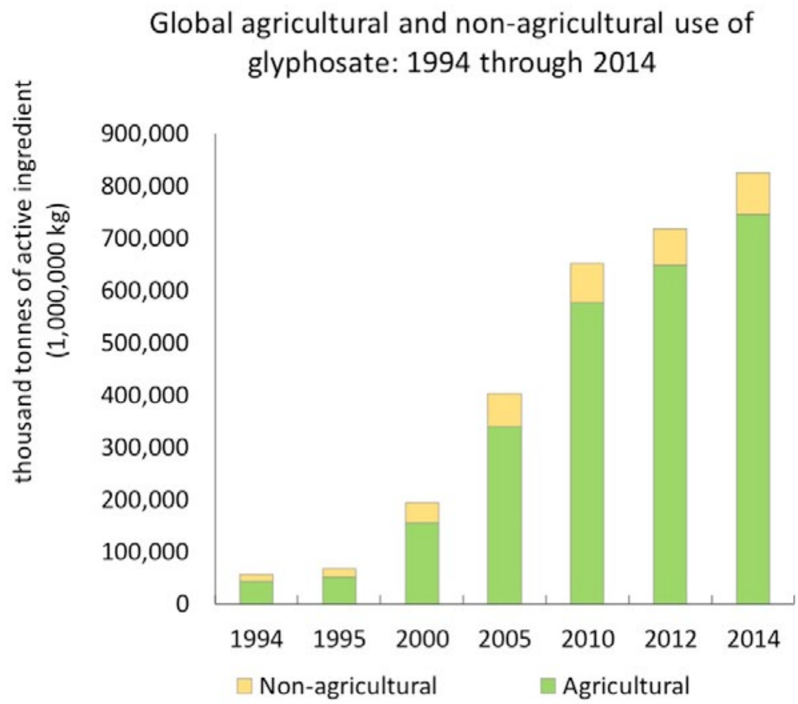

Figure 1. Global agricultural and non-agricultural uses of glyphosate (adapted from James, 2016).

ly 130,000 ha, which is just below 0.1% of EU agricultural land. 95% of that land growing GM crops (124 227 ha in 2017) is in Spain[11]. Currently there is only one GM crop authorised for cultivation in the EU, the maize variety MON 810; although the crop is not glyphosate-tolerant, glyphosate would be used before crop emergence and as a desiccant pre-harvest, like other crops grown in industrial scale monocultures.

There are no official data on the overall amount of glyphosate used for agricultural or non-agricultural purposes across the EU. A publication in 2016, based on an analysis of U.S. and global official data or data from the industry gives an overall picture of the agricultural and non-agricultural use of glyphosate (Benbrook, 2016) presented in Figure 1. These data also reveal that global use of glyphosate has increased almost 15 times in the last 10 years.

For the EU some data are collected by Member States. In Germany for example, glyphosate is applied in approximately 4.3 million ha of arable land (39% of total arable area) and a German study from the University of Göttingen estimated that in 2009 application of glyphosate was about 4,197 tonnes of active ingredient (Steinmann et al., 2012). In the UK, in 2014, glyphosate-based herbicides were the most used of all herbicides and accounted for almost 1,800 tonnes of active substance (Garthwaite et al., 2014).

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

04
Glyphosate and Herbicide Sales in EU

According to the global organisation Transparency Market Research, Europe held around 16.6% of the global glyphosate market in 2012[12] and according to its manufacturers glyphosate accounted for 25% of the global herbicide market in 2012[13].

The EU does not publish data on the use or sales of individual herbicide products, making it difficult to find out how much glyphosate-based herbicides are being sold (or is being used) in EU countries. Nevertheless, the statistical office of the European Union, Eurostat, provides statistics for the sales of pesticides (expressed in weight of active ingredients) in the EU[14], of which the results for the EU Member States are presented below.

Figure 2 shows the summary of pesticide sales in the EU during 2011-2014. Herbicides are the second most-widely sold category of pesticides in the EU (131,300 tonnes of active ingredients), and in 2014 they accounted for 33.1% of all pesticide sales (396,200 tonnes of active ingredients in total).

However, looking at pesticide sales at country level, for some countries, herbicides are the most widely

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

[13] http://www.glyphosate.eu/glyphosate-basics/what-glyphosate

[14] http://ec.europa.eu/eurostat/statistics-explained/index.php/Pesticide_sales_statistics

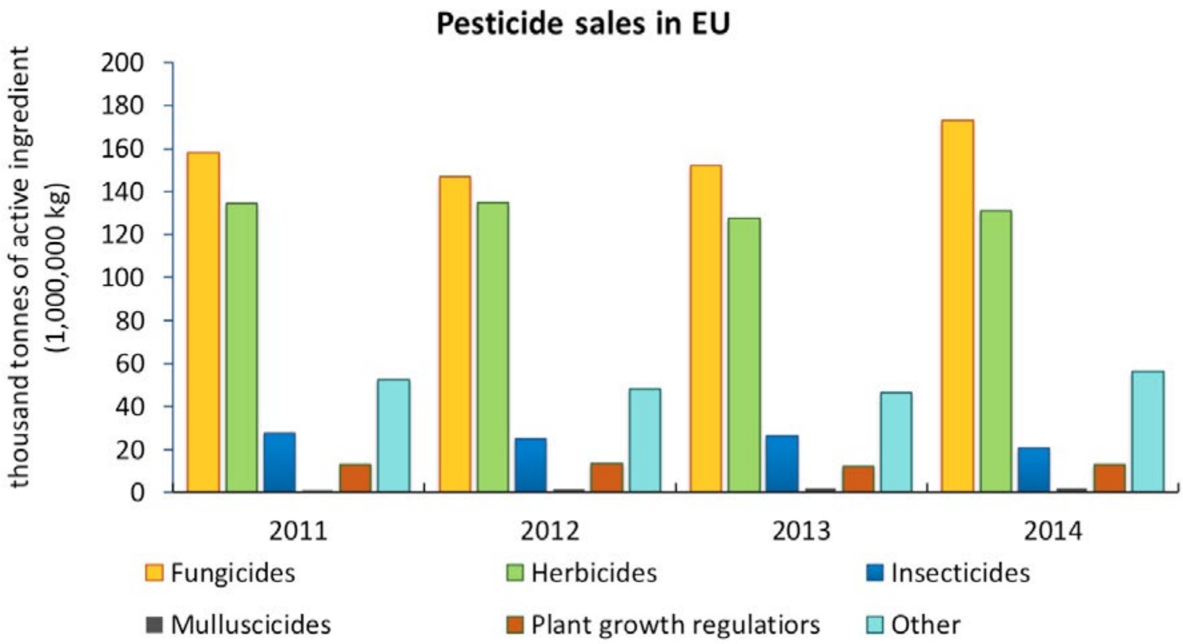

Figure 2. Pesticide sales in EU (2011-2014) by type, expressed as thousand of tonnes of active ingredient (Eurostat)

sold pesticide product category (Figure 3). For example, in 2014, more herbicides than fungicides were sold in 14 EU countries: Bulgaria, the Czech Republic, Denmark, Finland, Germany, Hungary, Ireland, Latvia, Lithuania, Poland, Romania, Slovakia, Sweden and the United Kingdom.

France, Germany, Spain, the UK and Poland are the countries with the highest herbicides sales (Figure 4). Together, these countries accounted for sales of 88,200 tonnes of active ingredients in 2014, or 51% of the entire herbicide sales in the EU. It is worth noting that Spain is the country where most glyphosate-resistant crops are grown in the EU, and it is also has the EU's second largest area of agricultural land after France. In general, herbicide sales changed little during 2011-2014, with the exception of Denmark, where there was a clear reduction (Figure 4).

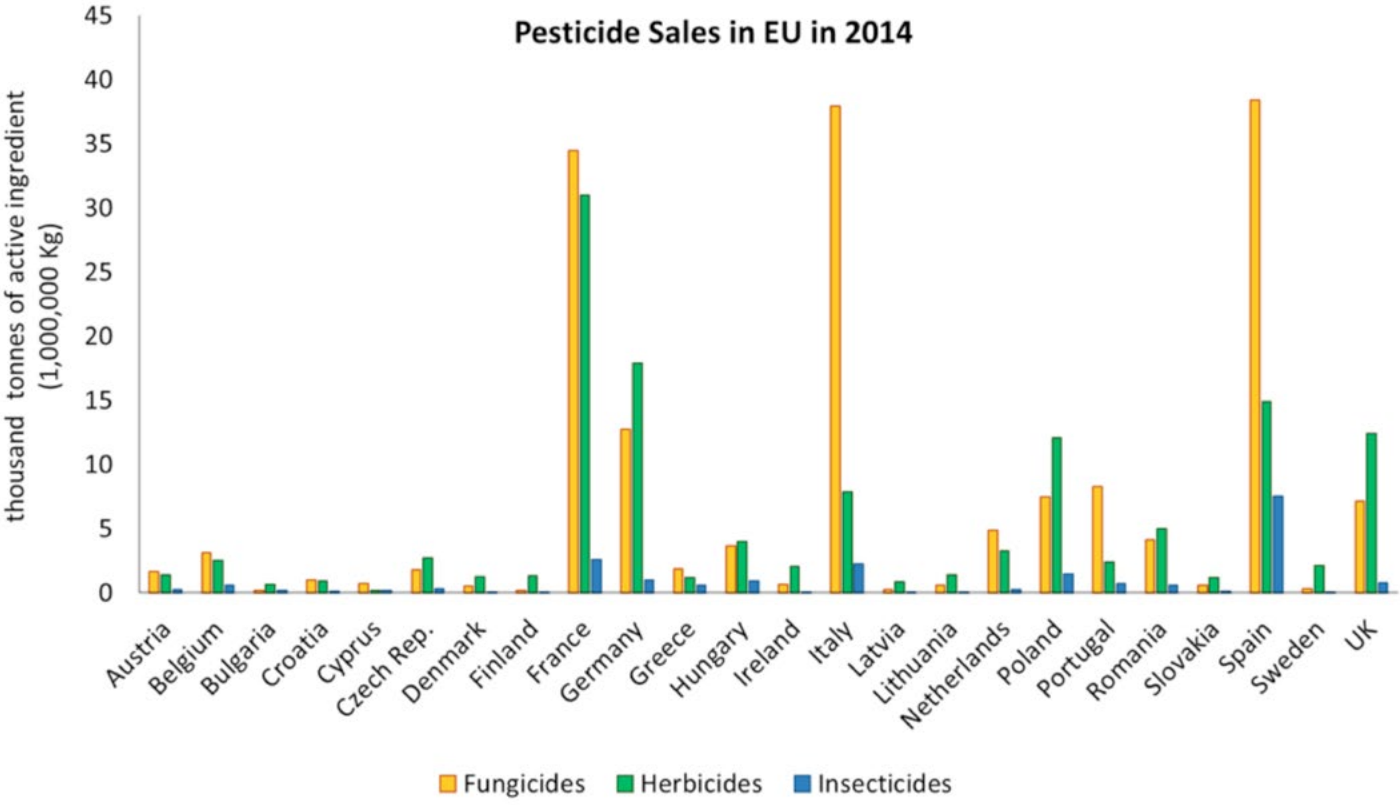

Figure 3. Sales of herbicides, fungicides and insecticides across EU countries in 2014 (Eurostat). Countries with sales below 1 million tonnes are excluded.

Figure 4. Sales of herbicides across EU countries in 2011-2014 (Eurostat)


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05 Health concerns

The scientific literature contains many examples where exposure to glyphosate alone and to glyphosate-based herbicides is associated with a wide range of adverse health effects in humans, laboratory animals, farm animals and wildlife (a summary on glyphosate toxicity is given in Annex 1). Importantly, concerning farmers, clinical studies have shown that workers who had previously used glyphosate had a higher incidence of non-Hodgkin lymphoma, a rare form of cancer, compared to those who had not used glyphosate (De Roos et al., 2003; Eriksson et al., 2008; McDuffie et al. 2001). In 2015, the International Agency for Research on Cancer (IARC), of the World Health Organisation (WHO), after carrying out an assessment on the potential of glyphosate to cause cancer, classified it as "probably carcinogenic to humans" (IARC classification of substances 2A; IARC, 2016). Other studies from the scientific literature have reported a range of adverse effects in laboratory animals following exposure to glyphosate alone and glyphosate-based products: carcinogenicity, genotoxicity, reproductive, developmental and endocrine disruption, etc. (Annex 1). The glyphosate monograph of Pesticide Action Network International (Watts et al., 2016) presents a large number of studies that have reported adverse effects in humans, laboratory animals, ecosystems and the environment.

Despite this evidence, the European Food Safety Authority (EFSA)[15] and the European Chemicals Agency (ECHA)[16] both concluded, based on the methodology they use to assess safety, that

[15] https://www.efsa.europa.eu/en/press/news/151112

[16] https://echa.europa.eu/-/glyphosate-not-classified-as-a-carcinogen-by-echa

glyphosate does not present any carcinogenic risk for humans and overall that its use poses no health risk for humans. Here, one should note that at the European Union level, EU agencies carry out the toxicity assessment of pesticides on the level of individual active substances rather than the whole products. The final pesticide products that include the active substances and the different co-formulants (other chemicals in the final products) are evaluated by the Member States using a much less rigorous assessment[17].

This discrepancy between the conclusions of the European Authorities and IARC brought reactions from the scientific community around the world, and a group of scientists published a Statement of Concern (Box 2). Further, the detection of glyphosate in food[18] as well as in people's urine (Conrad et al., 2017), has raised concerns in the general population about to how much glyphosate it is exposed to, and what are the potential health effects.

Box 2. Statement of concern published in 2016 in the Environmental Health journal (Myers et al., 2016)

Statement of Concern directed to scientists, physicians, and regulatory officials around the world:

"(1) Glyphosate Based Herbicides (GBHs) are the most heavily applied herbicide in the world and usage continues to rise;

(2) Worldwide, GBHs often contaminate drinking water sources, precipitation, and air, especially in agricultural regions;

(3) The half-life of glyphosate in water and soil is longer than previously recognized;

(4) Glyphosate and its metabolites are widely present in the global soybean supply;

(5) Human exposures to GBHs are rising;

(6) Glyphosate is now authoritatively classified as a probable human carcinogen;

(7) Regulatory estimates of tolerable daily intakes for glyphosate in the United States and European Union are based on outdated science. We offer a series of recommendations related to the need for new investments in epidemiological studies, biomonitoring, and toxicology studies that draw on the principles of endocrinology to determine whether the effects of GBHs are due to endocrine disrupting activities."

