

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 (all plants share the blocked mechanism and are therefore sensitive to varying degrees) and systemic (travels through the tissue in order to reach the root system)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 fora⁴⁻⁶.

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 glyphosate¹. 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

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

already which could reduce or totally suspend dependency on glyphosate (and other herbicides)? Is the focus on "killing weeds" the right and only angle



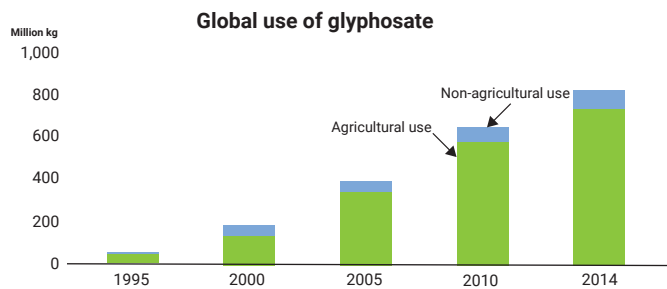
Figure 1: Spraying of glyphosate is being done on large areas

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?

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 herbicideⁱⁱ. 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. alone⁷. 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.



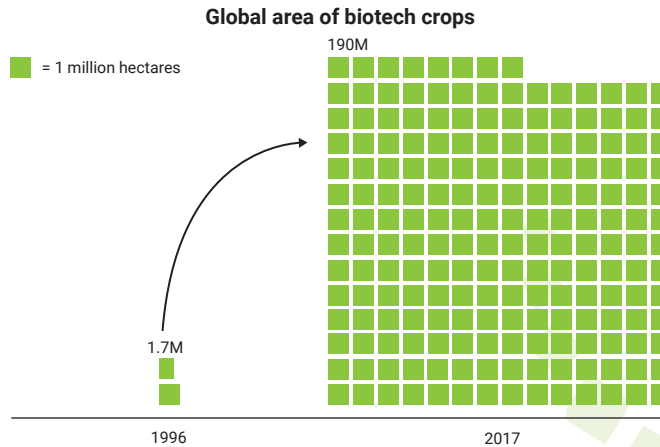
Source: Benbrook, C. (2016). Trends in glyphosate herbicide use in the United States and globally.

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 glyphosate⁷.



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 fuel¹⁰. 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 farming¹²⁻¹⁵.

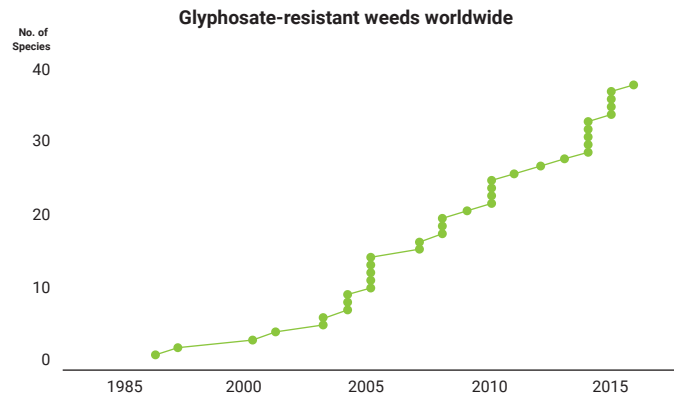
In the last few years, a rich scientific literature on the use of glyphosate has emerged showing possible impacts on human health and the environment.

Human health impacts

- According to the IARC report on glyphosate³, 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 problems²⁰⁻²². 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 crops²⁴. So far, 38 weed species distributed across 37 countries and in 34 different crop situations have developed resistance to glyphosate (Figure 4) and other herbicides as well²⁴.



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

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 fungi²⁸⁻³⁰, which play a vital role in facilitating water and nutrient uptake from plant roots³¹⁻³³.



- 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 bees³⁷.
- 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 pathogens³⁸.
- 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 insects³⁹⁻⁴² 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?

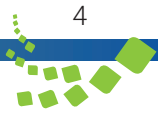
Alternatives

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 glyphosate⁶⁵.

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 techniques⁶⁶ which, besides, increases soil fertility, plant health, biodiversity and yield⁷⁰⁻⁷³. 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 animals⁶⁸.

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 soil⁷⁸. 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 teasⁱⁱⁱ, 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 fields⁸⁶⁻⁸⁸. 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 decrease⁹¹⁻⁹².

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 fungi⁹³. When reduced tilling is combined with the use of cover crops it raises nitrogen



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 fungi⁹⁴. In general, crop yields in reduced tillage are reduced by 7% compared to conventional tillage at 30 cm depth, with minimal increases in weed competition⁹³.

