Farming without plant protection products

Can we grow without using herbicides, fungicides and insecticides?

IN-DEPTH ANALYSIS

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Can we grow without using herbicides, fungicides and insecticides?

Plant Protection Products (PPPs) are often perceived by citizens as very harmful for human health and for the environment. The tendency in EU policy is to stimulate reduction in use of PPPs.

Can we maintain high yield while using less PPPs?

This paper presents the current state-of-the-art regarding the role of PPPs in securing global food production, preserving biodiversity and supporting farmers' income. The role various stakeholders play in the current perception of risk by the general public is explored, and the paper comments on promising alternative, and more sustainable, strategies to further reduce PPP use.

AUTHORS

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Executive summary

Food security and healthy food for 11 billion people by 2100 is one of the biggest challenges of this century. It is one of the most important, if not the most important, human rights, and any agricultural system has to fulfil this requirement within the planetary sustainability boundaries. This implies that no further land increase for agriculture is acceptable, since this is the most important driver for biodiversity loss, greenhouse gas increase and environmental impact. According to scientific literature, there is no other option than to increase the global yield efficiency and reduce the yield gap to guarantee global food security. As such, one can ask the question if it is possible to maintain current yields in north-west Europe and increase yields in other regions of the world without plant protection products (PPPs) or with reduced PPP use. But how can we deal with the public perception that PPPs are unhealthy, with very negative impacts on biodiversity and environment?

PPPs include herbicides, fungicides and insecticides. PPPs can be synthetic PPPs or natural PPPs ('biopesticides'), used in organic agriculture. The amount of PPPs used has doubled since 1980 but the development of new conventional (synthetic) PPPs has decreased, partly because of legislation issues, while the number of biopesticides has increased in the last decades. The increased use of PPPs was one of the drivers of the 'green revolution', and contributed to the 2.5-times increase of crop yields in developed countries. Looking at the EU countries, there are considerable differences in PPP use and this correlates with differences in crop yield. The shift from broadly acting PPPs to more specific PPPs, that only target specific pests or diseases and avoid impact on non-target organisms, implies that farmers have to spray more with these specific acting PPPs. This is the most important reason for the recent increase in PPP use, without the positive effect on crop yield increase of the past.

The introduction of PPPs in the EU is very strictly regulated and involves a long procedure, including a science-based risk assessment. This includes an evaluation of the toxic effects on humans and other organisms. PPPs are today, when applied properly, much safer than in the past and there is a strict control on residues. A safety factor of 100 ensures a much lower risk level than other daily risks to which humans are exposed. Also the application technology of PPPs has improved considerably, which contributes to lower impacts on the environment and risks for applicants. Risk assessment costs for the crop protection industry per active substance increased from US$41 million in 1995 to US$71 million nowadays.

Crop protection not only entails the use of PPPs but also other alternative measures, such as crop rotation, the implementation of resistant cultivars (not at all or less available in many crops), soil management and others. Without PPPs, yields will be reduced, depending on the crop, and reductions of between 19 % (wheat) and 42 % (potato) have been reported. These reductions are higher in regions with high actual production, the latter also as a result of the input of fertilizers, high-yielding varieties, irrigation, etc. Without PPPs, including biopesticides, the food security of 11 billion people in the future is threatened. On the other hand, it is still an open question whether it is possible to reduce the use of PPPs without yield reduction. There are several indications that, for specific crops, a reduction in PPP use is feasible. The general tendency is that a reduction seems possible in the case of (very) high actual PPP use, but not in the case of low use.

PPPs still have unwanted and unavoidable side effects, such as their negative impact on biodiversity. However, this correlation is not always well-studied and it seems that the most important effect on biodiversity (loss) is due to land use changes. In this respect it is clear that organic farming, and its implementation in agro-ecology, is often not the best choice. At farm level, all scientific meta-studies indicate that the increase in biodiversity is rather marginal, but that, at global level, there will be a

drastic decrease in biodiversity, since organic farming is approximately 25 % less productive than conventional farming. This implies that, to feed 11 billion people, more land is needed at the expense of biodiversity. Moreover, the perception that natural PPPs, used in organic farming, are less toxic and lead to less residues is not always correct and needs further scientific confirmation.