[17] http://www.efsa.europa.eu/en/interactive_pages/pesticides_authorisation/PesticidesAuthorisation#pesticides

[18] https://www.slu.se/globalassets/ew/org/centrb/ckb/publikationer/dokumentation/p12-ramo.pdf

06 Impact on ecosystem functions and soil

Herbicides are applied on fields in the open air, and therefore inevitably contaminate the wider environment, i.e. the atmosphere, soil, surface and ground water, and the seas and oceans, potentially exposing the organisms living there, which puts ecosystems at risk (Carvalho, 2017).

Glyphosate works on all plant species; no other herbicide is so broad-spectrum. Hence, 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). Indirect effects include the unprecedented elimination of all weeds/wildflowers, which have knock-on effects on agro-ecosystems (Watts et al., 2016). Farmland biodiversity and ecosystem functions, such as pest control by their natural predators, pollination services by insects and functional soil structures 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 3). This impact on ecosystem services has a direct economic cost (Box 4). 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).

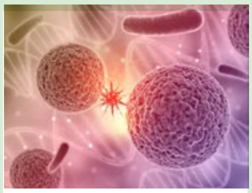
Glyphosate blocks plants' natural defence mechanisms that respond to infections (Johal & Huber 2009). Glyphosate has been shown to alter soil microbial communities, for example, a decrease in arbuscular mycorrhizal fungi (Zaller et al., 2017), which facilitate nutrient and water uptake by the plant roots. It is also toxic to beneficial soil bacteria, such as those of the Bacillus family (Yu et al., 2015) that have a key role in suppressing pathogenic fungi, as well as making soil minerals available to plants. Glyphosate also binds to the soil minerals manganese and iron, blocking their bioavailability for plants (Johal & Huber, 2009): Glyphosate *"significantly increases the severity of various plants diseases, impairs plant defence to pathogens and diseases, and immobilises soil and plant nutrients rendering them unavailable for plant use"*[19]. Due to these effects, and the growth of weed tolerance and resistance to glyphosate-based herbicides, farmers are obliged to use fungicides and additional herbicides on their crops, resulting in an even higher ecological impact.

Box 3. Examples from the scientific literature on how glyphosate use affects ecosystem services

Ecosystem services and glyphosate

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 decomposing plant residues and leaf litter, mineralising organic matter, creating topsoil and especially humus, cycling carbon and nutrients, etc[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 plant nutrient uptake[5].



Pollinators: Honey bees, wild and solitary bees, butterflies and other insects play a key role in the pollination of plants, including agricultural crops. As a broad-spectrum herbicide, glyphosate 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 synthesizing 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.

[19] Full review: Science in society 2012. Glyphosate Hazards to Crops, Soils, Animals, and Consumers. http://www.i-sis.org.uk/USDA_scientist_reveals_all.php

Picture 1. Effects of long term use of glyphosate on crops[16]

Box 4. Economic costs of gradual loss in ecosystem services

The United Nations Environment Programme (UNEP) carried out a study in 2005 and found that 40% of the world's economy actually relies directly on ecosystem services (SCBD, 2010). Hence, it is of great concern that, according to the Millennium Ecosystem Assessment (2005), 60% of ecosystem services have deteriorated in the last 50 years. A study on the economics of ecosystems and biodiversity recently confirmed that the cost of inaction and the degradation of ecosystem services could account for up to 7% of world GDP (Gross domestic product) per year by 2050 (UNEP, 2008).

Box 5. Soil contamination by glyphosate

Soil contamination by glyphosate:

- Studies show that glyphosate and its degradation product aminomethylphosphonic acid (AMPA), which is also of toxicological concern, get quickly metabolised down to 50% by soil bacteria in silt/clay soil (9 and 32 days, respectively). Nevertheless, traces of glyphosate and AMPA can be detected 21 months after application (Simonsen et al., 2008).
- A recent study shows that glyphosate and AMPA are detected in 45% of European soil (300 samples from 10 European countries) (Silva et al., 2017). These substances are strongly (>90%) adsorbed to soil particles but are not necessarily immobilised in soil. On the contrary, they are transported together with the soil particles through atmoshpere and water, and can be taken up by living organisms or are deposited in rivers and lakes.
- In soils high in phosphate, glyphosate may become easily mobile in water. Phosphate in fertilisers reduces the adsorption of glyphosate to soil particles, increasing the amount of free glyphosate molecules in the soil, which can then be absorbed by the plant roots, metabolised by microorganisms or can leach into the groundwater (Munira et al., 2016).

07
Weed management without herbicides

Weed management is one of the dominant challenges in agriculture, particularly in arable and vegetable cropping systems, because all crops become colonised by many different species of weeds. In extreme but rare cases, long term failure to manage weeds can result in complete crop loss, particularly, if no 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' interest in managing weeds is reflected in EU herbicide sales, which accounts for 33% of all pesticide sales (Figure 2).

Yet in order to restore long-term soil fertility and ecosystem services needed in farming, as well as environmental and human health, 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 Annex 2 and 3, show that it is possible to reduce or even eliminate the use of herbicides in agriculture, and in many places it is already being done, without necessarily being a fully organic farmer. Many weed management methods already exist that any farmer can adopt, that allow them to reduce and then eliminate herbicide use. Even complex issues, like the use of glyphosate in so-called "conservation" agriculture that avoids ploughing can be resolved without herbicide use (TILMAN-ORG 2016).

Box 6. Herbicide-free conservation tillage

Conservation tillage: mulching, reduced tillage / shallow ploughing plus green manure

"No-till" systems have been promoted on the basis that they increase soil organic matter (SOM) and soil carbon, but this is now considered incorrect: rather, different tillage systems distribute SOM and soil carbon differently through the soil profile (Baker et al., 2007). Ploughing / tillage can have negative effects on soil structure and biota, so minimum till systems can have benefits. However, no-till systems are entirely dependent on glyphosate-based herbicides to control weeds, in the complete absence of ploughing. But recent studies show that reduced tillage (RT) methods such as shallow ploughing (inversion or non-inversion) not only reduce weed density but also cause less disturbance to the soil in the long-term, as it has a lower impact on soil communities, such as earthworms and mycorrhizal fungi, compared to deep tillage (over 25cm soil depth). Therefore, when combined with other agronomic practices, RT can be considered a good weed management technique that overcomes the need to use herbicides. For example, when reduced tilling is combined with a leguminous cover crop, mulch, then green manure to raise nitrogen levels, crop yields can be comparable, while soil fertility and carbon storage capacity is maintained (TILMAN-ORG, 2011-2014).

A standard definition of a weed is "a plant growing in the wrong place". A more nuanced view is that calling a plant a weed is a judgement about the value of that plant, or a value judgement. Such value judgements can be economic, aesthetic, or based on safety. For example, in agriculture, the main reason for managing weeds is that they reduce yields and therefore profit, so the value judgement is economic. In home gardens and urban areas, the value judgements are more aesthetic. Some plants are hazardous, being toxic or spiny, and so are judged to be weeds.

The judgement as to whether a plant is a weed is entirely context-dependent: an EU farmer may use herbicides to kill other plant species in their crops because they are judged to be weeds. That farmer may then be subsidised to sow many of 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. There is therefore a need to manage more intelligently non-crop plant flora, both within crops and in non-cropped areas. For example, a 20-year study in Denmark found that 80% out of a total of 200 weed species growing in cultivated fields were too weak to compete with the crops and so affect crop yield (Andreasen et al., 1996). Only 20% of species affected the yield significantly; the other 80% of weeds also have a beneficial role by providing biological diversity and supporting ecosystem services. For example, they offer a habitat for both beneficial biocontrol insects and 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 habitat for biocontrol insects, which are vital for pest control, and the pollen and nectar they produce helps maintain populations of pollinators. So the solution would be not to completely eradicate all weeds, as they play an important ecological role that is useful for farmers.

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 in order to maintain yields, while allowing non-crop plants 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 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 is the basis of integrated weed management (IWM), where techniques such as rotation, 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 if all other methods have failed. This is often called the "many little hammers" approach (Liebman & Gallandt, 1997). While herbicides are part of the IWM approach / weed management pyramid, the use of synthetic (xenobiotic) herbicides are not covered in this report and only natural (eobiotic) herbicides are discussed. The metaphor has even been extended to say that using "many little hammers", a farmer can keep on top of weeds without resorting to the chemical "wrecking ball" of blanket use of broad-spectrum pesticides. This helps create a higher biodiversity system where beneficial ecosystem processes are allowed to function.

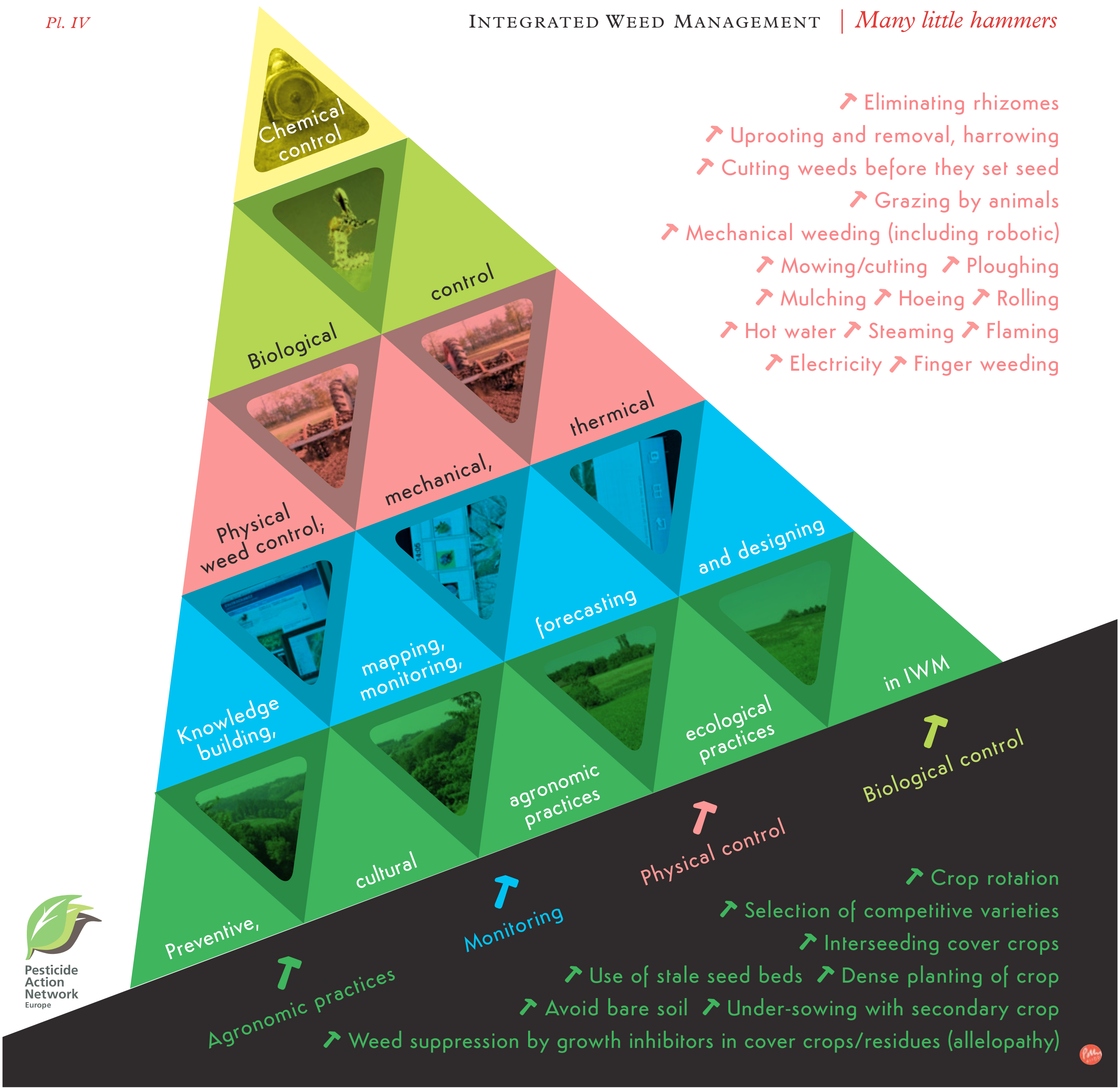


Figure 5. The Integrated Weed Management pyramid. Building from bottom to top

The practices of weed management can be divided in four parts (the IWM pyramid; see Figure 6):

- Monitoring - observation and identification of weeds, assessment of potential value or harm
- Physical control
- Biological control

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

The foundation of the weed management pyramid is preventative measures, typically system or whole farm techniques such as rotations, including those that mix arable cropping and livestock phases. Good hygiene practices, for example ensuring 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 theoretical and empirical 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 by the producer, so they know 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 xenobiotic herbicides, be considered.

Figure 6 illustrates an example of an integrated weed management approach for vineyards.

Figure 6. Integrated Weed Management approach plan in vineyards

7.1 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, use of cover crops / green manures, management of soil quality (e.g. avoiding compaction), land preparation (surface working vs. deeper ploughing), fertiliser / nutrient management and application (e.g. banding of nutrients), crop species and cultivar (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"[20] on the soil surface to be predated), etc.

All these cultural techniques are preventative - they are not about controlling weeds that have already become established, but rather they prevent the weeds establishing themselves in the first place. In addition, as in many other aspects of farming, prevention is much better than cure: it is often much more effective and much cost-effective than interventional techniques to kill already well-established weeds.

"

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, rather than controlling the weed flush resulting from a large "weed seed rain" event.
- Leave less open soil for colonisation by weeds - cover crops, undersowing and tighter row spacing can all be used to reduce the space available for establishment of weed seedlings.

"

7.1.1 Crop rotations

Rotations are one of the oldest and most effective cultural controls to manage weeds. At 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 control (Snapp et al., 2005). They are even more valuable for pest and disease control, particularly soil borne pests and diseases. They are also vital for maintaining soil quality, by ensuring a wide diversity of plant residues / or-

[20] The production by annual plants of a huge number of seeds; one plant can produce thousands of seeds.

ganic matter is returned to the soil. Moreover, where leguminous plants are grown in rotation as crops or as green manures, they boost soil nitrogen reserves, thanks to nitrogen-fixing bacteria that form a 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 control weeds by introducing spatial diversity to arable 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 so much. If the same crop is grown year after year on the same land parcel, then the populations of those pests will accumulate year-on-year until they become unmanageable. By rotating crops, weeds that thrive in one crop will be suppressed by the next crop, 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 arable crops and temporary grassland with livestock is so effective because exceptionally few weed species can thrive in both arable and grassland cropping systems.

7.1.2 Cover crops / green manures

Cover crops are 'non-cash' crops. They are also called green manures when they are a nitrogen-fixing species. They are not grown to be harvested and sold (a cash crop): rather, they are ploughed into the soil to increase soil organic matter. This firstly allows topsoil and humus to be created, which increases the retention and availability of many nutrients to the following crop. Secondly, when leguminous cover crops are grown, this fixes nitrogen in the soil and improves soil quality, as well as helping control pests, diseases and weeds.

