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Early Warning, Emerging Issues and Futures

Alternatives for the use of glyphosate

Background

Glyphosate is the most widely applied herbicide in agriculture and is often used in conjunction with crops that are genetically modified. Farmers' dependency on glyphosate has grown steeply in recent years as it is easy to apply and relatively inexpensive. However, glyphosate is also increasingly controversial, with accumulating evidence that it can lead to a wide range of health and environmental impacts. Two countries have already banned glyphosate and others are considering to do the same. This Foresight Brief shows that there are alternative methods which can help to avoid the use of glyphosate as well as other harmful chemicals to kill weeds. The alternative methods offer the benefits of restoring soil fertility and increasing biodiversity in the environment.

Introduction

Since the 1950s, modern or industrial agriculture succeeded in rapidly increasing yields through methods that rely strongly on diverse chemical treatment of crops and fields. These range from the use of chemical fertilisers to substances that kill unwanted life forms, such as herbicides to suppress weeds, insecticides to eradicating pests, and fungicides to kill fungi. Other methods include the use of rodenticides to work against rodents, molluscicides to eliminate slugs and nematicides to destroy nematodes.

The world's most common molecule in herbicides is glyphosate which was introduced in 1974 under Monsanto's brand "Roundup". In 1996, the company began selling genetically modified organisms (GMOs) such as corn and soybeans, which were engineered to be resistant to glyphosate. From the end of 2014, products containing glyphosate as the active ingredient can be found under multiple generic names from many other herbicide manufacturers.

Glyphosate's enormous success worldwide is due to the fact that it presents "the double property of being total and systemic [1]. It kills any weedy vegetation by contact through its leaves. While its relatively straightforward use has simplified weed management systems and triggered an important growth in yields in the first place, its potential impacts on human health (such as its possible carcinogen effect, [2,3]) and - to a much lesser extent - the environment (changes in the soil life community and loss of biodiversity), as well as the evolution of nearly 40 "super weeds" which became resistant to glyphosate, have stimulated much, often controversial, research and on-going debates in various fora [4–6].

As a result, several countries and many municipalities are considering restricting or have already introduced legislation to ban or restrict the sale and use of glyphosate[i]. In the European Union (EU), its license was recently renewed, but only following intense discussions and strong public opposition, and for another five years only.

Can agriculture manage without glyphosate, and other even more harmful herbicides? What methods exist already which could reduce or totally suspend dependency on glyphosate (and other herbicides)? Is the focus on "killing weeds" the right and only angle in approaching that subject? While it seems that the central question for farmers, is on how to combat weeds, the real question to ask should be on how we can have an agricultural system whose weed control measures ensure not only food security, but also protects human and environmental health?

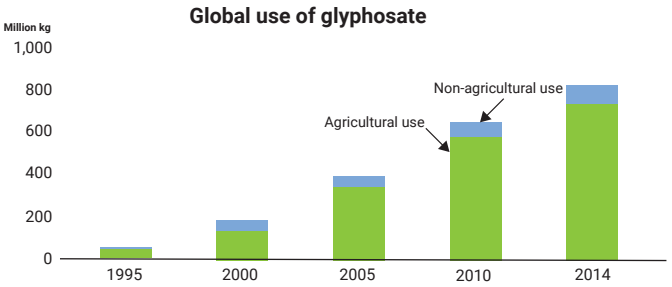
Figure 1: Spraying of glyphosate is being done on large areas

[1] https://www.baumhedlundlaw.com/toxic-tort-law/monsanto-roundup-lawsuit/where-is-glyphosate-banned/

Why is this important?