Although there has been a lot of progress in the past concerning the impact of PPPs on humans and environment, considerable improvements are still possible. Reduction of PPP use seems one way, e.g. based on sophisticated warning and decision support systems, but such reduction is only realistic when the risk of yield or food quality reduction is acceptable for the farmer. Precision farming, including remote sensing with unmanned aerial vehicles, can also contribute to more targeted application and reduction of PPP use. An important contribution will also come from the breeding of more resistant varieties, both by classical breeding and by new breeding techniques, such as precision mutation breeding using the CRISPR-Cas approach or by genetic transformation. The latter techniques will be unavoidable to reach the SDGs concerning food security, and healthy foods with respect to the planetary sustainability boundaries.

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1 Introduction: Sustainable and healthy food production for 11 billion people

The production of high quality food for 11 billion people by 2100 and this within sustainable boundaries of the planet will be one of the biggest challenges of this century. Malthus (1798) predicted that the food availability per person would decrease because the increase in population is exponential while the increase in food production is linear. These evolutions would lead to malnutrition, health problems, more deaths and social conflicts. Today the opposite is true: there is much more food available per capita than in the past. Historically the food production increase was based on conversion of natural ecosystems to agricultural land. Land use change is by far the major driver of biodiversity loss and loss of CO_2 capture and by that has a drastic effect on the planets ecosystem, including climate change and biodiversity loss, the latter estimated at 80%. In 1960 around 1,280 million ha of crop land was available to feed 3 billion people (0.43 ha/capita, more or less constant in the traditional circular production system until 1960). Today around 1,750 million ha crops is available to feed 7.5 billion people (around 0.23 ha/capita). This increase in yield efficiency was possible thanks to the green revolution, with more external input of synthetic fertilizers and PPPs and with improved crop varieties, result of intensive breeding activities. Today we see that yield in the intensive agriculture no longer increases, indicating that the yield limit is attaint given the available cultivation techniques and varieties. This is illustrated for wheat in Europe in figure 1. It is expected that this yield efficiency is more or less at its maximum in a sustainable agriculture, unless new technologies can be implemented (e.g. CRISPR-Cas).

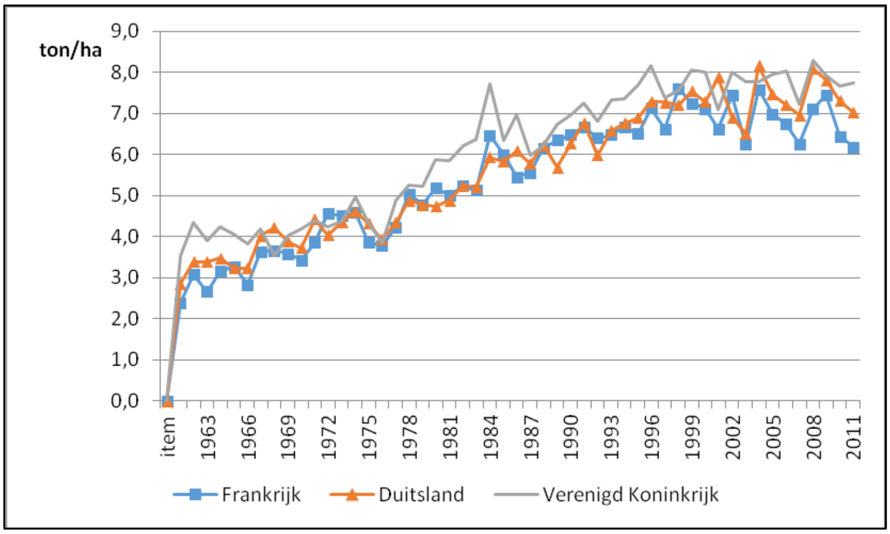

Figure 1 Evolution of wheat yields in France (blue), Germany (red) and UK (grey) (source FAOstat, 2019[1])

The increase in yield has several side effects: eutrophication of superficial water (rivers, basins…), acidification, loss of biodiversity, soil erosion,… On average, alternative production systems (e.g. organic agriculture; agro-ecology) give no better results concerning the environmental impact of agriculture (see meta-studies of Seufert *et al.*, 2012; Clark and Tilman, 2017; van Wagenberg *et al.*, 2017).