Cover crops is a huge topic in itself (Sustainable Agriculture Network, 2007) and they are useful in weed management in many ways. For example, short term cover crops of two to three months duration can be used to allow a flush of weed seed to germinate, but these weed seedlings are soon out-competed by the cover crop, which is also 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 cover 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.

7.1.3 Mixed cropping and under-sowing

Mixed cropping, also known as polyculture, inter-cropping, under-sowing or co-cultivation, is a method that involves planting two or more plants simultaneously in the same field, so that the properties of one plant facilitate the growth of the other. Benefits of mixed cropping include the legume supplying nitrogen to the non-legumes in a mixture, suppression of weed germination and growth, suppression of insect pests and plant diseases and an increase in overall productivity. Suppression of weed germination is typically due to the shading of the soil by crop foliage, but it can also be through allelopathy, where the crop puts out allelochemicals that directly inhibit seed germination. Indeed, suppression of weed growth can be due to both aboveground competition for light and belowground competition for resources such as 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 polyculture 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 cover crops underneath the main cash crop, typically with the sowing of the cover crop delayed for several weeks, to allow the cash crop to be sufficiently established that the cover crop does not compete with it and reduce yield. When the cash crop is harvested, the cover 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 plough after the harvest of the cash crop because the under-sown crop is already developed, and is often used to establish temporary grassland. This technique also reduces the time between the crops to zero, cutting out erosion from ploughing or exposure of bare soil, so it is also better for soil communities. 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).

7.1.4 Crop competition

For both grassland 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 a number of approaches. Firstly, the breeding and use of cultivars that are more competitive, for example ones that grow taller or have a horizontal canopy structure that shades the soil quicker (Andrew et al., 2017). For allelopathic crops, cultivars can vary significantly in the amount of allelochemicals they produce, and more strongly allelopathic cultivars can have a significant competitive edge. Secondly, density of sowing, which can be highly variable, can have a large effect: using higher densities, e.g. an extra 10-20%, 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, will also increase crop competitiveness.

7.1.5 False and stale seedbeds

False and stale seedbeds are two related techniques based on three principles. Firstly, around 90% of the weed seed bank (the seeds present in the soil profile) is dormant at any given time, but the 10% non-dormant seeds near the top of the soil profile will rapidly germinate given the right conditions. Secondly, tillage / cultivation is the most effective way to trigger weed seeds to germinate by bringing them higher up in the soil profile. Thirdly, and most critically, most seeds of crop weeds can only emerge from the uppermost two to five centimetres of soil; if the seeds are any deeper, their energy reserves become exhausted before they reach the soil surface.

Both techniques create an optimum planting tilth (prepared surface soil), which must include sufficient soil moisture. Then, crop planting or sowing is delayed for one to three weeks to allow the non-dormant weed seeds to germinate. In the false seedbed technique, the weed flush (rapid germination of weed seeds) is killed by specialist tillage equipment that only ploughs the top two to four centimetres of soil, while achieving a 100% weed kill. For stale seedbeds, the crop seeds are drilled into the soil among the emerging weeds, which are then killed with a thermal weeder (either a flame or steam weeder), 12 to 24 hours prior to crop emergence (Hooks et al., 2014, Merfield, 2015).

Both techniques are very powerful as they can rapidly deplete the weed seed bank that is able to emerge, and manage both the inter-row and the more difficult to control intra-row weeds. Using false seedbeds is an exceptionally valuable but highly underappreciated weed control technique, because it uses inexpensive tillage, both in terms of the capital cost of the machines and the low cost and high speed of the work. However, results can limited by farmers failing to carry out the second tilling correctly by ploughing too deep (i.e. deeper than 4 cm), risking to bring up additional dormant seeds into the active germination layer of the soil or to damage the crop.

7.2 In-crop weed management

Many farmers and growers new to non-chemical weed management erroneously continue to 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 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. In-crop weed management should therefore be viewed as the icing on the cake of weed management, not the cake itself. Any farmer that believes non-chemical weed management starts at crop establishment is unlikely to be successful.

7.2.1 In-crop weeders

Thanks to organic agriculture having prohibited the use of xenobiotic herbicides (and pesticides) in the 1960s, there is now a plethora of weeding machinery that has been developed to meet the weed management needs of organic producers and these are now available for all farmers and growers to use. Indeed, there are so many machines that it can be confusing for producers new to non-chemical weeding as to what weeders they need for the job. However, just as herbicides have different "modes of action", the same is true of weeding machinery. Understanding the different modes of action of the various types of weeder, what they can and cannot do, allows farmers and growers to identify easily 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.

7.2.2 Weeding machinery classification

In-crop weeders are classified into two main types: Contiguous and incontiguous (Figure 7).

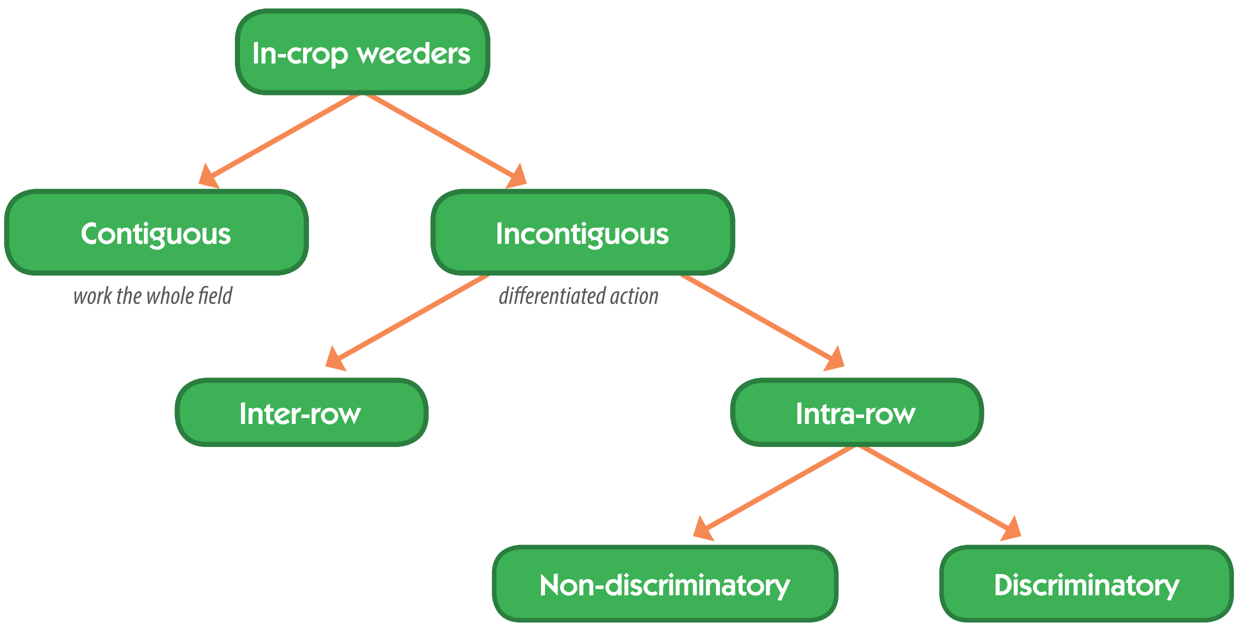


Figure 7. In-crop weeder classification / hierarchy

Contiguous weeders work the entire field surface and are also called 'broad acre' weeders. Incontiguous weeders have gaps for the crop to pass through. The inter-row hoe is the classic example of this type of machine, where the inter-row space is vigorously hoed while the crop row is untouched. However, modern incontiguous machines often also have tools for weeding the intra-row. These are in turn divided into two types: non-discriminatory weeders apply the weeding action to crop and weeds alike and are therefore comparable to the contiguous weeders (see below for more detail), while the discriminatory weeders have a sensor to determine crop from weeds and then only apply the weeding tool to the weeds (Figure 7).

Contiguous weeders

As contiguous weeders weed the whole soil surface both crop and weeds alike, the crop must therefore be able to survive or 'resist' 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 crop, which kills the weeds while the crop survives. Contiguous weeders are mostly used in grass and arable crops, especially those sown with row spacings less than 20 cm, although some can also be used in hardier vegetable crops.

Picture 2. Spring tine weeder.

Spring tine weeder

The spring tine weeder is the original contiguous weeder and the most versatile (Picture 2).

The concept 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 are easy for the tines to pass around.

The machine is highly flexible with a number of 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 setting that allow it to be used for final tillage passes. The weeders also come in a wide range of widths, from the width of a tractor up to around 20 m wide, comparable in size to many agrichemical boom sprayers. The ability to work at speed (e.g. greater than 10 km/h) means they have a substantial work rate. They can also be fitted with pneumatic seeders, allowing the broadcasting of smaller grains, which makes them an ideal tool for establishing temporary grassland and particularly under-sowing cover crops.

Rotary hoe / spoon weeder

The rotary hoe, also called a spoon weeder, is another well-established tool, especially in North America (Picture 3).

The rotary hoe consists of two rows of spoked wheels, with the ends of the spokes bent backwards slightly and flattened into a spoon shape, hence the name. They work by picking up small cones of soil, which are thrown in the air, burying and breaking some weeds as they hit the ground. The amount of soil directly impacted by the tool is lower than the spring tine weeder that can affect the whole field surface, so the weed kill of the rotary hoe is generally lower, but its key advantages are that it can work in crop residue, harder packed soils and moist soils that would defeat a spring tine harrow. In turn it is defeated by stony soils as these blunt and wear out the spoons.

Picture 3. Rotary hoe or spoon weeder

Picture 4. Aerostar Rotation *(photos Einböck GmbH & CoKG)*

Aerostar Rotation

The 'Aerostar Rotation' is a new machine produced only by Einböck (Picture 4).

It is a variation on the spring tine weeder, in that it has vertical tines, but, these 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. However, it should not be considered an alternative to the spring tine weeder. Rather, they are complimentary 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 more delicate crops.

Combcut®

The Combcut® is another recent and entirely novel weeding approach (Picture 5).

The Combcut® is based on a series of forward pointing, dagger-like knives arranged like a comb, that cut the weeds while the crop slides between them unharmed. It is therefore almost exclusively used in monocotyledonous arable crops and in grassland against dicotyledonous weeds. It is also different from the previously mentioned contiguous weeders and nearly all incontiguous weeders in that it does not engage with or work the soil. 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 boot stage (reproductive stage when the grain begins to develop the flower head), when the weeds have thicker stems. After the crop enters the boot stage there is a risk of cutting the crop's flower stems, so at that point the weeder should be used to cut off the weeds above the top of the crop. As it does not kill the weeds entirely, the main effect is to set back the weeds so the crop can out-compete them and to cut off weed flowers or seed heads to prevent weed seed rain.

Picture 5. Combcut® (photos Just Common Sense AB)

Electrothermal weeders

Contiguous electrothermal weeders are a 'back to the future' technology, as although it originated in the late 1800s, it is only in the last few years that it has become more popular. The technology works by passing high voltage electricity down the plants' foliage, through the hypocotyl (stem of an embryo plant between the seed leaves/cotyledons and the root) and into the roots and then into the soil. This means electrothermal weeding has a systemic mode of action, like glyphosate, as it destroys the hypocotyl and the top of the root system, thereby killing the whole plant. But unlike glyphosate, it can also be a very selective systemic weedkiller where the weeds are taller than the crop, as the electricity does not easily jump from the treated plant to its neighbours and so only targeted plants are killed. Electrothermal weeding is used in a similar fashion to the Combcut® in that it is used later in the crop's life rather than early on, as for the spring tine weeder, rotary hoe and Aerostar Rotation. However, unlike Combcut® that works in the crop and so can cut weeds shorter than the crop, contiguous electrothermal weeders can only work with weeds that are taller than the crop. Nevertheless, unlike Combcut® that only sets back the weeds, electrothermal treatment kills them outright.

Incontiguous weeders

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

Parallelogram inter-row hoes

The design of the parallelogram inter-row hoes has reached an optimum, based on a tractor-mounted toolbar upon which multiple parallelogram units are mounted with tool frames; on these are clamped the weeding tools (Picture 6). This design permits very wide machines (15 meters on a single toolbar, more on multiple toolbars), while allowing the weeding tools to be kept at a very accurate depth (± 1 - 2 cm) even in uneven fields. It is also highly customisable and many different tools, both for inter-row and intra-row weeding, can be clamped to the tool frames. Therefore the parallelogram inter-row hoe is not so much a single weeding tool, it is more of a platform on which to mount many different tools. This versatility is reflected in the fifty or more different manufacturers that make parallelogram inter-row hoes.

For inter-row weeding there are a wide range of hoe designs, most of which are based on a steel blade cutting horizontally through the soil (Picture 7).

To control weeds in the intra-row there are an ever growing range of non-discriminatory weeders for parallelogram inter-row hoes. The most effective of these is the 'mini ridger' (Picture 8) which creates a small ridge of soil in the intrarow, just sufficient to bury the weedlings under one to two centimetres of soil, while leaving the crop protruding (Merfield, 2014).

Germinating seedlings can grow through many centimetres, even decimetres, of soil from the place they are buried as a seed to reach the soil surface. However,

Picture 6. Parallelogram inter-row hoe

Picture 7. Inter-row hoe blades. Left to right: duck or goose foot, A blade sweep, L blade hoe, T hoe

Picture 8. Mini-ridger blades

once they have emerged and put out their cotyledon leaves, they loose this ability to push up through the soil and just a centimetre or two of soil cover will kill them. Clearly this technique requires the crop to be larger than the weeds, but this is often the case, both for the quick-growing, large-seeded arable crops and particularly transplanted vegetables. To create the ridges, the bar or blade is moved through the soil and the excess soil flows over the top of the bar; so the height of the ridge can be precisely controlled by mounting ridger blades at different heights.

A highly complementary tool to mini-ridgers is the finger weeder (Picture 6). 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 are a wide range of designs to suit just about any crop, even trees, with the fingers made from hard materials such as metal and plastic, through to softer materials such as rubber and even brushes. When used with the mini-ridger, the finger weeder can be used to pull the ridge down, covering and killing any remaining weeds. In this way, a weed kill is achieved by first moving through the soil to build up the ridge and secondly when it is pulled down. Potatoes are often weeded in this way.

Further tools include the torsion weeder which uses sprung steel bars to break up the soil in the intra-row thereby breaking and uprooting weedlings. There are a number of tools based on thin vertical wires that rake through the intra-row, which are particularly valuable for upright, monocotyledonous crops such as maize, leeks, onions, etc. These vertical wire weeders can be either ground-driven using angled, spoked wheels, like a miniature Aerostar Rotation wheel (Picture 4) or engine-powered machines with many wires.