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 pathogens¹⁰⁰. 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 fertility¹⁰⁷⁻¹¹¹. 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 years⁹⁷. 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 abundant⁹²: "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.

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

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 cowpea¹¹². Brust¹⁰⁷ 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 life¹²⁴⁻¹²⁶.



Figure 6: Multispecies cover crop enhances soil fertility

Undersown: An undersown crop covers and protects the soil, suppress weeds and if legumes are being used¹¹⁹ 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 herbicide¹²⁹. 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 undersown¹³⁰. 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 suppress 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 productivity¹¹⁹. Intercropping systems have the potential to increase the long-term sustainability of food production^{133,136,137,138}.

Controlling the biological cycles of weeds: 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

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	Reduce inequalities	Enhance and sustain farm productivity
 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Responsible consumption	Reduce input of water, nutrients and energy by decreasing losses
 13 CLIMATE ACTION	Climate action	Sequester carbon and mitigate climate change
 15 LIFE ON LAND	Life on land	Increase activity and species diversity of soil biota

Table 1: Advancing sustainable development goals through management of soil health

addressed by NGOs, such as Regeneration International, the Rodale Institute, Holistic Management International and other established or newly created alternative “think tanks” on regenerative agriculture¹⁵³⁻¹⁵⁶. 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.

“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 farmers abandoned complex weed control strategies in favour of simple, cheap and effective weed control^{23,24}. As multiple resistant weeds proliferate, farmers will be forced towards more complex integrated weed management programmes that are environment friendly²³. As a consequence, this would lead to developing a fundamentally different model of agriculture based on diversifying farms and landscapes to fulfil many of the sustainable development goals (SDGs)^{23,72,73,157,158}. Sustainable management of soil health and sustainable

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.

Acknowledgement

Author: Stefan Schwarzer (UNEP/GRID Geneva).
Reviewers: We thank Pascal Peduzzi (Science Division, UN Environment) for the coordination of inputs and review during the production of the brief. We sincerely acknowledge the editorial inputs and overall review provided by Ron Witt (former UNEP staff member), Sunday Leonard (Scientific & Technical Advisory Panel of the Global Environment Facility, UN Environment), Stella Kiambi, Tabitha Kimani, and Stenely Kimereh (FAO Kenya Office).

^{iv} <https://www.dw.com/en/farming-without-glyphosate-how-would-that-work/a-41104393>