Although there is enough food today, this can become a problem in the future. The world population will still increase to an estimated maximum around 11 billion in 2100. Since more land

[1] FAOstat (2019): http://www.fao.org/faostat/en/#data/RP (January 2019)

conversion to agriculture is excluded, this can only be realized by further increasing crop yield, especially in low yield situations. On average there will be 0.16 ha available per capita in 2100, compared to 0.43 ha/capita before the green revolution. Therefore one of the most important solutions is closing the yield gap (Fig. 2). This yield gap is also in East Europe a serious problem. To close the gap, a sustainable green revolution is needed: with more or alternative fertilizers, PPPs, and irrigation, new varieties, and innovative cultivation techniques and breeding technologies. This means a sustainable intensification of agriculture, within the ecological boundaries of the planet (Willett *et al.*, 2019). Also other transitions will contribute including reduction of food losses and food waste, change in diet (less animal proteins) and a ban of crop production for bio-energy.

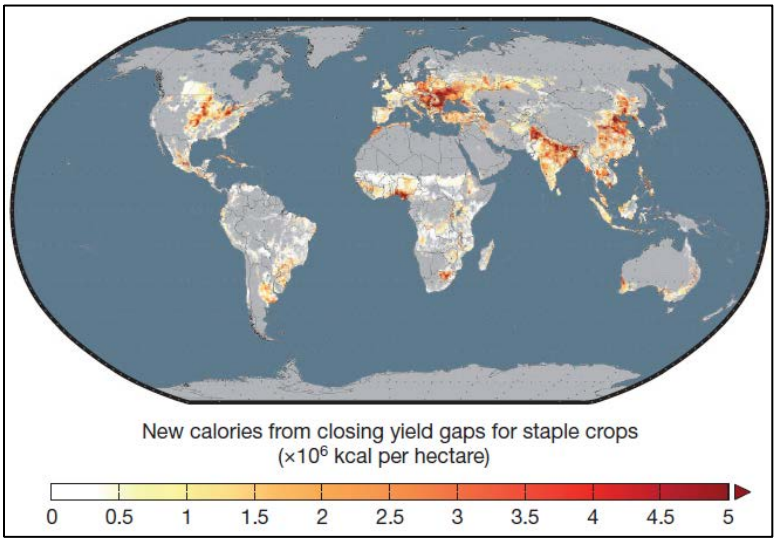

Figure 2 Closing the yield gap will contribute to more food security. In this figure more red coloration indicates a bigger yield gap for the 16 most important crops. Yield gap is defined as the gap between the optimal production in that environment and the actual production. Most of these 16 crops are not cultivated in many regions in Africa (Foley et al., 2011).

As mentioned, PPPs can help to increase the yield of food crops, besides fertilizers, new varieties and adapted cultivation techniques such as tilling instead of plowing. The parallel increase of yield and PPP use during the past decades is illustrated in figure 3. This illustrates how PPPs can help to partially close the yield gap, also in Eastern Europe.

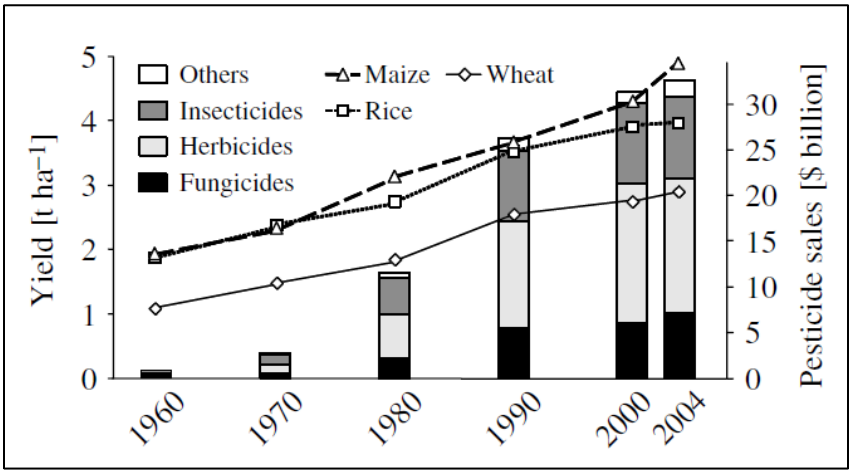

Figure 3 Increase in yield of 3 major crops and increase in PPP sales *(Oerke, 2006)*

The tendency in EU policy is to stimulate the reduction of the use of PPPs.
Is it possible to reduce the input of PPPs and maintain high yield levels?

No uniform answer to this question can be formulated and therefore we provide in this position paper scientific-based information on the advantages and disadvantages of PPP use and discuss alternative and more sustainable strategies that could complement synthetic PPPs including the implementation of resistant cultivars, biopesticides, implementation of innovative breeding technologies, precision agriculture, etc.