Picture 9. Horizontal axis brush hoe

Brush weeder inter-row hoe

Beside the very popular parallelogram inter-row hoe, there are a number of other inter-row 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 (Picture 9).

The brush 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 also achieves a high weed kill rate in wet soils and with larger weeds that would challenge and even stop other inter-row 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.

Picture 10. Basket weeder

The basket weeder has a similar approach to the brush weeder but uses a cylinder of wire cages instead of the brush hoe's brushes, with gaps for the crop rows (Picture 10).

Yet unlike the brush hoe's single brush which is powered from 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 so less expensive than the brush hoe, making it ideal for smaller producers. In addition, it 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 as the brush hoe at penetrating the soil and stones bend the bars, while the brush hoe can cope with the stoniest of soils.

The final common inter-row hoe design is the vertical axis powered tine weeder (Picture 11).

This has tines on small rotors that spin round in the soil, with an aggressive weeding action, meaning they cut through hard-packed soil and can kill larger weeds. Their main disadvantage is that their mechanical complexity makes it difficult to adjust row spacings. In addition, while they can handle pebbly soil, stones tends to be caught between the tines and shields and may cause damage to machine and crop.

Picture 11. 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. Before 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 (Picture 10). With a skilled operator these approaches could be guided very accurately, but the job requires high levels of continuous concentration, which is hard on staff: There is a limit to human reaction speeds and strength which limits vehicle movement speeds and machine size. Computerisation has created a massive 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. Then exceptionally sophisticated computer programmes and algorithms determine the location of crop row and position the weeder to match. The GPS systems use real time kinematic (RTK) technology, which increases the level accuracy of standard GPS from metre to centimetre level accuracy. This is used to automatically steer the tractor, and in some cases both tractor and weeding tool are independently steered, giving exceptional accuracy. When the crop is drilled using GPS, the system is 'blind' to the crop's location; it simply works to a pre-determined line. However, the vision systems follow the crop row, so there must be sufficient crop visible for them to line up and work. Both systems have pros and cons, and larger farming operations may well run both GPS and computer vision systems. The computer vision systems have also created a further revolution by allowing discriminatory intra-row weeding.

Discriminatory intra-row weeding

Once computer vision systems had been developed to identify crop rows, the logical progression was to identify individual crop plants, and then hoe the weeds around each plant. These systems are mostly used in transplanted vegetables, as they have larger intra-row distances between the individual plants. Top of the range machines such as the 'Robovator' can operate at speeds of up to 8 km/h and working widths of up to 12 meters (Picture 12).

A combination of computer-guided inter-row hoes and both computer vision based discriminatory intra-row weeders and mechanically based non-discriminatory intra-row weeders can achieve exceptional weed control. This control is as good, if not better, than herbicides, over large crop areas with high work rates and low costs.

Picture 12. K.U.L.T. Robovator (photo K.U.L.T.)

Robotic weeders

The logical end game for computer vision systems is fully autonomous weeders, i.e. robots. The concept of weeding robots has been around almost as long as robots have, but 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, weeding robots have moved from very expensive research projects to robots that are economically and practically viable on-farm (Picture 13). However, currently the cost and work rate mean that in most situations, non-robotic options are still the most economic and effective. However, it is expected that the technology will continue to improve at a rapid rate, and that in the next decade or so, robotic weeders will come to have an important role.

Picture 13. Weeding robot

7.2.3 Thermal weeding

Thermal weeding refers to weed control technologies that use heat or cold to control weeds. Nearly every conceivable means of thermal weeding has been tried, including lasers, microwaves, liquid nitrogen, carbon dioxide snow, focused sunlight, etc., but the only ones that have proved practical, safe and economic are flame, steam and electrothermal weeding techniques. 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 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 7.1.5) to kill weedlings between the cotyledon and two true leaf stages, 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 do not compete well against weeds, such as carrots and onions. Flame weeders for implementing stale seedbeds typically consist of a shield or hood under which the flames burn, which keeps the heat close to the soil to maximise heat transfer and protect the flames from the wind (Picture 14).

Picture 14. A bed flame weeder for stale seedbeds

Selective flame or steam weeding

The next most common use of thermal weeding is selective intra-row flame weeding in established annual row crops such as cotton, soybean and maize. This is where the flames are directed at the stem of well-established plants where they exit the soil (Picture 15). The crop survives as the stems are thick enough or have a thick bark so they can withstand the heat, but the smaller weeds are either killed or defoliated, which sets them back and allows the crop to out-compete them.

The same technique as above is also used in perennial crops (Picture 16), but steam is generally used preferentially over flames. Steam has a much lower fire risk and provides more rapid heat transfer, due to latent heat of condensation, and it can operate better in windy and wet conditions. Some machines can be used to weed over plastic and even paper mulches without causing damage (Schonbeck, 2012).

Another approach to intra-row weed control is used on specific direct-seeded crops at early stages of growth. Called post crop emergence bed flaming, it is based on the ability of some crop species to be resistant to foliar thermal weeding, such as the monocotyledons, including 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 and yields are unaffected.

In situations where controlling inter-row weeds using mechanical means is difficult, e.g. the soil is too wet, flaming can be used on the inter-row weeds (Picture 17).

Picture 15. Selective, intrarow flame weeder working in sweetcorn

Picture 16. Weed control using steam

Picture 17. Inter-row flamer

Electrothermal weeding

Like flame weeding, electrothermal weeding has been around since the end of the 1800s, but was overtaken by herbicides in the 1940s. Given the current problems associated with herbicides, it is undergoing a resurgence. It works by applying a high voltage (5,000 to 15,000 V) to the plants' foliage, which then travels down the stem, through the hypocotyl into the roots and then back to the weeder via the soil. Like steam and flame, the electrical current heats the water inside the plant cells, turning it into steam, which destroys the plant from the inside out. However, unlike flame and steam which can only kill plant foliage because it takes much greater amounts of energy to heat the soil, electrothermal treatments can kill the hypocotyl and top of the root system. This achieves a systemic weed kill like glyphosate. In addition, where the weeders are taller than the crop, the electricity can be applied only to the weeds, leaving the crop unharmed, thus achieving a selective weed kill. Additionally, because electrothermal only heats the water inside the plant and nothing else (unlike flame and steam that heat the air which then heats the weed), it is over an order of magnitude more energy efficient. For example, electrothermal weeding has a typical energy output of 10 kW per metre width, while bed flame and steam weeders have heat outputs of 200 to 400 kW per metre width.

With these attributes, electrothermal weeding is a very powerful technology. Firstly, it can be used to kill all existing vegetation, like glyphosate is used for non-till and min-till systems. In grasslands, most of the weeds are taller than the pasture species, especially after grazing, so electrothermal weeding can be used to systemically and selectively them without killing the grassland. In both arable and vegetable cropping systems, there are a range of weeds that end up growing higher than the crop, often the last few weeds that escaped previous management techniques; electrothermal weeding can be used to kill them, to prevent them going to seed. It can also be used at a great range of scales, from backpack versions equivalent to a knapsack sprayer for spot treating individual weeds, through to large machinery-mounted versions that can be used to kill scrub / woody weeds.

Use of fossil fuels

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

Another concern with thermal weeding is harming soil biology, but due to the enormous thermal mass of the soil, the weeders only raise the temperature of the top few millimetres of soil by tens of degrees Celsius for a few tens of seconds. Direct radiation from the sun on a hot day heats the soil to a much higher temperature, to much greater depth, and for much longer. Other farm activities, such as ploughing / tillage cause much greater damage to soil biology.

7.2.4 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, and biological sheet mulches include paper and bio-plastics. Most sheet mulches are made of plastics, mainly polythene.

Sheet mulches work by creating a physical barrier to the weeds, and are typically light-proof, so they kill the weeds by preventing them photosynthesising, i.e. sheet mulches can kill established weeds. Sheet mulches also alter the soil environment and can inhibit weed seed germination. Particulate mulches also work by changing the soil environment, so that the weed seeds do not receive the environmental cues that trigger them to germinate. They therefore need to be sufficiently thick, typically a minimum of five centimetres. They therefore 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.

Using plastic mulches has the disadvantage of needing to dispose of the plastic once it has been used, but because it is contaminated by soil and plant material, many plastic recycling facilities will not accept it (Ngouajio et al., 1991). There is also the risk that the soil and adjacent habitats become contaminated with such single-use plastics. On the other hand, particulate biological mulches decompose, so they 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).

7.3 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 weed control approaches:

- Classical biocontrol, where an exotic bio-control agent (BCA) is introduced to control an exotic weed or pest;
- Augmentative, which is sub-divided into:
  - Inundative, where very large amounts of the BCA is applied to the weed or pest;
  - Inoculative, where the BCA is inoculated introduced into the weed's or pest's environment and multiplies to levels that control the weed or pest;
- Conservation, where the environment is manipulated to benefit the naturally occurring BCA of the weed or pest, so that the BCA can then control the weed or pest.

Globally, classical biological control has achieved some remarkable successes, completely solving apparently intractable weed problems, such as the elimination of prickly pear cactus (Opuntia stricta spp.) in Australia by the Cactoblastis cactorum caterpillar. However, as Europe is part of the continental landmass of Eurasia, and also close to Africa, there is a large natural traffic of both weeds and their pests. This means that the number of exotic plants introduced in to Europe 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). In addition, classical biocontrol has significant risks associated with it, as there are many examples from history where the introduced BCA has turned into a pest itself, causing significant ecological disturbance (Zimdahl, 2013). However, host specificity testing is now a well-developed science, and few modern introductions have had unforeseen effects. While the number of exotic pests weeds in Europe is limited, some, like Japanese knotweed (Fallopia japonica), are particularly problematic (analogous to the prickly pear in Australia) and would be ideal candidates for classical biocontrol, so more research should be focussed in this area.

Inundative biocontrol typically involves applying a microorganism to the pest in large volumes, often by spraying, although insects are also applied inundatively. Inundative control for insect pests and plant diseases is an increasingly valuable tool, and is starting to replace agrichemicals as the pests and diseases develop resistance and social and legislative changes see their use restricted. The advantage for insect control is most microbial BCAs are highly specific and will only kill a specific species or narrow range of species, so that beneficial species are unharmed. However, for weeds, this specificity is a problem as any given crop or pasture often has dozens of weed species, so a BCA would be required for each weed. Also, if were there broad-spectrum weed biocontrol agents, they would also 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 product. Likewise, for inoculative biocontrol of weeds, finding a BCA for weeds that is suitable for such an approach has been a significant challenge (Lundkvist & Verwijst, 2011).

In addition, there has been no conservation biocontrol of weeds, as has been done for insect pests. For example, floral resources (pollen and nectar) are provided, which boost the longevity and fecundity of an existing BCA so that it is then able to reduce the pest population below economically damaging 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.

7.4 Weed management by livestock

Animal grazing is a traditional and valuable method for physical control of weeds. While the use of animals for weed management is still widely practiced 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. 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 control is part of a mixed rotation of grassland and arable crops. As discussed in section 7.1.1, few arable weeds can survive in pasture and likewise pasture weeds seldom thrive in arable cropping systems. Arable weeds are often highly palatable to livestock, with common names such as 'fat hen' / lambsquaters (*Chenopodium album*) and 'chickweed' (*Stellaria media*) illustrating the point.

Pigs (Picture 18) are very good in controlling the growth of weeds and grass, and cleaning up dropped apples in orchards, and therefore are commonly used for vegetation control 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, not just for removing weeds and controlling grass and canopies in place of machines, but also because sheep dung is a good fertiliser for the soil. Sheep should obviously be prevented from eating the grapes, and one way to do this is with nets (Picture 19).

Picture 18. Pig feeding on apples dropped during harvest

Picture 19. Sheep grazing in vineyards with a protective net

7.5 Eobiotic herbicides

Eobiotic refers to substances that is endogenous to an ecological system. Eobiotic herbicides are therefore made with ingredients extracted directly from plants or animals, or microbial synthesis, e.g. vinegar, as opposed to being produced synthetically i.e. xenobiotic. A range of eobiotic materials have been tried for weed control, including plant oils such as pine, cypress, cedar, manuka, eucalyptus, red clover, clove, lemongrass, cinnamon, mint, rosemary and sage. Allelopathic maize and mustard seed mixes, fatty acids derived from plant oils including pine, coconut and rape seed, and concentrated organic acids including acetic acid and citric acid have also been researched. Being eobiotic, they are biodegradable and leave no residues. However, all of them are general biocides so they do not just kill weeds, but they may well impact non-target species as well. Thus, in the interest of preserving species beneficial to the faming system, eobiotic herbicides should be used as a last rather than a first resort.

Nevertheless, there is an urgent 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.

08
Economics of banning glyphosate

The pesticides industry and most farming organisations across the EU claim that a ban on glyphosate will be catastrophic for the EU farming sector because there are no affordable alternatives. The previous chapters describe that alternative practices to glyphosate use already exist and provide a list of many well-developed methods. In this section we wish to look into the potential economic costs of an agricultural model without the use of glyphosate (mainly replaced with non-chemical techniques).

Apart from the supposed evidence brought to the discussion by the pesticide industry, the quality and impartiality of which are often highly questionable[21], two recent interesting scientific papers provide another insight on the costs of banning glyphosate:

- The first study (Kehlenbeck et al., 2016) on the 'Economic assessment of alternatives for glyphosate application in arable farming' studied the technique of crop rotation in German arable farming for winter wheat, winter oilseed rape, winter barley, maize and summer barley and different tillage systems (plough, no-plough). The report concluded that *'The economic advantages and disadvantages of substituting glyphosate by mechanical alternatives were strongly dependent on the treatment-area, the efficacy concerning yield expectations (in comparison to glyphosate use), the tillage*

[21] PAN Europe is aware of the European Crop Protection Association's report 'Pesticides: with or without' as well as the report from Oxford Economics. Findings in these reports are based on two controversial reports written some years ago: the Anderson and the Humboldt reports, both economic studies based on extrapolation of questionable datasets. PAN Europe already showed the Humboldt report was based on incorrect assumptions: http://www.pan-europe.info/sites/pan-europe.info/files/public/resources/briefings/pan-europe-opinion-on-humboldt-report-2013.pdf

system, the necessity of grain drying as well as further operational factors such as the availability of sufficient field work days and mechanical equipment.' Note the use as a ripening / drying agent, which is not weed management, was also included.

- The second study (Böcker et al., 2017) on 'Modelling the effect of a glyphosate ban on weed management in maize production' develops a bio-economic model looking into replacing glyphosate applied before sowing with mechanical techniques, 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'.*

While none of the studies describe any catastrophic impact on EU agriculture, both studies do argue that the shift to agronomic and physical methods will increase the workload in the fields.