Bibliography

1. Reboud, X. *et al.* Usages et alternatives au glyphosate dans l'agriculture française. (2017).
2. Andreotti, G. *et al.* Glyphosate Use and Cancer Incidence in the Agricultural Health Study. *JNCI J. Natl. Cancer Inst.* (2017). doi:10.1093/jnci/djx233
3. International Agency for Research on Cancer, W. H. O. WHO IARC Monographs Volume 112. Evaluation of five organophosphate insecticides and herbicides. 2 (2015).
4. European Food Safety Authority, E. European Food Safety Authority. Peer Review Report on Glyphosate. (2015).
5. Friends of the Earth. *Problems with glyphosate overuse and alternatives for farmers.* 16 (2013).
6. Watts, M. *et al.* Glyphosate Monograph. (2016).
7. Benbrook, C. M. Trends in glyphosate herbicide use in the United States and globally. *Environ. Sci. Eur.* **28**, (2016).
8. Pesticide Action Network Europe. Alternatives to herbicide use in weed management – The case of glyphosate. (2017).
9. Reboud, X. *et al.* Usages et alternatives au glyphosate dans l'agriculture française. (2017).
10. Crovetto Lamarca, C. *Conservation Agriculture. Impact on farmers' livelihoods, labour, mechanization and equipment.* (Eumedia, S.A., 1999).
11. Kassam, A., Friedrich, T., Derpsch, R. & Kienzie, J. Overview of the Worldwide Spread of Conservation Agriculture. (2015).
12. Chauhan, B. S., Singh, R. G. & Mahajan, G. Ecology and management of weeds under conservation agriculture: A review. *Crop Prot.* **38**, 57–65 (2012).
13. Llewellyn, R. S., D'Emden, F. H. & Kuehne, G. Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Res.* **132**, 204–212 (2012).
14. Nalewaja, J. D. Weeds and Conservation Agriculture. in *Conservation Agriculture* 201–210 (Springer, Dordrecht, 2003). doi:10.1007/978-94-017-1143-2_25
15. Nichols, V., Verhulst, N., Cox, R. & Govaerts, B. Weed dynamics and conservation agriculture principles: A review. *Field Crops Res.* **183**, 56–68 (2015).
16. Jayasumana, C., Gunatilake, S. & Senanayake, P. Glyphosate, Hard Water and Nephrotoxic Metals: Are They the Culprits Behind the Epidemic of Chronic Kidney Disease of Unknown Etiology in Sri Lanka? *Int. J. Environ. Res. Public Health* **11**, 2125–2147 (2014).
17. Jayasumana, C. *et al.* Drinking well water and occupational exposure to Herbicides is associated with chronic kidney disease, in Padavi-Sripura, Sri Lanka. *Environ. Health* **14**, (2015).
18. Jayasumana, C., Gunatilake, S. & Siribaddana, S. Simultaneous exposure to multiple heavy metals and glyphosate may contribute to Sri Lankan agricultural nephropathy. *BMC Nephrol.* **16**, (2015).
19. Jayatilake, N., Mendis, S., Maheepala, P. & Mehta, F. R. Chronic kidney disease of uncertain aetiology: causative and causal factors in a developing country. *BMC Nephrol.* **14**, (2013).
20. Schäffer, A. *et al.* *Der stumme Frühling: zur Notwendigkeit eines umweltverträglichen Pflanzenschutzes.* (Deutsche Akademie der Naturforscher Leopoldina e.V. - Nationale Akademie der Wissenschaften, 2018).
21. Cox, C. & Surgan, M. Unidentified Inert Ingredients in Pesticides: Implications for Human and Environmental Health. *Environ. Health Perspect.* (2006). doi:10.1289/ehp.9374
22. Bai, S. H. & Ogbourne, S. M. Glyphosate: environmental contamination, toxicity and potential risks to human health via food contamination. *Environ. Sci. Pollut. Res.* **23**, 18988–19001 (2016).
23. Schütte, G. *et al.* Herbicide resistance and biodiversity: agronomic and environmental aspects of genetically modified herbicide-resistant plants. *Environ. Sci. Eur.* **29**, (2017).
24. Heap, I. & Duke, S. O. Overview of glyphosate-resistant weeds worldwide: Overview of glyphosate-resistant weeds. *Pest Manag. Sci.* (2017). doi:10.1002/ps.4760
25. Gaupp-Berghausen, M., Hofer, M., Rewald, B. & Zaller, J. G. Glyphosate-based herbicides reduce the activity and reproduction of earthworms and lead to increased soil nutrient concentrations. *Sci. Rep.* **5**, (2015).
26. Kremer, R. J. & Means, N. E. Glyphosate and glyphosate-resistant crop interactions with rhizosphere microorganisms. *Eur. J. Agron.* **31**, 153–161 (2009).
27. Shehata, A. A., Schrödl, W., Aldin, A. A., Hafez, H. M. & Krüger, M. The Effect of Glyphosate on Potential Pathogens and Beneficial Members of Poultry Microbiota In Vitro. *Curr. Microbiol.* **66**, 350–358 (2013).
28. Zaller, J. G., Heigl, F., Ruess, L. & Grabmaier, A. Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. *Sci. Rep.* **4**, (2015).