2 General information on plant protection products

2.1 Definitions

Plant protection products (PPPs) are products that protect plants or plant products from harmful organisms during production and storage. These products are primarily used in agriculture and horticulture but also in silviculture, home gardens and amenity areas. The term 'pesticide' is often used interchangeably with PPP, however, pesticide is a broader term that also covers biocides, products that control organisms which are harmful to human or animal health. Biocides will not be covered in this paper and therefore we will further refer in this paper to plant production products (PPPs).

PPPs include synthetic PPPs and biopesticides, products that originate from a chemical synthesis process or products derived from a biological origin (animals, plants, bacteria, minerals…), respectively. PPPs contain at least one active substance/ingredient and often contain components such as safeners, co-formulants, adjuvants and synergists. As such, active substances can be any chemical, plant extract, pheromone or micro-organism that protects plants or plant products from diseases, pests and weeds. EU legislation on PPPs is very strict and designed to ensure a high level of protection for human health and environment, making PPPs[2] among the best-studied categories of products. In the EU, no PPP can be used unless it has first been scientifically established that (1) they have no harmful effects on consumers, farmers and local residents and passers-by; (2) they do not cause unacceptable effects on the environment; (3) they are sufficiently effective against pests.

[2] http://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_IDA(2017)599428

Since 2009, PPPs are regulated by Regulation (EC) No 1107/2009 (substituted Directive 91/414/EEC), for placing a PPP on the market[1] and entails the regulation of both synthetic or bio-based (biopesticides) active substances, regardless of their mode of action, as well as safeners, synergists, co-formulants and adjuvants that are incorporated into the end products. In contrast, biostimulants, products stimulating plant nutrition processes independently of the product's nutrient content with the sole aim of improving nutrient use efficiency, tolerance to abiotic stress, crop quality traits, availability of confined nutrients in the soil and rhizosphere do not follow the strict regulation of PPPs. As such, quality control and product stewardship is often lacking. This is striking since some biopesticides and biostimulants could contain the same active substances e.g. micro-organisms.

2.2 Evolution of plant protection products

2.2.1 PPP use

As figure 4 shows, the volume of active substances used worldwide between 1980 and 2016 is still increasing and a steep increase between 2000 and 2010 could be observed which can be explained by several factors including the no-till farming, increasing the amount of herbicides used, a more productive agriculture in emerging economies and impact of climate change[3]. Herbicides are the main type of PPPs used.

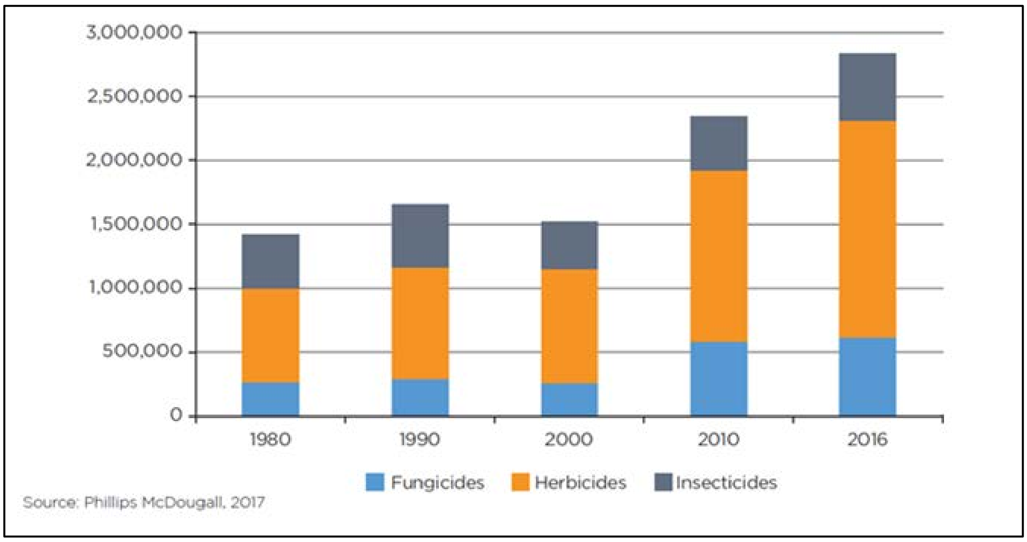

Figure 4 Crop protection volume, tonnes of active substances used globally. Data source[3]: Phillips McDougall 2017.