In the economic calculation that farmers have to make in a transition towards low impact farming (especially in reducing dependency on herbicides), the following issues should be considered:

- Many weeds do not compete with agricultural yield and therefore do not need to be removed/controlled (Andreasen et al, 1996).
- Non-crop plants in the field deliver positive ecological services useful for farming over time (Sengonca et al, 2002; Blaix et al, 2018; Storkey et al, 2018).
- Weeds can give farmers information about their soil, so can be used as soil indicators, as well as protecting against erosion (Hill et al, 1977).
- Glyphosate and its metabolite AMPA persist in soil, leading to soil pollution (Silva et al, 2017). Studies suggest that this alters soil community composition, which alters soil nutrient bioavailability and nutrient balance (Bai et al, 2016).
- Plants need healthy soils to be protected from pathogenic microorganisms (bacteria, fungi). The use of pesticides in agriculture strongly disrupts soil microorganism communities including beneficial species, increasing the presence of pathogens (Mentes et al, 2013).
- The financial costs of buying new machinery and/or increased workers costs etc. could be covered by public funding from within the Common Agricultural Policy (see below).
- There are also costs linked to the legal requirements for farmers hiring workers using pesticides (access to showers, use of protection equipment, health and safety, etc).
- Some argue that the growing demand from organic farmers for non-chemical weed control over the last decades has resulted in research into new mechanical tools (Van der Weide et al, 2007). Others argue that there has been a deadlock over the last two decades in developing machines for mechanical weeding, but that the increased debate about glyphosate and the increased attention on non-chemical weed management within the European Innovative Partnership on Agricultural Productivity and Sustainability will change this (see point 8.2).

Key ideas of the BHU Future Farming Centre, Permanent Agriculture and Horticulture: Science and Extension

With Chemical Weed Management, most of the skill and knowledge lies with the biochemist - farmers and growers just follow the instructions.

With Non-Chemical Weed Management (NCWM), most of the skill and knowledge lies with the farmer and grower.

Effective NCWM is impossible if you don't understand weeds /plants and how they interact with their environment.

Other reflections inspired by the same institute:

What is a weed?

Types of value judgements

- In farming - mostly economic
- In amenity - aesthetic
- Lived environment - hazardous
- In the natural environment - native vs. exotic

Judgements on right or wrong, good or bad are the domain of ethics, not science.

Therefore a weed is NOT a scientific, biological or ecological concept.

Conclusion:

Non-chemical weed management shifts the possession of knowledge from the biochemist to the farmer and grower, so the latter need some significant up-skilling but this also allows them to start working with nature again.

In the economic calculation that society has to make, one should bear in mind the following issues, often excluded from any economic calculations:

- The health impacts of heavy use of pesticides on workers and bystanders including communities living adjacent to farmland.
- The pollution of water[22] and soil resources as well as damages to the environment, particularly contribution to loss of biodiversity[23], up to local and regional extinctions and over-simplified ecosystems and decreased ecosystem functions.

[22] e.g. Masiol et al, 2018 https://www.ncbi.nlm.nih.gov/pubmed/29948720

[23] e.g. Ogeleka et al, 2017 https://www.tandfonline.com/doi/abs/10.1080/02757540.2017.1320393

8.1 European research into non-chemical weed control

Since the 1960s, the European Weed Research Society (EWRS) has been promoting and co-ordinating scientific research into all aspects of weed science, including publishing the international 'Weed Research' Journal of Weed Biology, Ecology and Vegetation Management.[24]

The EWRS's oldest working group on physical and cultural weed control is especially relevant for the debate on non-chemical herbicides: http://www.ewrs.org/pwc/.

8.1.1 EU financed Research into non-chemical weed control

The strategic approach to EU agricultural research and innovation[25] for the period 2014-2020 has one priority (Priority 3) focused on 'Integrated ecological approaches from farm to landscape level', aiming at providing the groundwork for better understanding of ecosystem services and fully using their potential for boosting primary production. It allows researchers to explore the role of functional biodiversity (pollinators, predators of pests, symbionts, etc.) in delivering ecosystem services to increase resilience at farm and landscape levels to biotic and abiotic threats.

8.1.2 EU-financed projects within Horizon 2020 of interest to non-chemical weed control

OK-net arable: http://farmknowledge.org

This project started in 2015 and ended in 2018. Based on scientific literature and input from farmers, it has collected practical information and generated more than 150 publications giving solutions for improving organic arable crop systems, including solutions for non-chemical weed management. All materials have been brought together on the farmknowledge platform (farmknowledge.org)

IWMPRAISE: https://iwmpraise.eu

The project started in 2017 and has been granted 6.6m Euro to support and promote integrated weed management (IWM) in Europe. Weed management in Europe will become more environmental friendly if the concept of integrated weed management becomes better established on European farms.

In addition, specific companies, like Weedingtech has received funding within Horizon2020 for the development of non-chemical weed control[26].

[24] http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1365-3180/issues
[25] https://ec.europa.eu/programmes/horizon2020/sites/horizon2020/files/agri_strategypaper_web_1.pdf
[26] http://ec.europa.eu/regional_policy/en/projects/united-kingdom/foamstream-effective-weed-control-without-the-chemicals

8.2 European Innovation Partnership for 'Agricultural Productivity and Sustainability'

The European Innovation Partnership for agricultural productivity and sustainability (EIP-AGRI) has been launched in 2012 to contribute to the Innovation Union flagship initiative under the European Union's 'Europe 2020' strategy for smart, sustainable and inclusive growth.

This strategy sets out actions to strengthen research and innovation as one of its five main objectives and supports a new interactive approach to EU research and innovation: European Innovation Partnerships. The so-called EIP-AGRI is starting to include non-chemical weed control into their work and have organised the following:

Operational groups on organic/non-chemical weed control, for example:

- An EIP operational group was established in Austria on "Organic Dock Control", testing whether docks can be controlled with the help of native clearwing moths instead of using herbicides[27].
- An EIP operational group was established in France on "Zero herbicides in perennial mediterranean crops"[28].

A **focus group** on 'non-chemical weed management in arable cropping systems'[29] was announced in June 2018, and experts have been invited to sign up to it by the following September, with the first meeting in November. The focus group intends to:

- Make an inventory and cluster non-chemical weed management practices in arable cropping systems for the different pedo-climatic zones in the EU;
- Analyse challenges and opportunities regarding the implementation of these practices, notably in terms of reliability and cost effectiveness at farm level as well as their transferability to other conditions (location, type of production);
- Identify key factors (such as knowledge requirements, decision support tools, partnerships) and analyse technical/economic/social barriers related to the adoption of these practices by farmers;
- Analyse the interaction of non-chemical weed management practices with other challenges, such as carbon sequestration, nutrient losses, soil degradation/erosion/compaction and biodiversity;
- Collect good practices and success stories on reducing herbicide use from different European areas, taking into account experiences of farmers and advisers as well as the findings of potential innovation activities carried out by EIP-AGRI Operational Groups and research projects in this field;
- Propose potential innovative actions and ideas for Operational Groups to stimulate the use and improvement of non-chemical weed management;
- Identify needs from practice and possible gaps in knowledge concerning non-chemical weed management which may be solved by further research.

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

[28] https://ec.europa.eu/eip/agriculture/en/find-connect/projects/z%C3%A9ro-herbicides-en-cultures-p%C3%A9rennes

[29] https://ec.europa.eu/eip/agriculture/en/focus-groups, see group number 32

8.3 The Common Agricultural Policy and pesticide use reductions

Since 2009, the European Union has had an EU Directive on Sustainable Use of Pesticides (Directive 2009/128/EC), which provides for a range of actions to achieve reductions of pesticide use and dependency by promoting the use of Integrated Pest Management (IPM) and of alternative approaches or techniques, such as non-chemical alternatives to pesticides.

However, as the evaluation report from 2017 states: *Integrated Pest Management is a cornerstone of the Directive, and it is therefore of particular concern that Member States have not yet set clear targets and ensured their implementation, including for the more widespread use of land management techniques such as crop rotation.*

Member States need to develop clearly defined criteria so that they can assess systematically whether the eight principles of IPM are implemented, and take appropriate enforcement measures if this is not the case. Such tools could confirm that the intended outcome of IPM as specified in the Directive, a reduction of the dependency on pesticide use, is being achieved.

It is positive to note that the European Commission states in the report: *'The Commission will support the Member States in the development of methodologies to assess compliance with the eight IPM principles, taking into account the diversity of EU agriculture and the principle of subsidiarity'.*

NGOs such as PAN have argued that an ambitious piece of legislation like the SUDP needs to be fully integrated into big spending programmes like the Common Agricultural Policy (CAP) in order to be successfully implemented, otherwise there will be no incentive for Member States to change the measures they offer or for farmers to change practices.

8.3.1 CAP measures which have the potential to reduce pesticide use and dependency

So far the current Common Agricultural Policy has no holistic approach to encourage famers to reduce pesticide use, and many of the measures attempted have been disappointing. See more details in PAN Europe's analysis 'Why the CAP is broken on pesticide use reductions'[30].

However, as the illustration below shows, there are a number of measures within the current CAP that

[30] https://www.pan-europe.info/sites/pan-europe.info/files/Why%20the%20CAP%20is%20broken%20on%20pesticides.docx.pdf

Member States can already apply now. A few policy tools can be used, especially in the CAP's second pillar, and as can be seen in figure 8 below, a few Member States are already using them to encourage farmers to reduce dependency on herbicides and other kinds of pesticides.

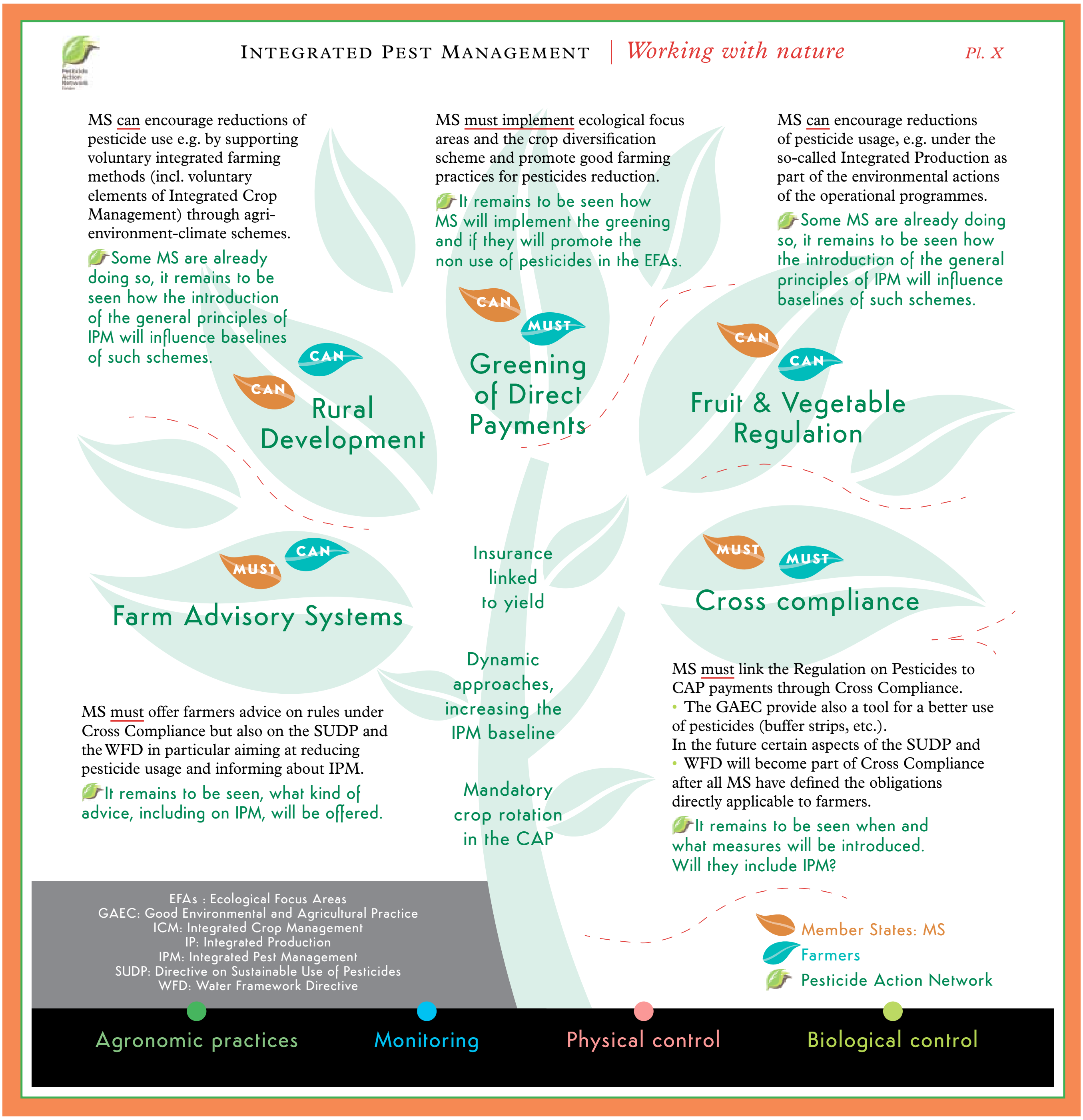


Figure 8. How the current Common Agricultural Policy can encourage pesticide use reductions

8.3.2 The Farm Advisory System (FAS)

Since 1999, all EU Member States have been obliged to set up a so-called Farm Advisory System (FAS) assisting farmers to fulfil legislative requirements, especially those relating to the environment[31].

As part of the 2013 reform of the CAP, this baseline was updated and Member States have been obliged as from January 2015 to advise on Integrated Pest Management, as called for in article 55 of the pesticide regulation (EC) 1107/2009 and article 14 of Directive 2009/128/EC on the sustainable use of pesticides.

However, while the FAS has a huge potential to develop independent advice, the actual implementation remains very limited. Only a few Member States, like the United Kingdom[32] have made their FAS visible, by establishing an easy-to-find homepage. Even the Member States who have made some progress are only focusing on how to apply pesticides better, rather that actually promoting uptakes of agronomic and physical alternatives to pesticides/herbicides, thereby tackling reductions in use and therefore dependency, which is the policy goal.

Example of farm advice in a Member State:

UK: The UK have published a clear and easily accessible web portal for farmers, as well as a dedicated helpline, newsletters, publishing guidance and sharing technical articles and events. The Farming Advice Service is funded by the Department for Environment, Food and Rural Affairs (Defra) "to help farmers understand and meet the requirements of Cross Compliance, Greening (the Basic Payments Scheme) and the European Directives on both water protection and sustainable pesticide use." https://www.gov.uk/government/groups/farming-advice-service

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

[32] https://www.gov.uk/government/groups/farming-advice-service

8.3.3 CAP's Rural Development Programmes targeted mechanical alternatives

PAN Europe had asked the European Commission, Directorate General for Agriculture and Rural Development for an overview of of rural development measures encouraging herbicide use reductions.