Glyphosate by the numbers

Glyphosate was initially patented in 1964 as a metal chelator, i.e. a molecule that has the unusual ability to attract and securely hold on to certain types of metal ions. It was used for cleaning heating systems, as it allows metals to be soluble in water. However, its main use since 1974 is as total herbicide[ii]. Between 1974 and 2014, 8.5 billion kilograms of glyphosate's active ingredient have been used world-wide, of which over 1.6 billion kilograms (19%) have been applied in the U.S. alone [7]. Globally, glyphosate use has risen almost 15-fold (Figure 1) since the "Roundup Ready" genetically engineered glyphosate-tolerant crops were introduced in 1996. Interestingly, 72% of the total volume of glyphosate applied globally from 1974 to 2014 has been sprayed in the last 10 years alone. Figure 2 portrays the 111-times increase of the global area of genetically engineered cultivated crops from 1996 to 2017. In 2014, farmers used glyphosate at an average rate of 1.5-2.0 kilograms per hectare, applying it to 22-30% of globally-cultivated cropland. In 2016 alone, 800,000 tons of this herbicide were sold globally, making it by far the primary herbicide used. Over 90% of glyphosate is used for agricultural purposes, and the remainder mainly used to control weeds in railway lines, public areas and private gardens.



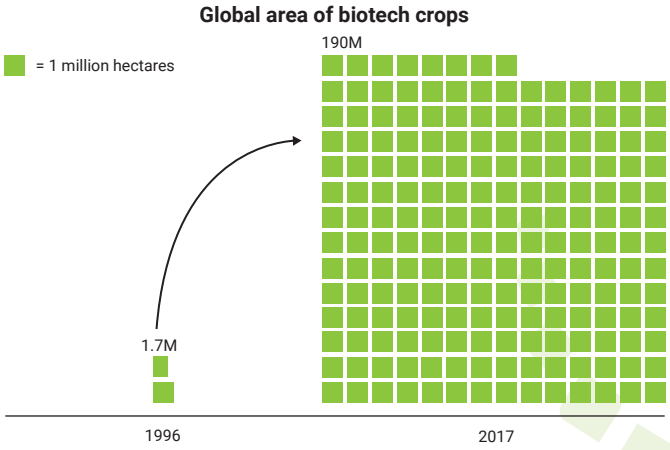
Source: Benbrook, C. (2016): Trends in glyphosate herbicide use in the Used States and globally.

Figure 2: Global use of glyphosate - steadily on the rise

[ii] Selective herbicides kill only specific targeted plants. Total herbicides kill all plants.

Use of glyphosate

Glyphosate is used in the agricultural sector to eliminate weeds during the pre-planting phase of crops. It is also used as a pre-emergent herbicide after sowing but before the crop shoots emerge. It can be used as a post-emergent herbicide in glyphosate-tolerant crops such as soybeans, corn, cotton and canola. Annually, 21 million hectares of soya resistant to glyphosate are planted worldwide, representing 60% of all soya cultivated. This implies regular use of glyphosate [7].



Source: ISAAA (2017): Global Status of Commercialized Biotech/GM Crops in 2017

Figure 3: The area of GMO crops has increased 111 times in 11 years

Farmers also use glyphosate for desiccation, to help dry out seeds of cereal crops more rapidly. As well, glyphosate is being used in the rows between permanent crops like vines and the ground beneath orchard crops to help eradicate invasive plant species. [4,8,9].

Conservation Agriculture

One of the main reasons for tilling is the disturbance and suppression of weeds. With the use of glyphosate, weeds can be killed without moving the soil. This diminishes the risk of soil erosion, and decreases the use of fossil fuel [10]. In a few South American countries, more than 70% of the agricultural area is therefore under "conservation agriculture (CA)" [11] and in the USA, Australia and Europe, the number of fields under conservation agriculture are increasing steadily. CA depends largely on glyphosate and other selective herbicides for successful farming [12–15].