29. Druille, M., Omacini, M., Golluscio, R. A. & Cabello, M. N. Arbuscular mycorrhizal fungi are directly and indirectly affected by glyphosate application. *Appl. Soil Ecol.* **72**, 143–149 (2013).
30. Druille, M., Cabello, M. N., Omacini, M. & Golluscio, R. A. Glyphosate reduces spore viability and root colonization of arbuscular mycorrhizal fungi. *Appl. Soil Ecol.* **64**, 99–103 (2013).
31. Leigh, J., Hodge, A. & Fitter, A. H. Arbuscular mycorrhizal fungi can transfer substantial amounts of nitrogen to their host plant from organic material. *New Phytol.* **181**, 199–207 (2009).
32. van der Heijden, M. G. A. *et al.* Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. *Nature* **396**, 69–72 (1998).
33. Walder, F. *et al.* Mycorrhizal Networks: Common Goods of Plants Shared under Unequal Terms of Trade. *PLANT Physiol.* **159**, 789–797 (2012).
34. Lehman, R. *et al.* Understanding and Enhancing Soil Biological Health: The Solution for Reversing Soil Degradation. *Sustainability* **7**, 988–1027 (2015).
35. Yu, X. M. *et al.* Glyphosate biodegradation and potential soil bioremediation by *Bacillus subtilis* strain Bs-15. *Genet. Mol. Res.* **14**, 14717–14730 (2015).
36. Zaller, J. G., Heigl, F., Ruess, L. & Grabmaier, A. Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. *Sci. Rep.* **4**, (2015).
37. Motta, E. V. S., Raymann, K. & Moran, N. A. Glyphosate perturbs the gut microbiota of honey bees. *Proc. Natl. Acad. Sci.* **115**, 10305–10310 (2018).
38. Johal, G. S. & Huber, D. M. Glyphosate effects on diseases of plants. *Eur. J. Agron.* **31**, 144–152 (2009).
39. Biesmeijer, J. C. *et al.* Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science* **313**, 351–354 (2006).
40. Hallmann, C. A. *et al.* More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLOS ONE* **12**, e0185809 (2017).
41. Lundgren, J. G., McDonald, T., Rand, T. A. & Fausti, S. W. Spatial and numerical relationships of arthropod communities associated with key pests of maize. *J. Appl. Entomol.* **139**, 446–456 (2015).
42. Lundgren, J. G. & Fausti, S. W. Trading biodiversity for pest problems. *Sci. Adv.* **1**, e1500558–e1500558 (2015).
43. Aktar, W., Sengupta, D. & Chowdhury, A. Impact of pesticides use in agriculture: their benefits and hazards. *Interdiscip. Toxicol.* **2**, 1–12 (2009).
44. Chamberlain, D. E., Fuller, R. J., Bunce, R. G. H., Duckworth, J. C. & Shrubbs, M. Changes in the abundance of farmland birds in relation to the timing of agricultural intensification in England and Wales. **18** (2000).
45. Cox, C. Pesticides and birds: from DDT to today's poisons. *Wildl Dis* **24**, 51–61 (1991).
46. Donald, P. F., Green, R. E. & Heath, M. F. Agricultural intensification and the collapse of Europe's farmland bird populations. *Proc. R. Soc. B Biol. Sci.* **268**, 25–29 (2001).
47. Gibbons, D. W. *et al.* Weed seed resources for birds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. *Proc. R. Soc. B Biol. Sci.* **273**, 1921–1928 (2006).
48. Mineau, P. & Whiteside, M. Pesticide Acute Toxicity Is a Better Correlate of U.S. Grassland Bird Declines than Agricultural Intensification. *PLoS ONE* **8**, e57457 (2013).
49. Jerrentrup, J. S. *et al.* Impact of recent changes in agricultural land use on farmland bird trends. *Agric. Ecosyst. Environ.* **239**, 334–341 (2017).
50. The Royal Society for the Protection of Birds, (RSPB). State of Nature 2016. UK-Report. (2016).
51. Guerrero, I. *et al.* Response of ground-nesting farmland birds to agricultural intensification across Europe: Landscape and field level management factors. *Biol. Conserv.* **152**, 74–80 (2012).
52. Jeliakov, A. *et al.* Impacts of agricultural intensification on bird communities: New insights from a multi-level and multi-facet approach of biodiversity. *Agric. Ecosyst. Environ.* **216**, 9–22 (2016).
53. Battaglin, W. A., Meyer, M. T., Kuivila, K. M. & Dietze, J. E. Glyphosate and Its Degradation Product AMPA Occur Frequently and Widely in U.S. Soils, Surface Water, Groundwater, and Precipitation. *JAWRA J. Am. Water Resour. Assoc.* **50**, 275–290 (2014).
54. Silva, V. *et al.* Distribution of glyphosate and aminomethylphosphonic acid (AMPA) in agricultural topsoils of the European Union. *Sci. Total Environ.* (2017). doi:10.1016/j.scitotenv.2017.10.093
55. Giesy, J. P., Dobson, S. & Solomon, K. R. Ecotoxicological Risk Assessment for Roundup<superscript>-</sup> Herbicide. in *Reviews of Environmental Contamination and Toxicology* 35–120 (Springer, New York, NY, 2000). doi:10.1007/978-1-4612-1156-3_2