Since 2011, sales of PPPs in the EU are fluctuating between 350,000 and 400,000 tonnes per year[3]. Figure 5 shows the sales of PPPs by utilized agricultural area in 2014. The variation between member states is considerable.

[3] https://croplife-r9qnrxt3qxgjra4.netdna-ssl.com/wp-content/uploads/2018/11/Phillips-McDougall-Evolution-of-the-Crop-Protection-Industry-since-1960-FINAL.pdf

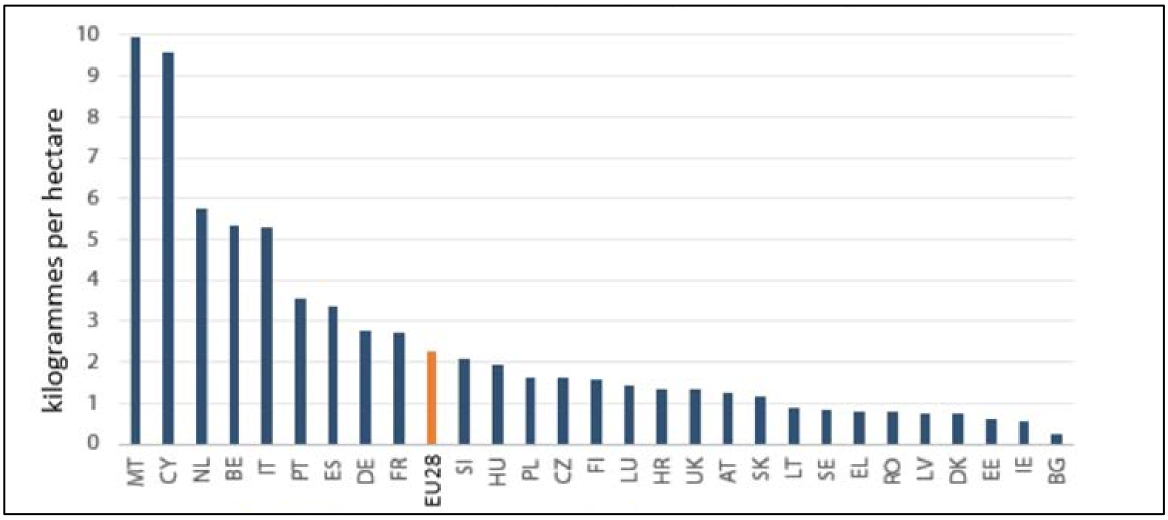

Figure 5 Sales (in kg) of PPPs by utilized agricultural area in 2014. Data source[2]: Eurostat, PP sales and land use.

2.2.2 Impact of the EU review program on active substances

In 1993, the EU launched a community-wide review for approximately all 1000 active substances used in PPPs within the EU. In this review process, each substance had to be evaluated as to whether it could be used safely with respect to human health (consumers, farmers, local residents and passers-by) and the environment, in particular groundwater, and non-target organisms, such as birds, mammals, earthworms, bees. This review program was finalized in March 2009 (Fig. 6). Under this process, industry decided not to submit dossiers for many of the active substances, for various reasons. Some were no longer profitable and better active ingredients existed. In other cases, companies realized certain active substances would not pass the stricter safety testing requirements. Many of these unsupported active substances belonged to toxic organophosphate and carbamate groups with broad spectrum activity. About 250 active substances, have passed the harmonized EU safety assessment. About 70 substances failed the review and have been removed from the market.

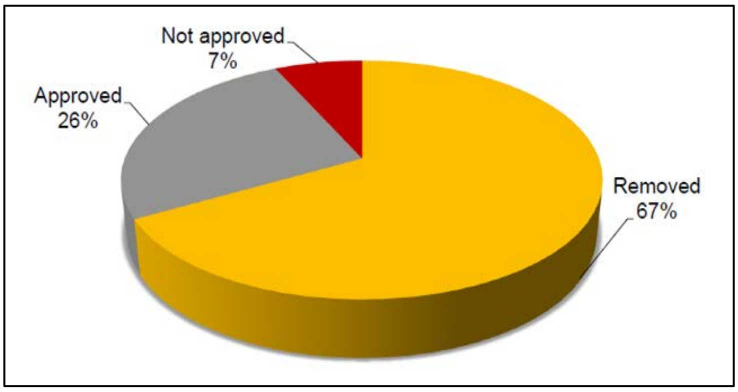

Figure 6 Overview of the results of the review program of EU on active substances.