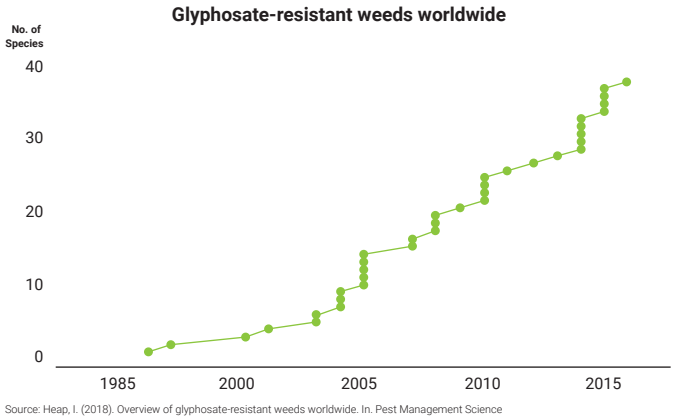
In the last few years, a rich scientific literature on the use of glyphosate has emerged showing possible impacts on human health and the environment.

Human health impacts

- According to the IARC report on glyphosate [3], the cancers most associated with glyphosate exposure were found to be non-Hodgkin lymphoma and other hematopoietic cancers, which is supported by other research [2,6,16–19].
- The IARC report further concluded that glyphosate exposure caused DNA and chromosomal damage in human cells, as well as genotoxic, hormonal and enzymatic effects in mammals.
- Although some studies portray the active ingredient itself, glyphosate, as not harmful to humans and the environment, the mixtures used have raised concerns. Laboratory studies show that the combinations of glyphosate with other substances used in "Roundup" and in other formulations are more toxic than glyphosate alone, and can cause cancer or other health problems [20–22]. These formulations that facilitate penetration of the active ingredient in the weeds are significantly more toxic than glyphosate on its own [21,23].

Environmental impacts

- Herbicide-resistant weeds present the greatest threat to sustained weed control in major agricultural crops [24]. So far, 38 weed species distributed across 37 countries and in 34 different crop situations have developed resistance to glyphosate (Figure 3) and other herbicides as well [24].



Source: Heap, I. (2018). Overview of glyphosate-resistant weeds worldwide. In. Pest Management Science

Figure 4: Cumulative glyphosate resistant weeds

- After the application of glyphosate, nitrate and phosphate available in the soil increase significantly due to the die-off of the plants, "pointing to potential risks for nutrient leaching into streams, lakes, or groundwater aquifers" [25].
- Glyphosate alters and disrupts the population of microbes in the soil [26,27]. It decreases the population of beneficial fungi [28–30], which play a vital role in facilitating water and nutrient uptake from plant roots [31–33].

- Glyphosate is toxic to beneficial soil bacteria that have a key role in suppressing specific pathogenic fungi, as well as in making soil minerals available to plants [34,35].
- Glyphosate reduces the activity and reproduction rates of earthworms [25,36] and perturbs the gut microbiota of honey bees [37].
- Glyphosate has been reported to bind to the soil minerals such as manganese, iron, etc. and blocks their availability to plants, leading to weakening of plant defenses against pathogens [38].
- One consequence of the suppression of weeds by glyphosate use is that food for insects, in the form of nectar, pollen, leaves and seeds, are eliminated from fields. This results in a diminished number of insects [39–42] and, as a further consequence, a lack of food for birds which feed on insects and seeds, leading to a further decrease in biodiversity [23,43–54].
- Although glyphosate degrades rapidly, its main metabolite degrades more slowly, and has been frequently and widely found in U.S. and EU soils, surface water, groundwater and precipitation [55,56]. Studies have shown its toxic effects on algae, plants, fish, invertebrates and mammals [57–59, 57,60–63,64].

What are the findings?

Alternatives

Commercially available alternative chemical products with the same effects as glyphosate do not exist. However, Dicamba is being used as a chemical alternative to glyphosate. Dicamba is extremely volatile and it damaged crops in 1.5 million hectares of land particularly in Arkansas, USA that were not protected against Dicamba . A comparative study on herbicides showed that Dicamba and its derivatives presented 75 and 400 times more risk, respectively, to terrestrial plants than glyphosate [65].