56. Mañas, F. *et al.* Genotoxicity of AMPA, the environmental metabolite of glyphosate, assessed by the Comet assay and cytogenetic tests. *Ecotoxicol. Environ. Saf.* **72**, 834–837 (2009).
57. Wan, M. T., Rahe, J. E. & Watts, R. G. A new technique for determining the sublethal toxicity of pesticides to the vesicular-arbuscular mycorrhizal fungus *Glomus intraradices*. *Environ. Toxicol. Chem.* **17**, 1421–1428 (2009).
58. Bringolf, R. B., Cope, W. G., Mosher, S., Barnhart, M. C. & Shea, D. Acute and chronic toxicity of glyphosate compounds to glochidia and juveniles of *Lampsilis siliquoides* (unionidae). *Environ. Toxicol. Chem.* **26**, 2094–2100 (2010).
59. Edginton, A. N., Sheridan, P. M., Stephenson, G. R., Thompson, D. G. & Boermans, H. J. Comparative effects of pH and Vision® herbicide on two life stages of four anuran amphibian species. *Environ. Toxicol. Chem.* **23**, 815–822 (2009).
60. Mesnage, R., Bernay, B. & Séralini, G.-E. Ethoxylated adjuvants of glyphosate-based herbicides are active principles of human cell toxicity. *Toxicology* **313**, 122–128 (2013).
61. Moore, L. J. *et al.* Relative toxicity of the components of the original formulation of Roundup® to five North American anurans. *Ecotoxicol. Environ. Saf.* **78**, 128–133 (2012).
62. Tush, D. & Meyer, M. T. Polyoxyethylene Tallow Amine, a Glyphosate Formulation Adjuvant: Soil Adsorption Characteristics, Degradation Profile, and Occurrence on Selected Soils from Agricultural Fields in Iowa, Illinois, Indiana, Kansas, Mississippi, and Missouri. *Environ. Sci. Technol.* **50**, 5781–5789 (2016).
63. Peterson, R. K. D. & Hulting, A. G. A comparative ecological risk assessment for herbicides used on spring wheat: the effect of glyphosate when used within a glyphosate-tolerant wheat system. *Weed Sci.* **52**, 834–844 (2004).
64. Abouzienna, H. F. & Haggag, W. M. Weed Control in Clean Agriculture: A Review. *Planta Daninha* **34**, 377–392 (2016).
65. Kremer, R. J. & Li, J. Developing weed-suppressive soils through improved soil quality management. *Soil Tillage Res.* **72**, 193–202 (2003).
66. Pesticide Action Network Europe. Alternatives to herbicide use in weed management – The case of glyphosate. (2017).
67. Ryan, M. R. *et al.* Weed-crop competition relationships differ between organic and conventional cropping systems: Weed-crop competition in organic and conventional systems. *Weed Res.* **49**, 572–580 (2009).
68. Altieri, M. A. & Nicholls, C. I. Soil fertility management and insect pests: harmonizing soil and plant health in agroecosystems. *Soil Tillage Res.* **72**, 203–211 (2003).
69. Gianinazzi, S. *et al.* Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. *Mycorrhiza* **20**, 519–530 (2010).
70. IPES-Food. From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. (2016).
71. Padel, S. *et al.* Transitions to Agroecological Systems: Farmers' Experience. 81 (2018).
72. Schütte, G. Herbicide resistance: Promises and prospects of biodiversity for European agriculture. **14** (2003).
73. Nicholls, C. I. & Altieri, M. A. Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. *Agron. Sustain. Dev.* **33**, 257–274 (2013).
74. Marshall, E. J. P. *et al.* The role of weeds in supporting biological diversity within crop fields*. *Weed Res.* **43**, 77–89 (2003).
75. Cao, Z., Li, D. & Han, X. The fungal to bacterial ratio in soil food webs, and its measurement. *Shengtai Xuebao/Acta Ecol. Sin.* **31**, 4741–4748 (2011).
76. Zhang, Q. *et al.* Alterations in soil microbial community composition and biomass following agricultural land use change. *Sci. Rep.* **6**, (2016).
77. Johnson, D., Ellington, J. & Eaton, W. Development of soil microbial communities for promoting sustainability in agriculture and a global carbon fix. *PeerJ Prepr.* (2015).
78. Nadeem, S. M., Ahmad, M., Zahir, Z. A., Javaid, A. & Ashraf, M. The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. *Biotechnol. Adv.* **32**, 429–448 (2014).
79. Ryan, M. H. & Graham, J. H. Is there a role for arbuscular mycorrhizal fungi in production agriculture? in *Diversity and Integration in Mycorrhizas* 263–271 (Springer, Dordrecht, 2002). doi:10.1007/978-94-017-1284-2_26
80. Six, J., Frey, S. D., Thiet, R. K. & Batten, K. M. Bacterial and Fungal Contributions to Carbon Sequestration in Agroecosystems. *Soil Sci. Soc. Am. J.* **70**, 555 (2006).
81. Garbeva, P., van Veen, J. A. & van Elsas, J. D. Microbial Diversity in Soil. Selection of Microbial Populations by Plant and Soil Type and Implications for Disease Suppressiveness. *Annu. Rev. Phytopathol.* **42**, 243–270 (2004).