Under (EC) No 1107/2009, any exposure, regardless of level, is deemed unacceptable when a substance triggers the hazard criteria and the product will not be registered. This regulation has had a tremendous impact on the number of active substances developed for the EU market. But also globally development of novel active substances has decreased (Fig. 7). At the moment (consulted in February 2019) 484 active substances have been approved by the EU.

The availability of less active substances could lead to more PPP resistance, as alternation of active ingredients with a different mode of action is one of the measures to prevent resistance formation. Furthermore, the tendency to go to more specific and more selective PPP's (necessary to minimize unwanted side effects) increases the risk for resistance as PPPs with a single site of action (the specific ones) are more vulnerable for resistance formation than the broad spectrum PPPs with a multiple site of action.

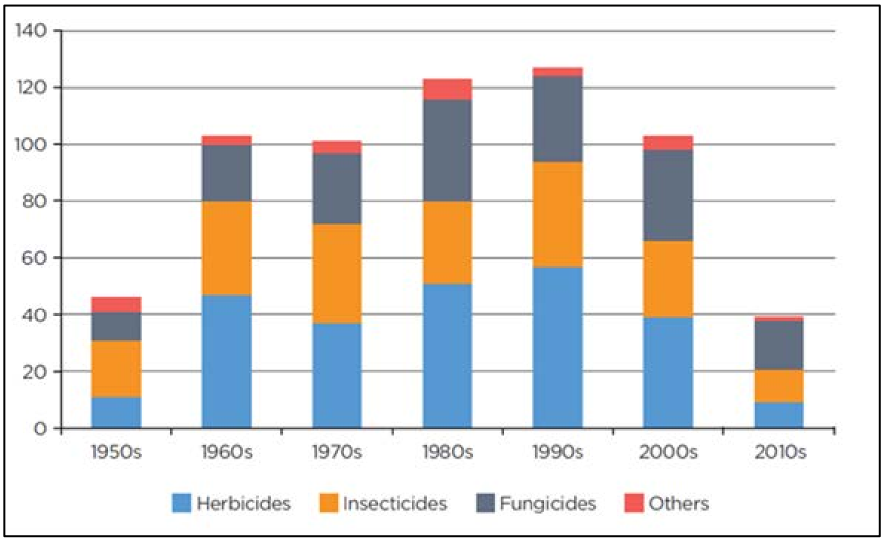

Figure 7 Number of new active substances introduced per decade. Datasource[3]: Phillips McDougall

Partially due to the strict regulations, the discovery and development costs of PPPs has almost doubled since 1995 (Fig. 8). Moreover, while it took approximately 8.3 years between the first synthesis and first sale of a PPP in 1995, it now takes 11.3 years for the same procedure.

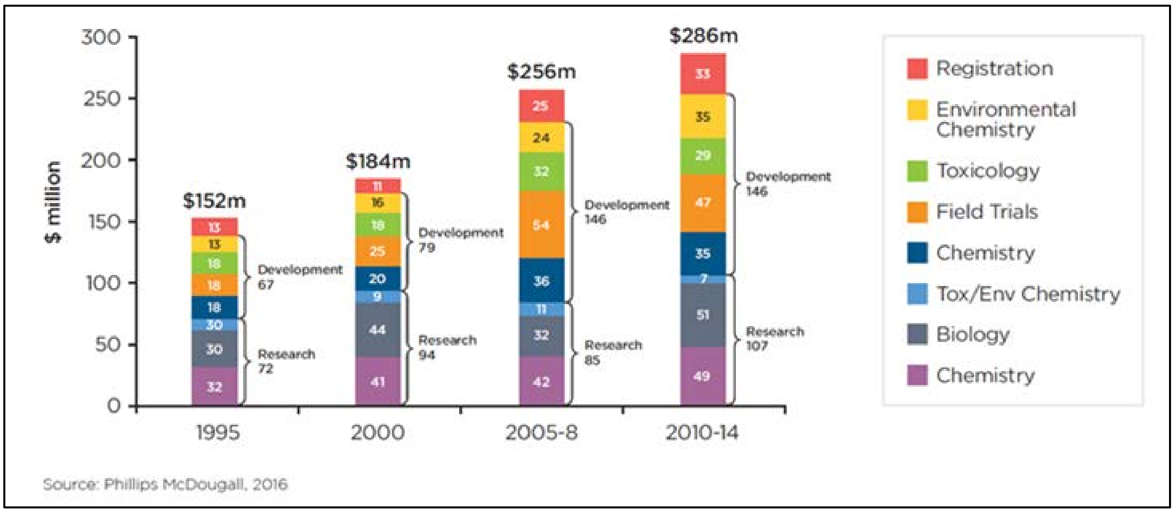

Figure 8 Discovery and development costs of novel PPPs according to Phillips McDougall[3]