Before the rise of glyphosate, farmers managed to cope with weeds using a toolbox of methods which are now being revived at all farm scales. Successful, sustainable weed management systems are those that employ combinations of techniques [66] which, besides, increases soil fertility, plant health, biodiversity and yield [70–73]. Weed management systems fall into four main categories:

1) preventive and cultural agronomic practices that reduce weed germination;
2) monitoring (observation and identification throughout the process);
3) physical control either through mechanical or thermal control; and
4) biological control through selected crops or animals [68].

Applying and integrating the following weed management methods demands expertise and experience. While yields may not be as high as they are with conventional methods, especially in the first years of transition, success should be measured not only in "yield per hectare", but should include additional parameters, such as the well-being of people, soil, plants, animals and future generations.

New approach to weeds: In organic farming, weed populations is maintained at manageable levels, as weeds can have a beneficial role by providing biological diversity and supporting ecosystem services [74,75]. They offer pollen, nectar and habitat for beneficial biocontrol insects, which in turn improve the pollination of crops [75,76]. They cover bare soil after harvest and keep beneficial soil microorganism communities alive.

Fungi and bacteria: Studies have found that the more mature an ecosystem/biome is, the higher is the fungi to bacteria (f:b) ratio of its soil [78] . Increasing the f:b ratio by favouring the development of fungi can lead to a diminished amount of weeds. This can be achieved, for example, through the addition of compost, compost teas[iii], shallow tillage, increased organic matter, the use of perennial plants (as hedges or tree rows) or through seeds which are inoculated with beneficial fungi. Fungi increases carbon partitioning into plant shoot and plant fruit partitions, plant photosynthates, and decrease soil carbon respiration [31,33,79–82]. Among the many potential benefits that mycorrhizal fungi have been shown to confer to their plant hosts is pest- and pathogen-resistance [71,83–85]. Total microbial biomass, in combination with the fungi to bacteria (f:b) ratio, is an important measure of a soil's health, and tends to be reduced in conventionally cultivated fields compared to organic fields [86–88]. Biological interactions between beneficial soil bacteria, fungi contributes significantly to improved soil structure [80,85] and increased plant growth and health [34,70,90]. Therefore increasing the f:b ratio leads naturally to an environment in which the number and strength of weeds will continuously decrease [91-92].

Mechanical weed control: Reduced shallow tilling at soil depth of 3-5cm not only decreases weed density, but in contrast to the normal tilling depth of 30cm, it has less negative impact on soil communities such as earthworms and beneficial fungi [93]. When reduced tilling is combined with the use of cover crops it raises nitrogen

[iii] Actively aerated compost tea is a water-based oxygen rich culture containing large populations of beneficial aerobic bacteria, nematodes, fungi, and protozoa.

Figure 5: Shallow non-turning mechanical weed control

levels, crop yields can be comparable, and soil fertility and its carbon storage capacity are high. It also increases the total biomass of beneficial bacteria and fungi [94]. In general, crop yields in reduced tillage are reduced by 7% compared to conventional tillage at 30 cm depth, with minimal increases in weed competition [93].

Thermal weed control: Thermal weed control is a flash-burn method used for controlling weeds before crops are planted or germinate. It uses a "torch" of hot steam or hot air to damage or kill the leaf membranes of weeds to eliminates weeds ability to photosynthesis. The effectiveness of the method is close to 100%, especially for annual weeds, but is relatively expensive and creates carbon dioxide emissions through the fossil gas burning. It's main use is in vegetable production, especially in organic farming systems [95,96].

Crop rotation: A large rotation cycle of crops over multiple years is an effective agricultural control mechanism to regulate weed presence [12,98,99,] besides enriching the soil with nutrients and suppressing pathogens [100]. It leads to an increase in soil species richness and density, which reduces the emergence of weeds [91,101–106]. Organic producers often employ up to a nine-year crop rotation, with a different crop every year, compared to industrial agriculture which has a reduced rotation of commonly to soy and corn.