82. Rillig, M. C. Arbuscular mycorrhizae and terrestrial ecosystem processes. *Ecol. Lett.* **7**, 740–754 (2004).
83. Rillig, M. C. & Mummey, D. L. Mycorrhizas and soil structure. *New Phytol.* **171**, 41–53 (2006).
84. Lori, M., Symnackiz, S., Mäder, P., De Deyn, G. & Gättinger, A. Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. *PLoS One* **12**, e0180442 (2017).
85. Seidel, R., Moyer, J., Nichols, K. & Bhoekar, V. Studies on long-term performance of organic and conventional cropping systems in Pennsylvania. *Org. Agric.* **7**, 53–61 (2017).
86. Romaniuk, R., Giuffrè, L., Costantini, A. & Nannipieri, P. Assessment of soil microbial diversity measurements as indicators of soil functioning in organic and conventional horticulture systems. *Ecol. Indic.* **11**, 1345–1353 (2011).
87. Roper, M. M. & Gupta, V. Management-practices and soil biota. *Soil Res.* **33**, 321–339 (1995).
88. Sherwood, S. & Uphoff, N. Soil health: research, practice and policy for a more regenerative agriculture. *Appl. Soil Ecol.* **15**, 85–97 (2000).
89. Brussaard, L., de Ruiter, P. C. & Brown, G. G. Soil biodiversity for agricultural sustainability. *Agric. Ecosyst. Environ.* **121**, 233–244 (2007).
90. Kelly, M. Meet This Third-Generation Farmer Who Converted His 1,400 Acres to Growing Organic Food. (2015).
91. TILMAN-ORG. TILMAN-ORG. Reduced TILlage and Green MANures for sustainable ORganic Cropping System. (2014).
92. van Groenigen, K.-J. et al. Abundance, production and stabilization of microbial biomass under conventional and reduced tillage. *Soil Biol. Biochem.* **42**, 48–55 (2010).
93. Kerpauskas, P., Sirvydas, A. P., Lazauskas, P., Vasinauskienė, R. & Tamosiunas, A. Possibilities of weed control by water steam. *5* (2006).
94. Virbickaitė, R., Sirvydas, A. P., Kerpauskas, P. & Vasinauskienė, R. The comparison of thermal and mechanical systems of weed control. *5* (2006).
95. Tallman, S. No-Till Case Study, Brown's Ranch: Improving Soil Health Improves the Bottom Line. *Butte MT Natl. Sustain. Agric. Inf. Serv. Natl. Cent. Approp. Technol.* (2012).
96. Liebmann, M., Mohler, C. L. & Staver, C. P. *Ecological management agricultural weeds*. (2001).
97. MacLaren, C., Storkey, J., Strauss, J., Swanepoel, P. & Dehnen-Schmutz, K. Livestock in diverse cropping systems improve weed management and sustain yields whilst reducing inputs. *J. Appl. Ecol.* (2018). doi:10.1111/1365-2664.13239
98. Bullock, D. G. Crop rotation. *Crit. Rev. Plant Sci.* **11**, 309–326 (1992).
99. Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M. & Liebman, M. Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. *PLoS ONE* **7**, e47149 (2012).
100. Kovačević, D., Dolijanović, Z., Milić, V., Gršić, N. & Kovačević, A. The effect of multi-year crop rotation on the weediness of maize. in *Book of Proceedings 2017*, 519–524 (2017).
101. Liebman, M. & Dyck, E. Crop Rotation and Intercropping Strategies for Weed Management. *Ecol. Appl.* **3**, 92–122 (1993).
102. Nikolić, L. Weed infestation and biodiversity of winter wheat under the effect of long-term crop rotation. *Appl. Ecol. Environ. Res.* **16**, 1413–1426 (2018).
103. Ramseier, H. & Crismaru, V. Resource-conserving agriculture. Under-sowing and mixed crops as stepping stones towards a solution. (2010).
104. Snapp, S. S. et al. Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agron. J.* **97**, 322–332 (2005).
105. Brust, J. Weed suppression with cover crops and undersown crops in modern cropping systems. *Gesunde Pflanz.* **63**, 191–198 (2011).
106. Fisk, J. et al. Weed Suppression by Annual Legume Cover Crops in No-Tillage Corn. *Agron. J. - AGRON J* **93**, (2001).
107. Mirsky, S. B., Gallandt, E. R., Mortensen, D. A., Curran, W. S. & Shumway, D. L. Reducing the germinable weed seedbank with soil disturbance and cover crops. *Weed Res.* **50**, 341–352 (2010).
108. Mischler, R. A., Curran, W. S., Duiker, S. W. & Hyde, J. A. Use of a Rolled-rye Cover Crop for Weed Suppression in No-Till Soybeans. *Weed Technol.* **24**, 253–261 (2010).