The European Commission replied (Europe Direct – 101000226804)

"The Directorate-General for Agriculture and Rural Development can confirm that it does not have the information and data mentioned in your enquiry. Nevertheless, we would like to provide information and data which is available and relevant in the context of your enquiry concerning rural development support for pesticides-related objectives.

There are several measures in the framework of rural development which can be used by Member States to address the issue of management and use of pesticides. These are:

- *Knowledge transfer under which trainings on pesticides use can be provided*
- *Advisory services which can advise on integrated pest management can be supported*
- *Investment in physical assets which may grant support for equipment improving the application of pesticides e.g. in terms of safety for the environment*
- *Agri-environment-climate measure where support can be granted to encourage integrated methods of farming, alternatives methods to the use of pesticides etc.*
- *Organic farming supporting conversion and maintenance of organic farming methods*
- *Natura 2000 and Water Framework Directive payments compensating for the restrictions on farming which can include the use of chemical input*
- *Co-operation promoting joint approaches to environmental projects and practices.*

The Agri-environment-climate measure is the main measure to deliver environmental public goods. Unfortunately, the monitoring and indicators systems do not allow to distinguish within this measure the actions specifically linked to pesticides either in terms of surface or financial allocation. However, the figures on surface concerned by management of inputs including integrated production (reduction of both mineral fertilisers and of pesticides) in Member States' rural development programmes can be provided: 16.2 million ha for all MS (see details in annex). Furthermore, it can be of interest to see the programmed overall financial allocation for this measure for all EU-28: almost EUR 16.5 billion (see details in annex). It is impossible to say how much of it is allocated to the specific actions on pesticides use.

While the above information concerns the current 2014-2020 programming period, it can be said that in the period 2007-2013 (based on DG AGRI internal working analysis), the support within agri-environment measure for integrated farming was provided in 38 rural development programmes in 14 Member States. The main management activities supported were those linked to the use of less toxic products, certified seeds, integrated weed and pest control and reduction in pesticide use."

Examples of Member States who within the current programming period 2014-2020 offer farmers financial compensation for the uptake of mechanical weeding under their rural development programmes:

8.3.3.1 Flanders (Belgium)

The Flemish rural development plan[33] states: 'In Flemish agriculture and horticulture, most crops are kept free from weeds with the help of pesticides. However, it is possible to keep certain crops weed-free via mechanical weed control. The elimination of pesticides has an immediate positive effect on the quality of the soil, on the ground and surface water and on the biodiversity of the plot and of its surroundings.

Mechanical weed control is eligible for support if it is applied on a plot of at least 0,5 hectares'.

Their agri-environmental scheme for 2018 offers 260 euro/ha for the uptake of mechanical weeding to replace herbicide use[34].

8.3.3.2 Luxembourg

The Luxembourg government offers 20% co-financing to invest into machinery, while also offering specific agri-environmental support in the form of per hectare payments for wine, maize and potatoes[35].

8.3.3.3 France

The French rural development programme offers financial compensation for growers of cereal (87 euros/ha), protein crops (85 euros/ha), orchards (90 euros/ha) and grapes (96 euros/ha) for training on and implementing reductions of herbicide use.[36]

An evaluation from 2015[37] indicates that the impact of this measure remains less efficient than expected, and that the level of pesticide use reduction is not able to ensure the expected water quality.

[33] http://lv.vlaanderen.be/sites/default/files/attachments/gr_201501_brochure_en_rdp_vrn_21x21_digi.pdf

[34] http://lv.vlaanderen.be/sites/default/files/attachments/fiche_subsidie_mechanische_onkruidbestrijding_-_versie_02102017.pdf

[35] http://www.ma.public.lu/actualites/communiques/2015/07/031/PDR14-20.pdf

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

[37] https://www.st-andrews.ac.uk/media/dept-of-geography-and-sustainable-development/pdf-s/DP%202015%2005%20Kuhfuss%20&%20Subervie.pdf

8.4 The proposed New Delivery Model of a reformed CAP

On the 1st June 2018, the European Commission published its legislative proposals for CAP reform (COM/2018/392 final - 2018/0216 (COD)). The main innovation of this reform approach was the proposal that Member States take more responsibility in fulfilling objectives set at an EU level by drawing up "strategic plans", then work out rules to achieve them.

One of the key elements is that these legislative proposals give much more flexibility to Member States on how to support farmers in the future. However, this approach has been heavily criticised for allowing for lower ambition by the Member States, who would be setting their own targets. It is expected that this would extend to the reluctance of Member States to transition to low impact farming.

Unfortunately, the indicator that the European Commission is proposing as a result indicator for reduction of pesticide use (R.37), is extremely disappointing. It states: *'Sustainable pesticide use: Share of agricultural land concerned by supported specific actions which lead to a sustainable use of pesticides in order to reduce risks and impacts of pesticides'.* Yet measuring area-based schemes that "reduce risks and impacts of pesticides" is not the same as measuring actual reductions in use, or even measuring area covered by schemes that aim to reduce use.

It should be stressed that some practices will form part of a baseline that all farmers in all Member States have to comply with, just as now: This is conditionality, formerly termed as "cross compliance", which was based on existing EU regulations and directives plus good farming practice. To this list of conditions has been added crop rotation, as essential element of IPM; this represents a positive step forward in reducing monocultures and pesticide use.

If Member States, or their farmers, wish to go beyond the baseline to fulfil extra ambition they are free to do so and will be supported by EU funds. This can either be done by authorities designing so called 'agri-environment-climate commitments' in the so called 2nd pillar of rural development (formerly agro-environmental measures) to deliver pesticide use reduction; their farmers would then sign up to these, committing themselves for the longer-term, typically 5 years.

Alternatively, the Commission proposes that funding from the 1st pillar (direct payments) is set aside to fund 'eco-schemes'[38], which could also support farmers to transition to low input, non-chemical systems.

At this stage, the most straightforward aspect in the new legislative proposals towards non- chem-

[38] The factsheet from DG AGRI published on 1 June 2018 explains (http://europa.eu/rapid/press-release_MEMO-18-3974_en.htm): A new system of so-called "eco-schemes", funded from national direct payment allocations, will be mandatory for Member States, although it will be voluntary for farmers to join them. These eco-schemes will have to address the CAP environment and climate objectives in ways that complement the other relevant tools available and go beyond what is already requested under the conditionality requirements. However, it will be up to each Member State to design them as they see fit. One example could be an eco-scheme to fund zero use of fertilisers in order to improve water quality. The payments involved could be offered either as "top-ups" to farmers' direct payments, or as stand-alone schemes whose payment values are based on the extra costs and income losses involved for farmers.

ical weed control is the work of the AGRI-EIP and the reinforced wording on 'Farm advisory services', with recital (24) saying:

Member States should set farm advisory services for the purpose of improving the sustainable management and overall performance of agricultural holdings and rural businesses, covering economic, environmental and social dimensions, and to identify the necessary improvements as regards all measures at farm level provided for in the CAP Strategic Plans. These farm advisory services should help farmers and other beneficiaries of CAP support to become more aware of the relationship between farm management and land management on the one hand, and certain standards, requirements and information, including environmental and climate ones, on the other hand. The list of the latter includes standards applying to or necessary for farmers and other CAP beneficiaries and set in the CAP Strategic Plan, as well as those stemming from the legislation on water, on the sustainable use of pesticides, as well as the initiatives to combat antimicrobial resistance and the management of risks. In order to enhance the quality and effectiveness of the advice, Member States should integrate advisors within the Agricultural Knowledge and Innovation Systems (AKIS), in order to be able to deliver up-to-date technological and scientific information developed by research and innovation.

09
Policy relevance

9.1 The European Citizens' Initiative to 'ban glyphosate and protect people and the environment from toxic pesticides'

Citizens' awareness around glyphosate is illustrated by the sheer speed at which the #StopGlyphosate European Citizens' Initiative (ECI) fulfilled the requirements to be officially deemed successful: having reached a million signatures in only six months from its launch, it has been the fastest-growing ECI ever.

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 in to the European Commission on 3rd July 2017, with a total of 1,320,517 signatures having been collected from all across the EU[39]. This petition was presented to the European Commission in the autumn of 2017.

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

9.2 EU reply to the ECI

On 12 December 2017, the European Commission responded to the ECI saying[40]:

"1. 'Ban glyphosate-based herbicides, exposure to which has been linked to cancer in humans, and has led to ecosystems degradation':

Member States are responsible for the authorisation, use and/or ban of glyphosate-based products on their territories. In the EU, only substances for which there is objective evidence of safe use are approved. Following a thorough scientific assessment of all available data on glyphosate concluding that there is no link between glyphosate and cancer in humans, and a positive vote by Member States' representatives on 27 November 2017, the Commission today adopted a renewal of the approval of glyphosate for 5 years. President Juncker put this issue on the College agenda on several occasions, to ensure full political ownership by the Commission. Based on these political discussions, and taking account of the position of the European Parliament, the Commission decided to reduce the length of the proposed renewal from the standard 15 years to 5 years, which also ensured the widest possible support from Member States.

2. 'Ensure that the scientific evaluation of pesticides for EU regulatory approval is based only on published studies, which are commissioned by competent public authorities instead of the pesticide industry':

The Commission fully agrees that transparency in scientific assessments and decision-making is vital to ensuring trust in the food safety regulatory system. Maintaining and improving a strong, transparent and independent scientific assessment is crucial. The Commission will put forward a legislative proposal in 2018 covering these and other relevant aspects such as the governance of the European Food Safety Authority (EFSA), by spring 2018. The Commission will propose to change the current rules to make sure that scientific studies are publicly available. Citizens must be able to understand how such far-reaching decisions to authorise or ban certain substances are taken. Political responsibility and greater transparency are two sides of the same coin.

3. 'Set EU-wide mandatory reduction targets for pesticide use, with a view to achieving a pesticide-free future':

EU policy is already directed towards reducing dependency on pesticides and achieving a pesticide-free future as requested by the European Citizens' Initiative. The Commission will strive to ensure that Member States comply with their obligations

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

under the Sustainable Use Directive and reduce dependency on pesticides. Member States have also been invited to establish more precise and measureable targets in their National Action Plans. In addition, in order to monitor trends in risk reduction from pesticide use at EU level, the Commission will establish **harmonised risk indicators** on top of the existing national risk indicators. These would enable the Commission to determine the effectiveness of measures when assessing future policy options. The Commission will re-evaluate the situation on the basis of the resulting data and assess the need for EU-wide mandatory targets for pesticides.

Decision on Glyphosate renewal:

Due to the public and government concerns, on the 27th of November 2017, the majority of EU Member States (19 out of 28) finally agreed to reauthorize all the uses of glyphosate in Europe just for a 5-years period, instead of the initial 15-years period that was proposed in 2015[41]. Nevertheless, nine Member States voted against this renewal, most of them calling for a gradual phase out or a complete ban of glyphosate-based herbicides.

Next steps:

- On the **preparation of a legislative proposal**, in January 2018, the European Commission completed the Fitness Check[42] on the General Food Law Regulation (Regulation (EC) No 178/2002), an assessment to evaluate whether the GFL Regulation, including its principles as applied in subsequent legislation, is still 'fit for purpose'. The evaluation was followed by a public consultation, which received 471 replies[43]. The results from this consultation together with the feedback from Commission's and EFSA's stakeholder groups, highlighted the lack of trust in the current pesticide risk assessment system, and the need to increase transparency, sustainability and improve the risk communication of the EU risk assessment in the food chain[44].
- On a more **sustainable use of pesticides**, the Commission will follow-up with the Member States on the basis of a report published in October 2017.
- As a **response to the concerns expressed by European citizens**, the Commission published in April 2018 a proposal to improve, to an extent, the transparency of scientific studies in the food safety area. However, this only addresses, to some degree, the second demand of the ECI[45].

[41] https://ec.europa.eu/food/plant/pesticides/glyphosate_en

[42] Launched in 2014, the Fitness Check assessed whether the GFL is 'fit for purpose' for the entire food/feed sector and whether it still captures and reflects policy trends of today. It focuses on five evaluation criteria: relevance, effectiveness, efficiency, coherence and EU added value.

[43] https://ec.europa.eu/info/consultations/public-consultation-transparency-and-sustainability-eu-risk-assessment-food-chain_en

[44] https://ec.europa.eu/food/sites/food/files/gfl_transparency_comm_proposal_synopsis_20180410_en.pdf

[45] http://europa.eu/rapid/press-release_IP-18-2941_en.htm

9.3 Six Member States asking the EU for an exit plan on glyphosate

On 19 December 2017, six ministers of agriculture and environment from France, Belgium, Luxembourg, Slovenia, Malta and Greece wrote to the European Commission[46] inviting the European Commission to accompany the decision of the renewal with measures intended to limit the risks and to prepare the exit plan for glyphosate by supporting farmers to do so.

They specified that this should result in:

- carrying out a study in order to identify and make available for all actors the possible alternatives (chemical, mechanical or biological) to the main agricultural uses of glyphosate, the necessary conditions and the methods of implementation, including the necessary adaptations and evolution of practices at the level of farms and sectors;
- carrying out a new study conducted by the EU agencies in cooperation with the national agencies of those Member States and IARC / WHO, regarding the carcinogenic nature of the active substance glyphosate, as well as obtaining and examining additional data available;
- launching a reform of the EU chemical assessment framework with the aim of enhancing its transparency, as announced by the European Commission on independence;
- simplifying the framework governing the comparative evaluation of substances, to facilitate the substitution of substances, specifically during the examination of applications for authorisation for placing on the market and the development of alternatives to chemicals;
- strengthening research on the consequences of population exposure to chemical substances in order to work on a non-toxic European environment.

The letter from the six ministers ended by stating:

'We as member states, maintain our commitment to encourage the development and implementation of integrated pesticides management and of alternative approaches or techniques in order to reduce dependency on the use of pesticides.

We reaffirm our willingness to develop alternatives to the use of this substance by accompanying farmers in this process, to ensure a short-term exit of glyphosate and invite Member States that wish to associate themselves to this initiative to join us in a working group that France will put in place'.

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[46] http://www.minagric.gr/images/stories/docs/ypoyrgeio/dt271217c-Glyphosate-en.pdf

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Examples of policy on restricting herbicide use in the Member States:

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

- A report by INRA, the French state institute for agronomic research, published in December 2017 a report on alternatives to glyphosate and its phase-out which showed that many alternatives are already available. http://institut.inra.fr/Missions/Eclairer-les-decisions/Etudes/Toutes-les-actualites/Usages-et-alternatives-au-glyphosate

- 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 and extension services and using the existing networks of regional chambers of agriculture and state funded plant & animal production institutes. The service will be dedicated to disseminating alternative techniques among farmers. Both the ministries of environment and agriculture will be involved in the task force, together with INRA and other existing research and extension networks.