Cover crop: Cover crop mixtures can effectively suppress weeds while improving soil fertility [107–111]. In Pennsylvania (USA), Mirsky et al. [109] demonstrated that combining tillage with cover cropping during a summer fallow can result in 98%, 85%, and 80% reductions in foxtail, common lambsquarters, and velvet leaf respectively. Research in Illinois (USA) reported that Canada thistle

Success stories

Gabe Brown is a prominent American conventional farmer, who turned his farm from a monoculture model into a prolific (and profitable) business with increasing levels of humus (from <2% in the early 1990s to >6% in 2013), soil fertility, nutrient content, water holding capacity and ever-diminishing amounts of herbicide use once every few years [97]. He is a no-till farmer, who integrates crop rotation with multi-species cover crops, undersown and crop-livestock integration. Yields are higher than county average especially in dry years while input costs are low.

Michael Reber, a conventional farmer in Germany, started focusing on enhancing soil biology using cover crop mixtures, effective microorganisms, undersown and shallow tilling some years back. He does not need to use glyphosate anymore on his 250 hectares as weed levels are in decline and plant health on the rise (personal communication).

Klaas Martens converted his 600 hectare farm to organic farming and through a holistic cultivation approach weeds became less and less abundant [92]: "We've been conditioned to think that crop diseases, pests and weeds are random events that we can only react to them", states Klaas Martens. "Even velvet leaf, the most bothersome weed was overcome", he adds.

shoot density and biomass were greatly reduced over the course of two growing seasons by using either sorghum-sudangrass or a mixture of sorghum-sudangrass and cowpea [112]. Brust [107] reported weed suppression rates of over 90%. In addition, cover crops are used for reducing nutrient leaching, increasing biodiversity and maintaining or improving soil structure [113, 114–117]. Covering the soil with living plants improves soil quality, nutrient density and availability, water holding capacity, soil compaction and stability, and generates favourable conditions for healthy growth of the main crop, while weeds are suppressed [100,115,118–123]. Fodder cover crop offers additional benefits to the farm as fodder for animals while manure from the animals enriches the soil with nutrients and microbial life [124–126].

Figure 6: Multispecies cover crop enhances soil fertility

Undersown: An undersown crop covers and protects the soil, suppress weeds and if legumes are being used [119] they have positive impacts on the main crop and feed beneficial bacteria and fungi [127,128]. In Switzerland, the seeding of an undersown crop was found to produce only slightly less yield of winter barley without application of herbicide, compared with barley alone and treated with herbicide [129]. Undersown crops such as white clover and lucerne reduce weed density by 35-49%, and significantly increase yields of the main crop, than the same crop without an undersown [130]. They offer habitat and food for beneficial insects, which improve insect pest management [42,70,131,132].

Figure 7: Undersown in an important practice to surpress weeds while at the same time reducing erosion and raising soil fertility

Intercropping: Intercropping is a farming practice involving two or more crop species, growing together and coexisting for a time. This offers early canopy cover and seedbed use resulting in reduced weed growth [12,133–135]. Additional benefits include promoting pest-suppression, soil and water quality, nutrient cycling efficiency, and cash crop productivity [119]. Intercropping systems have the potential to increase the long-term sustainability of food production [133,136,137,138].

Controlling the biological cycles of weeds: According to a 20-year study in Denmark, about 80% out of a total of about 200 weeds growing in cultivated fields are too weak to compete with the crops and therefore do not affect the overall crop yield [139]. This method of weed control requires an understanding of weed germination, growth and proliferation; the conditions that enhance or diminish the presence and growth of weeds; and the various measures one can use to control them [66,67,140–142].

No-till: No-till, as it is being applied in the Conservation Agriculture practice, is mostly used in conjunction with the use of herbicides, as perennial weeds can easily propagate without tillage. However, with the right set of tools and knowledge, chemical inputs can be decreased while helping to suppress weeds [93,140,141,143,144].

Integration of animals into the cropping system: An increasing number of farmers are using animals to suppress the cover crop before seeding the main crop, instead of using glyphosate. The animals, for example sheep and cows, can live off the cover crop, and help to prepare the field for sowing [124,125,147]. In addition, the hoof impact, excrements and the trampling of green leaves improves the soil biotic community and may alter the supply of nutrients in the rhizosphere for plant uptake and regrowth for improved soil quality [118,126,126,148].