109. Treadwell, D. D., Creamer, N. G., Schultheis, J. R. & Hoyt, G. D. Cover Crop Management Affects Weeds and Yield in Organically Managed Sweetpotato Systems. *Weed Technol.* **21**, 1039–1048 (2007).
110. Bicksler, A. J. & Masiunas, J. B. Canada Thistle (*Cirsium arvense*) Suppression with Buck-wheat or Sudangrass Cover Crops and Mowing. *Weed Technol.* **23**, 556–563 (2009).
111. Peltonen-Sainio, P., Rajala, A., Känkänen, H. & Hakala, K. Chapter 4 - Improving farming systems in northern Europe. in *Crop Physiology (Second Edition)* (eds. Sadras, V. O. & Calderini, D. F.) 65–91 (Academic Press, 2015). doi:10.1016/B978-0-12-417104-6.00004-2
112. Eisenhauer, N. et al. Root biomass and exudates link plant diversity with soil bacterial and fungal biomass. *Sci. Rep.* **7**, 44641 (2017).
113. Jones, C. Liquid carbon pathway unrecognised. (2008).
114. Jones, C. E. Building soil carbon with yearlong Green Farming. *Evergr. Farming Sept.* 4–5 (2007).
115. Steinauer, K., Chatzinotas, A. & Eisenhauer, N. Root exudate cocktails: the link between plant diversity and soil microorganisms? *Ecol. Evol.* **6**, 7387–7396 (2016).
116. Bardgett, R. D., Wardle, D. A. & Yeates, G. W. Linking above-ground and below-ground interactions: how plant responses to foliar herbivory influence soil organisms. *Soil Biol. Biochem.* **30**, 1867–1878 (1998).
117. Snapp, S. S. et al. Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agron. J.* **97**, 322–332 (2005).
118. Sarrantonio, M. & Gallandt, E. The Role of Cover Crops in North American Cropping Systems. *J. Crop Prod.* **8**, 53–74 (2003).
119. Lu, Y.-C., Watkins, K. B., Teasdale, J. R. & Abdul-Baki, A. A. Cover Crops in Sustainable Food Production. *Food Rev. Int.* **16**, 121–157 (2000).
120. Fageria, N. K., Baligar, V. C. & Bailey, B. A. Role of Cover Crops in Improving Soil and Row Crop Productivity. *Commun. Soil Sci. Plant Anal.* **36**, 2733–2757 (2005).
121. Masilionyte, L. et al. Effect of cover crops in smothering weeds and volunteer plants in alternative farming systems. *Crop Prot.* **91**, 74–81 (2017).
122. Bonaudo, T. et al. Agroecological principles for the redesign of integrated crop–livestock systems. *Eur. J. Agron.* **57**, 43–51 (2014).
123. Russelle, M. P., Entz, M. H. & Franzluebbers, A. J. Reconsidering Integrated Crop–Livestock Systems in North America. *Agron. J.* **99**, 325 (2007).
124. Sulc, R. M. & Franzluebbers, A. J. Exploring integrated crop–livestock systems in different ecoregions of the United States. *Eur. J. Agron.* **57**, 21–30 (2014).
125. Urbatzka, P., Cais, K., Salzeder, G. & Wiesinger, K. Wirkung verschiedener Leguminosen als Untersaat im Vergleich zur Stoppelsaat auf Ertrag und Qualität der Deckfrucht Winterroggen und der Folgefrucht Hafer. in (International Conferences > 2011: Scientific Conference on Organic Agriculture > Pflanze und Boden > Fruchtfolge, Leguminosen, N2-Fixierung, 2017).
126. Brust, J. Weed suppression with cover crops and undersown crops in modern cropping systems. (2015).
127. Ramseier, H. & Crismaru, V. Resource-Conserving Agriculture: Undersowing and Mixed Crops as Stepping Stones Towards a Solution. in *Soil as World Heritage* (ed. Dent, D.) 353–363 (Springer Netherlands, 2014). doi:10.1007/978-94-007-6187-2_34
128. Ramseier, H. & Crismaru, V. Resource-conserving agriculture. Under-sowing and mixed crops as stepping stones towards a solution. (2010).
129. LaCanne, C. E. & Lundgren, J. G. Regenerative agriculture: merging farming and natural resource conservation profitably. *PeerJ* **6**, e4428 (2018).
130. Lundgren, J. G., Hesler, L. S., Clay, S. A. & Fausti, S. F. Insect communities in soybeans of eastern South Dakota: The effects of vegetation management and pesticides on soybean aphids, bean leaf beetles, and their natural enemies. *Crop Prot.* **43**, 104–118 (2013).
131. Brooker, R. W. et al. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytol.* **206**, 107–117 (2015).