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.

”

10 Conclusions

This report shows that there is already knowledge and tools available to replace widespread herbicide use.

A number of farmers already apply them, while the CAP already foresees support for agro-environmental measures to cover the additional costs of alternative approaches and investment support for the required mechanical tools, as well as the advisory services that should underpin such a transition, empowering farmers with knowledge. While research is still needed to develop combined approaches (e.g. in integrated weed management), in developing more specific weed-control machineries, in collecting and disseminating best practice and success stories, it is clear that the basic building blocks are already in place. Furthermore, the EU research and innovation agenda is also ripe to make use of, by fostering links between researchers, advisors and farmers, and indeed some Member States are moving ahead to lead the way.

However, to obtain a real transition towards low impact systems we all need to re-consider the concepts of weeds. Effective Non-Chemical Weed Management is impossible if one does not understand weeds/non-crop plants and how they interact with their environment.

So the transition towards lower impact systems and less reliance on glyphosate involves not only replacing glyphosate based herbicides by using mechanical means or other less harmful herbicides, but also discovering or re-discovering organic farming cycles and techniques, learning to work with nature again, following the guidelines of 'the many little hammers' approach (illustrated in Figure 5, Chapter 7) and in this way applying all aspects of the IWM as mentioned in Chapter 7, which over time will increase farmers' resilience while allowing a decrease in expenditures for inputs[47].

Nevertheless, in so doing the CAP legislative proposals need to be seriously changed to place much more emphasis to uptake of integrated pest management, encourage use of non-chemical alternatives and set appropriate result indicators with serious pesticide use reductions at their core.

[47] 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
Summary on the toxicity of glyphosate
(PAN Europe)

Cancer/Carcinogenicity

IARC: The International Agency for Research on Cancer (IARC) of the World Health Organisation (WHO), classified glyphosate as a "probable human carcinogen", following a thorough analysis performed by 17 independent and world's leading experts from 11 countries using only publicly available studies[1]. This conclusion was reached based on "limited evidence of carcinogenicity in humans" and "sufficient evidence" in experimental animals. For humans, IARC took into account evidence from human cancer studies from 3 different countries where 2592 people (workers), in total, had developed Non-Hodgkin lymphoma (NHL; a rare case of cancer) following exposure to glyphosate-based herbicides and from a combined analysis (meta-analysis) of all NHL studies available. The conclusion on experimental animals was based on two experiments where mice had developed malignant tumours as a result of exposure to glyphosate alone, one revealing a rare case of cancer (kidney), which is extremely important in assessing human risk. Furthermore, the experts took into consideration the strong evidence of genotoxicity (DNA damage) and oxidative stress (tissue/cell damage) in humans and laboratory animals following exposure to glyphosate-pesticides and its metabolites.

[1] Guyton KZ, Loomis D, Grosse Y, et al., 2015. Carcinogenicity of tetrachlorvinphos, parathion, malathion, diazinon, and glyphosate. The Lancet Oncology , 16: 490 – 491.

EFSA peer review and Revised Assessment Report (RAR)[2] – BfR (German Health Authority) acting as a Rapporteur Member State for the European Commission: In fact, BfR having access to undisclosed industry studies found not two but five experimental studies were mice fed with glyphosate had developed malignant tumours. But it decided to dismiss the findings as non-significant. Ironically, it then dismissed the mechanistic data on genotoxicity and cell toxicity as non-relevant, because apparently, there were no evidence of carcinogenicity in experimental animals. Furthermore, all results on genotoxicity, cell toxicity or any toxicity in fact due to exposure to glyphosate products were all considered non-relevant because according to the EU rules risk assessment is done only on the active ingredient, despite the fact that people are exposed to the whole products. EFSA in its peer review approved the work of BfR. The analysis of the carcinogenicity potential of glyphosate by the European Authorities has received criticism by the scientific community[3, 4, 5, 6].

Endocrine disruption: Glyphosate alone and glyphosate-based products alter the hormone metabolism in different mammalian cell lines[7,8] and have been reported to reduce the conversion of androgens to oestrogens (resulting in production of more male than female hormones), with formulations causing a stronger effect[9, 10] . In experimental studies with mice, glyphosate-based products also alter the reproductive hormone metabolism and reduce fertility[11, 12, 13]. Despite the fact that en-

[2] Before the authorisation of an active substance, the applicant (pesticide industry) submits a dossier with all data requirements (chemical properties, toxicity, environmental fate etc.) to a Member State which acts as a Rapporteur (RMS) for the European Commission. RMS then evaluates the dossier and produces first the Draft Assessment Report (DAR) or the Revised Assessment Report (RAR) in case of re-authorisation.

[3] Portier, C. J., Armstrong, B. K., Baguley, B. C., Baur, X., Belyaev, I., Bellé, R., ... Zhou, S. F. (2016). Differences in the carcinogenic evaluation of glyphosate between the International Agency for Research on Cancer (IARC) and the European Food Safety Authority (EFSA). Journal of Epidemiology and Community Health. DOI: 10.1136/jech-2015-207005

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docrine disruption can cause serious health effects, very few studies have examined the capacity of glyphosate to alter the hormonal system[4]. Actually, EFSA has requested industry to evaluate the endocrine disruption potential of glyphosate and will publish its opinion in August 2017.

Toxicity of glyphosate on reproduction and development: In the RAR[A], there are already several incidences of developmental effects of glyphosate in mammals and in many cases below the recommended regulatory limits[14] Experimental animals exposed to glyphosate have given birth to foetuses with increased heart malformations and abnormalities, absent kidneys, distorted ribs, lungs and skeleton, as well as embryonic deaths. These data were dismissed for unclear reasons that cannot be verified since the studies are not published. However, independent published scientific studies show that pups exposed to glyphosate-based products developed abnormal reproductive organs and had altered hormone levels and mating behaviour[15, 16]. In a Danish farm, 38 live-borne one-day-old piglets had extraordinarily high percentages of abnormalities including serious cranial and skeletal malformations. By switching to non-GM and glyphosate-free feed the farmer instantly observed positive changes in the health of the sow herd[17].

Nervous system toxicity: Glyphosate and Glyphosate-based products affect the growth and development of nerve cells[18]. Glyphosate has been reported to disrupt the function of brain nerve signalling, brain cell organelles (mitochondria) and cause neuronal cell death all hallmarks of Parkinson disease[19, 20, 21]. Exposure to glyphosate products has been associated to ADD/ADHD, Parkinson disease and autism[22, 23, 24].

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Plant Toxicity and effects on biodiversity: Glyphosate being a wide-spectrum herbicide, kills all plants and even large trees. No other herbicide is so non-selective. Significant reductions in plant biomass, flower and wild plants have been observed in green areas close to fields treated with glyphosate products[25]. This reduction in plant species causes in turn a reduction in terrestrial species that feed on them, including natural insect predators, amphibians, pollinators and birds, resulting in significant ecological impact and biodiversity loss[26, 27, 28].

Ecotoxicity: The ecotoxicity of glyphosate to aquatic and terrestrial organisms is already recognised in RAR and EFSA peer-review, reporting glyphosate toxicity with long-lasting effects. By using prediction models to estimate the environmental exposure and considering that mitigation measures are applied by the farmers, the European Authorities conclude that the risk for non-target organisms is low. But, studies have confirmed that these models often underestimate real environmental exposures, indicating that non-target organisms are at a much higher risk[29]. Nevertheless, glyphosate causes a wide range of adverse effects in non-target organisms.

Aquatic ecotoxicity: Glyphosate and glyphosate-based herbicides are toxic to microorganisms, and alter plankton and algae communities[30]. Adverse effects following exposure have been reported in insects[31], crustaceans[32], molluscs, amphibians[33] and fish[34] and effects include reproductive and developmental abnormalities, DNA damage, immune effects, oxidative stress, decreased capacity to cope with stress, altered feeding and mating behaviour that can threaten their survival. Glyphosate products are usually more toxic to fish than glyphosate alone[35].

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[35] A review of effects of glyphosate and glyphosate-based herbicides on aquatic and terrestrial organisms is given in Glyphosate Monograph 2016, PAN International http://pan-international.org/wp-content/uploads/Glyphosate-monograph.pdf

Terrestrial ecotoxicity: Glyphosate has adverse effects on some earthworms and arthropods; and a number of beneficial insects useful in biological control, particularly predatory mites, carabid beetles and ladybugs[23, 36]. It can also adversely affect other insects that play an important part in ecological balance such as wood louse and field spiders[24]. Glyphosate use may result in significant population losses of a number of terrestrial species, including birds through habitat and food supply destruction[33].

Anti-bacterial properties and toxicity implications: The anti-microbial activity of glyphosate is known since it was first licensed in 1970s[37]. It is also toxic to certain soil bacteria of the Bacillus and Pseudomonas families that have a key role in suppressing specific pathogenic fungi, as well as in making the soil minerals available to plants. Thus, glyphosate alters the microbial community of the soils, which has a direct impact on the health of the crops. Glyphosate also seems to bind to the soil minerals (Manganese, Iron, Copper and Zinc) and blocks their bioavailability to the plants. In fact, glyphosate has been characterised to "significantly increase the severity of various plants diseases, impair plant defence to pathogens and diseases, and immobilize soil and plant nutrients rendering them unavailable for plant use". Due to these effects and weed resistance farmers are obliged to use fungicides and additional herbicides on their crops[38].

Due to its antibacterial properties glyphosate has been reported to affect the gut microbiota of animals, killing the beneficial bacteria and leaving the pathogenic ones behind[39]. This has been linked to adverse effects in farm animals, which feed on glyphosate-treated soya and corn feed. Some studies suggest that this particular glyphosate action which affects the gut bacteria may have serious implications to humans[40].

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ANNEX 2 Non-chemical management of docks (*Rumex*)

By Charles Merfield, Head of the BHU Future Farming Centre

The BHU Future Farming Centre
Permanent Agriculture and Horticulture Science and Extension

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 / ploughing kills them so they don't survive in arable 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 and 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

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

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

profitability. If the answer is no, the plant or population of plants are not weeds. 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. 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. Therefore they should not be considered weeds, but rather natural components of farm ecosystems. However, large dock populations have clearly been shown to be detrimental, so they do need to be managed, but not exterminated.

Beyond farm profitability, dock is a host for a wide range of other species in its native ranges, particularly insects. Even where they are exotics, they potentially contribute to biodiversity and ecosystem functions. For example, docks are a dominant food source for the green dock beetle (*Gastrophysa viridula*, Picture A1) and the seed is important to a range of seed-feeders including invertebrates such as beetles. The importance and benefits of weeds is 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, elimination of docks from farmland is undesirable.

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

Picture A1. The green dock beetle (Gastrophysa viridula). Larvae skeletonising a leaf (left) adults (right)

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

2 Dock management

Non-chemical control of any weed 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.

2.1 Key components of dock biology and ecology

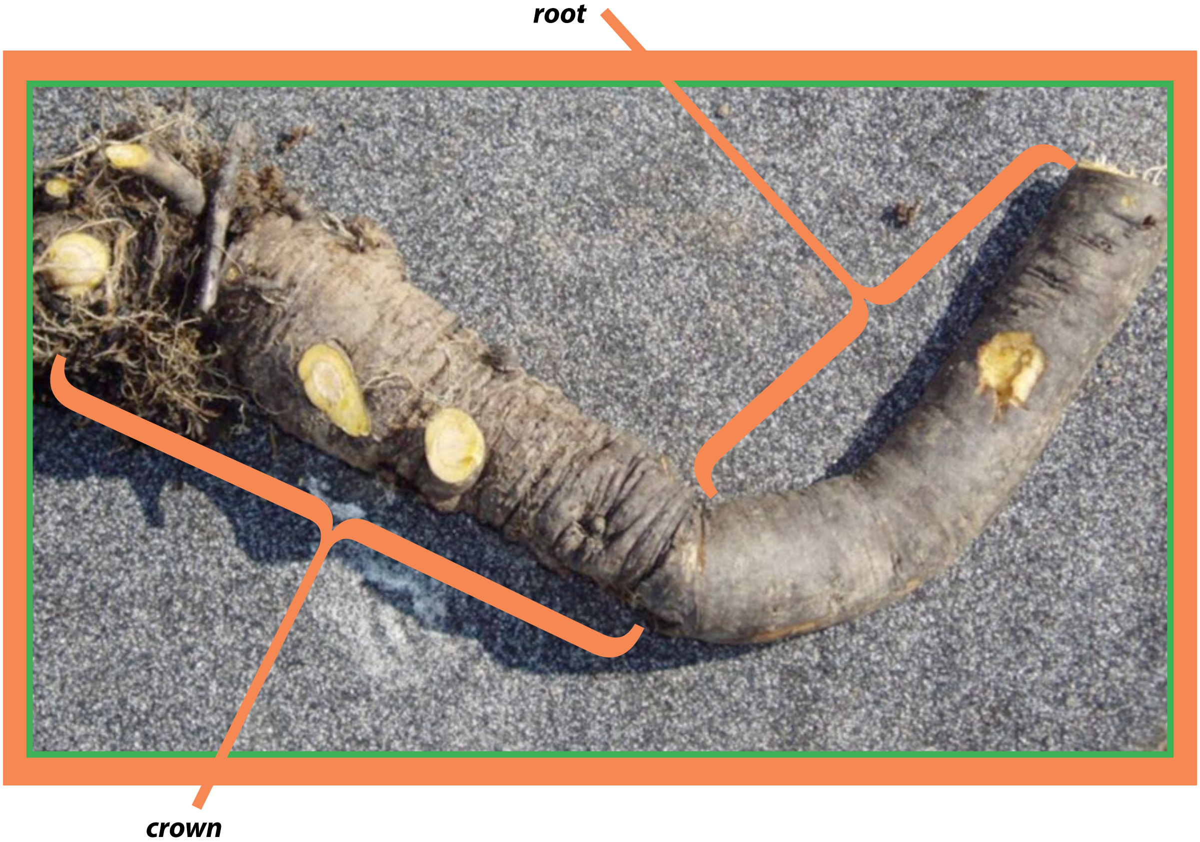
Non-chemical control of any weed requires a systems based or integrated approach. The metaphor of 'many little hammers', coined by Liebman & Gallandt (1997), highlights that multiple tools are needed. To work out which tools will be effective and how to use them it is essential to understand the biology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

Docks are rosette-forming, herbaceous perennials, consisting of a crown (short vertical underground true stem), with large fleshy tap roots (Picture A2).

Picture A2. 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



Picture A3. Section of dock showing the visual similarity between crown and root

land managers and scientists about the ability of docks to regenerate following disturbance, e.g. tillage / ploughing 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 true shoot material. However, in some cases the crown and root can appear quite similar (Picture A3), especially as the crown produces adventitious roots, which may be partly to blame for the confusion about whether roots can regenerate, as some people may confuse the crown for true roots.