Figure 8: Animals can be used to "kill" the cover crop. replacing the need for glyphosate

False seedbed: This technique is a preventive weed emergence method: several weeks before sowing, the seedbed is prepared, giving weeds the chance to germinate and helping to partially deplete the existing seed bank of weed species. The seeds that emerge are then eradicated mechanically or thermally before sowing the crop of interest [149,150].

Mulching: By covering the ground with organic or inorganic materials, one can block sunlight and prevent weeds from germinating. This is especially useful for the growth of vegetables on small scale. Materials used can be organic substrates such as straw and hay, biodegradable plastic sheets or inorganic materials.

Vinegar and other bio-products: Annual weeds can be partially controlled or hampered in their growth by the use of natural acids [151,152]. These alternative herbicides can be considered as short term "burn-down" products. They are used in conjunction with other cultural practices to improve soil and plant health.

What has/is being done?

While an increasing number of counties and States worldwide plan, or have already put in place a ban on glyphosate, organic agriculture is steadily growing. Due to the discussion around glyphosate, the political and the scientific communities continue to screen new ways of sustainable farming. The subject is being actively addressed by NGOs, such as Regeneration International, the Rodale Institute, Holistic Management International and other established or newly created alternative "think tanks" on regenerative agriculture [153–156]. The above-mentioned weed management approaches offer a holistic view on farm management and need to be mainstreamed by farmers' associations, political bodies and at agricultural schools and universities.

Goal	Objective	Impact from soil health and regenerative agriculture
1 NO POVERTY	No poverty	Increase farm income
2 ZERO HUNGER	End hunger	Enhance quantity and quality of food
3 GOOD HEALTH AND WELL-BEING	Good health	Produce nutritious food
5 GENDER EQUALITY	Gender equality	Improve crop productivity of women farmers
6 CLEAN WATER AND SANITATION	Clean water and sanitation	Improve water quality
8 DECENT WORK AND ECONOMIC GROWTH	Economic growth	An engine of economic development
10 REDUCED INEQUALITIES		

"Fundamentally, agriculture can manage without glyphosate," says Hella Kehlenbeck from the Julius Kühn Institute in Germany. In her research, she estimated the possible costs of a glyphosate ban for German agriculture and found that farming without herbicides "doesn't have to be more expensive in all cases" [159]. Similarly, Böcker et al. [160] found that "a glyphosate ban [in Germany] has only small income effects." On the other hand, if all costs involved with the use of herbicides such as glyphosate were to be considered, it "can be said that a ban of glyphosate and other herbicides could overall be cheaper," said Jörn Wogram from the German Environment Agency. [iv 161]

What are the implications for policy?

Herbicides were once seen as the final solution to weed control problems, but they have a limited lifespan because of herbicide resistance and concerns about human health and environmental issues. Glyphosate-resistant crops ushered in a short period during which agriculture is critical to advancing several SDGs (Table 1), especially those related to alleviating poverty (#1), ending hunger (#2), improving health (#3), clean water (#6), economic growth (#8), and climate action (#13).

Recommendations

- Thinking through the transition leading to the end of glyphosate requires a timescale that takes account of the implementation of the above-mentioned alternative techniques.
- Governments should secure more funds for whole-system approaches, organic farming, and allocate investments to research on "alternative" agricultural methods. Education, training, , advice and support to farmers are essential, and should be supported by governments.
- Agricultural schools (including universities) need a focused approach on (eco-)system "agriculture" and its many beneficial relationships between plants and soil.
- As chemical alternatives to glyphosate are possibly of greater environmental and human health concern, the use of glyphosate for farmers in trouble with serious weed problems could be kept as a "last resort", through controlled sale and usage.
- Policies which support the above-mentioned practices could help bring more diversity on farms, in the fields and the crops, while building a healthier agricultural system.