132. Hödtke, M., Lopes de Almeida, D. & Köpke, U. Intercropping of maize and pulses: an evaluation of organic cropping systems. *Org. Agric.* **6**, 1–17 (2016).
133. Martin-Guay, M.-O., Paquette, A., Dupras, J. & Rivest, D. The new Green Revolution: Sustainable intensification of agriculture by intercropping. *Sci. Total Environ.* **615**, 767–772 (2018).
134. Cardinale, B. J. et al. Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proc. Natl. Acad. Sci.* **104**, 18123–18128 (2007).
135. Theunissen, J. Intercropping in field vegetable crops: Pest management by agrosystem diversification - an overview. (1994).
136. Raseduzzaman, M. & Jensen, E. S. Does intercropping enhance yield stability in arable crop production? A meta-analysis. *Eur. J. Agron.* **91**, 25–33 (2017).
137. Andreasen, C., Stryhn, H. & Streibig, J. C. Decline of the flora in Danish arable fields. *J. Appl. Ecol.* 619–626 (1996).
138. Anderson, R. L. Integrating a complex rotation with no-till improves weed management in organic farming. A review. *Agron. Sustain. Dev.* **35**, 967–974 (2015).
139. Anderson, R. L. A Multi-Tactic Approach to Manage Weed Population Dynamics in Crop Rotations. *Agron. J.* **97**, 1579 (2005).
140. Andrew, I. K. S., Storkey, J. & Sparkes, D. L. A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Res.* **55**, 239–248 (2015).
141. Cooper, J. et al. Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. *Agron. Sustain. Dev.* **36**, (2016).
142. Friedrich, T. & Kassam, A. No-till Farming and the Environment: Do No-Till Systems Require More Chemicals? *Outlooks Pest Manag.* **23**, 153–157 (2012).
143. Ashford, D. L. & Reeves, D. W. Use of a mechanical roller-crimper as an alternative kill method for cover crops. *Am. J. Altern. Agric.* **18**, 37–45 (2003).
144. Davis, A. S. Cover-Crop Roller–Crimper Contributes to Weed Management in No-Till Soybean. *Weed Sci.* **58**, 300–309 (2010).
145. Gliessman, S. R. Animals in agroecosystems. in *Agroecology: The Ecology of Sustainable Food systems* 269–285 (CRC Press, Boca Raton, Florida, 2006).
146. Lemaire, G., Franzluebbers, A., Carvalho, P. C. de F. & Dedieu, B. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agric. Ecosyst. Environ.* **190**, 4–8 (2014).
147. Hooks, C. R. R., Buchanan, A. L. & Chen, G. The Stale Seedbed Technique. A Relatively Under-used Alternative Weed Management Tactic for Vegetable Production. (2014).
148. Rasmussen, I. A. The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. *Weed Res.* **44**, 12–20 (2004).
149. Chinery, D. Using Acetic Acid (Vinegar) As A Broad-Spectrum Herbicide. 3 (2002).
150. Johnson, E. *Efficacy of Vinegar, Acetic Acid, as an Organic Herbicide: Final Report*. (Saskatchewan Agriculture, Food & Rural Revitalization, Agriculture Development Fund, 2005).
151. Ohlson, K. *The Soil Will Save Us: How Scientists, Farmers, and Foodies Are Healing the Soil to Save the Planet*. (Rodale Books, 2014).
152. Scheub, U. & Schwarzer, S. *Die Humusrevolution: Wie wir den Boden heilen, das Klima retten und die Ernährungswende schaffen*. (oekom, 2017).
153. Schwartz, J. D. & Ehrlich, G. *Cows Save the Planet: And Other Improbable Ways of Restoring Soil to Heal the Earth*. (Chelsea Green Publishing, 2013).
154. Shepard, M. *Restoration Agriculture*. (Acres U.S.A., 2013).
155. Frison, E. From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. (2016).
156. Anderson, R. L. A Multi-Tactic Approach to Manage Weed Population Dynamics in Crop Rotations. *Agron. J.* **97**, 1579 (2005).
157. Kehlenbeck, H., Salmann, J., Schwarz, J., Zwerger, P. & Nordmeyer, H. Economic assessment of alternatives for glyphosate application in arable farming. (2016).
158. Böcker, T., Britz, W. & Finger, R. Modelling the Effects of a Glyphosate Ban on Weed Management in Silage Maize Production. (2017).
159. Poux, X. & Aubert, P.-M. Une Europe agroécologique en 2050: une agriculture multifonctionnelle pour une alimentation saine. 78 (2018).

Contact: stefan.schwarzer@unepgrid.ch or charles.sebukeera@un.org