As a comparison, docks are morphologically identical to another member of the Polygonaceae or buckwheat family, rhubarb (Rheum rhabarbarum), which 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 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 increases. Therefore defoliation intervals greater than four weeks allows 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. It also needs regular diurnal temperature fluctuations to germinate, so is 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 almost entirely down to 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;
- Minimising soil compaction.

A 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; these weeds will out-compete pasture species. 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 a 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, so it is not clear if they prefer wet areas or are more tolerant of waterlogging than the pasture species, gaining a competitive advantage. Regardless, improving drainage through minimising compaction, increasing artificial drainage and improving soil structure are all important remediation tools.

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 components, i.e. grasses, legumes and forbs (e.g. plantain and chicory), the amount of vacant ecological space is significantly reduced, decreasing the space available to weeds. Further, different species grow at different times of year, so 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 the animal 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.

The traditional grazing method, called 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 eat 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, which coupled with a small amount of leaf, 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 new pasture. This gives the pasture time to grow lots of leaves to capture sunlight and develop a large root system to capture water and nutrients. After it is grazed, it then has 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 setting them back.

After incorrect 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, but even small livestock such as sheep will cause compaction when the soil is in a plastic state (saturated with water). It is therefore important to have strategies and systems in place to avoid having livestock on fields when they are in the plastic phase and susceptible to compaction. However, docks are most problematic in the colder, wetter, higher latitudes where the soil can be in the plastic state 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 (Picture A4), while horses avoid docks as much as possible. Where practical, cross grazing dock tolerating species with intolerant species can assist with keeping docks suppressed.

Picture A4. Beef finishers eating offered broad leaf docks plants while waiting to be moved to new pasture

2.4 Nutrient management

A number of 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 able to 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 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 because docks have a higher requirement for K than other pasture species, 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 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 optimum, the stronger and more persistent docks will become. Established docks are also highly competitive with pasture through shading from 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 due to slurry and farmyard manure application to the fields closest to the 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 only added where it will not bring any nutrient level above the optimum, particularly for nitrogen, phosphorous 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 favours grass; at lower defoliation frequencies, 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, 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 reasons for this are not due to the return of large numbers of dock seeds in slurry to silage fields, as 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 slurry. So there are multiple reasons why slurry contains zero viable dock seeds.

The key reasons silage fields have high dock populations is because 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. 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 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 the shorter term rotational grazing (less than a month return time) starts wearing the docks out.

2.6 The role of seedbanks

Much is made of the longevity of seeds, but many of these studies keep seeds in ideal conditions, typically under a controlled climate. In comparison, 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 soil is far less than seeds' 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, 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 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 seedbank 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 creation of that pasture or grassland. It is therefore considered that the dock seedbank is only truly relevant when grassland is newly-established.

A core component of any non-chemical weed management strategy for controlling therophyte weeds (weeds that survive winter as seeds) is minimising weed seed rain, to reduce the size of the weed seedbank. Docks have a mixed strategy of being a perennial, particularly the broad leafed dock, and also produce 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 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.

9.7. Dock management at grassland establishment

As the main route for docks into well-managed grassland is at its establishment, it is clearly a critical point for dock management. There are some well established techniques to minimise docks becoming established in new grassland. The key is to get the grassland 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 ensure the grassland 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 grassland at optimum times of 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 grassland a competitive edge (Humphreys, 1995).

9.8 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 addition of flowering plants.

Biological control of docks in Europe is difficult because they are in their native range. Importation biocontrol is best suited to an exotic pest that lacks its predators from its native range and even then, success (defined as reduction of the weed below economic levels) is only achieved in 10% of cases. Conservation biocontrol is challenging, because docks already have a large number of species that attack them, so it is particularly hard finding an ecological manipulation that would significantly boost predators of dock to a sufficient number to meaningfully decrease dock populations.

Augmentation techniques, particularly inundative ones using microbes, have potential as 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 or 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 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 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 enter pasture during grassland establishment, reducing dock numbers once the pasture is fully established, e.g. six months to a year after seeding, can pay dividends if the grassland is kept for many years, as the benefits of removal accrues year on year.

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. 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 then 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 at all costs. In hot dry weather, especially if there is a good thickness of pasture to keep the crowns off the soil, they can just be left on the field to desiccate and die. In less than ideal drying conditions, the crowns will 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' (Picture A5) which consists of two prongs and a pivot point to ensure a vertical clean lift and ease of use / good ergonomics.

Picture A5. Traditional dock fork (left), modern ergonomic design with interchangeable heads (right)

2.9.1 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 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. The key requirement is that the weeds need to be higher than the crop, so the electricity can be selectively applied to the weeds. Therefore electrothermal control has considerable potential for pasture weed management as a large majority of pasture weeds overtop the pasture, especially after low intensity grazing. Electrothermal weeding is both systemic and selective for tall pasture weeds, an accomplishment that even herbicides cannot achieve.

Some informal testing of electrothermal techniques has shown that for large established docks, it will take two or three treatments to fully kill the crown, but for younger plants, e.g. up to one to two years old, a single treatment should suffice.

Electrothermal weeding uses massively less energy than flame and steam weeders, with more than 20 times lower energy use; where plants are sparse this is even lower, as power is only used when the machine contacts a weed. Very large machines were developed in the 1980s, some over six meters wide, so it is possible to have significant work rates. There are also hand-held machines for spot treatment, so it is hoped that within a few years this technology will become widely available to farmers, both to own and for contractors to supply as a service.

2.9.2 Other techniques

A wide range of other techniques for direct dock control, such as thermal weeding using flame and steam, mechanised dock diggers, etc. have undergone trials. However, due to the need to kill the crown, which is buried in the soil, flame and steam control require large amounts of energy which makes them uneconomic, and mechanical approaches with their high capital cost and lower agility are considered unlikely to match a fit weeding gang using well designed dock forks both for speed and cost.

2.9.3 Renewing temporary grassland with high dock populations

Where dock populations are unfeasibly large, it is likely to be cheaper to terminate the grassland 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 and break up the crowns. The crown fragments will vigorously regrow unless the soil and weather is particularly dry, so follow up tillage to stop the fragments re-rooting every one to two weeks will be required. This can be done with tined cultivators and harrows rather than power tools to preserve soil structure. This follow up is 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. Tined cultivators also tend to drag the crowns to the surface where they will more quickly desiccate. If the crowns are completely killed through desiccation no further cultivation will be needed. If after a couple of passes they are still viable but weakened, they can be ploughed down, ideally fairly deeply, to kill then through light starvation. 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 (Picture A6).

Picture A6. 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. Effective non-chemical dock management is almost entirely down to good grassland management, both the management of the pasture plants themselves and how they are grazed. A long term view is required, up to a decade, to gradually reduce in-field dock populations and the weed seedbank that infests new pastures with dock seedlings.

ANNEX 3

Illustration of the "many little hammers" approach in the fight against weeds

Figure 9. Integrated management of docks on grassland

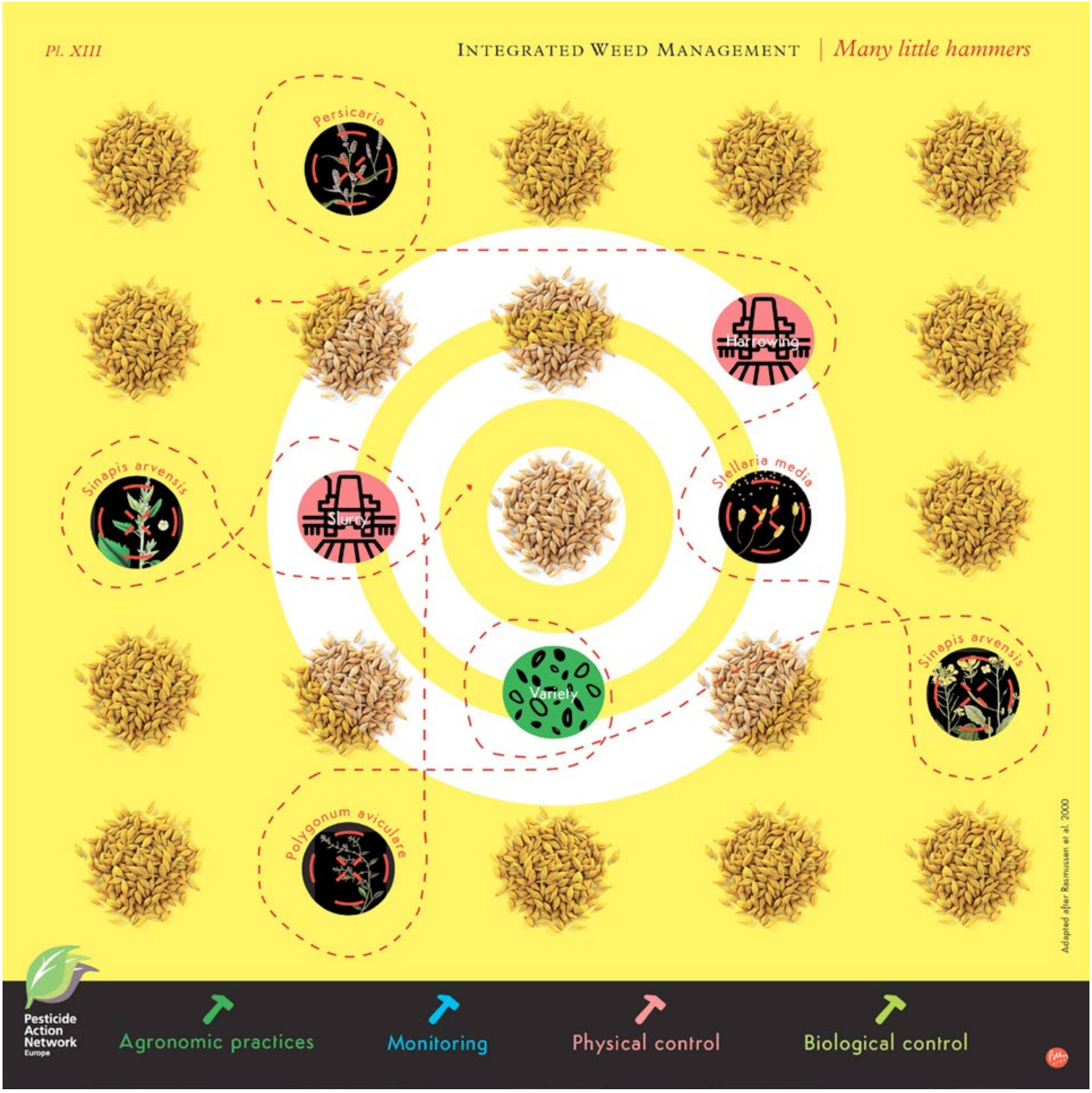


Figure 10. Integrated management of annual weeds in spring barley

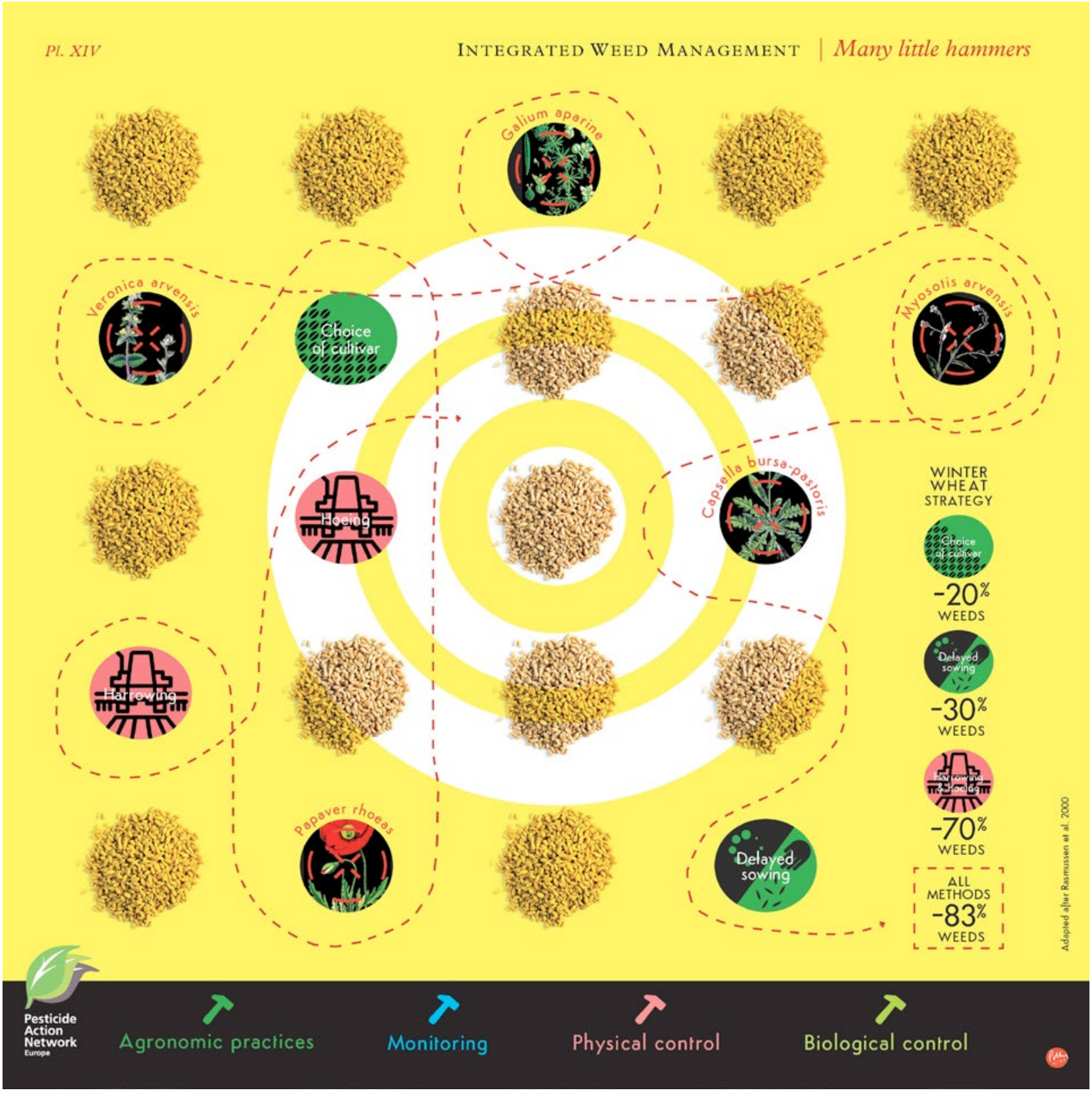


Figure 11. Integrated management of annual weeds in winter wheat