In contrast, the market of biopesticides is increasing (Fig. 9) and many phytopharmaceutical companies are implementing the development of biopesticides and significantly increase their budget on this PPP segment. Biopesticides or natural PPPs are derived from plant (e.g. pyrethrum), microbial (e.g. Bacillus thuringiensis), or mineral origin (e.g. sulphur) or include living micro-organisms (biocontrol organisms: yeasts, bacteria, fungi…). The latter act via competition for space or nutrients, via the production of antibiotics, via parasitism or via the induction of plant defense. In 2016, biopesticides accounted for 5.6 % of the total crop protection sales compared to 0.4 % in 1993.

Biopesticides can be used in both organic and conventional farming. Organic farming is an agricultural production method that aims to produce food using natural substances and processes. As such in organic farming no synthetic fertilizers and PPPs can be used. The regulatory framework of organic farming follows the general structure of EU legislation with Council Regulation (EC) 834/2007.

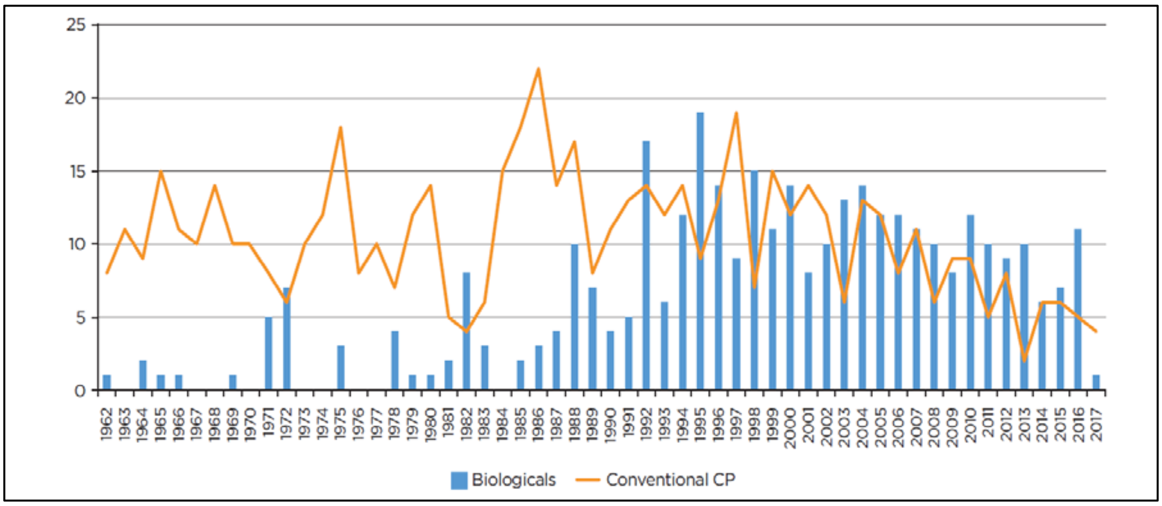

Figure 9 Annual new product introductions for biologicals and conventional PPPs (CPs)

PPP use is still increasing but in the last decade less novel active substances have been launched. On the other hand, the market for biopesticides is growing each year.

2.3 Risk assessment of PPPs

The evaluation of PPPs takes place under Directive 91/414/EEC concerning the placing of plant protection products on the market, since 2011 repealed and substituted by Regulation (EC) No 1107/2009. It is important to notice that the legislation process foresees a dual authorization system (Fig. 10): an approval at the EU level for the active substance contained in the plant protection product (PPP), and an authorization at Member State level for the PPP as placed on the market. The product registration at Member State level can only be obtained for those PPPs of which the active substances are included in a positive list (=registered) at EU level. Such registration is maximally approved for 10 years as scientific insights in risk assessments continuously progress and novel studies might be required to answer new questions.

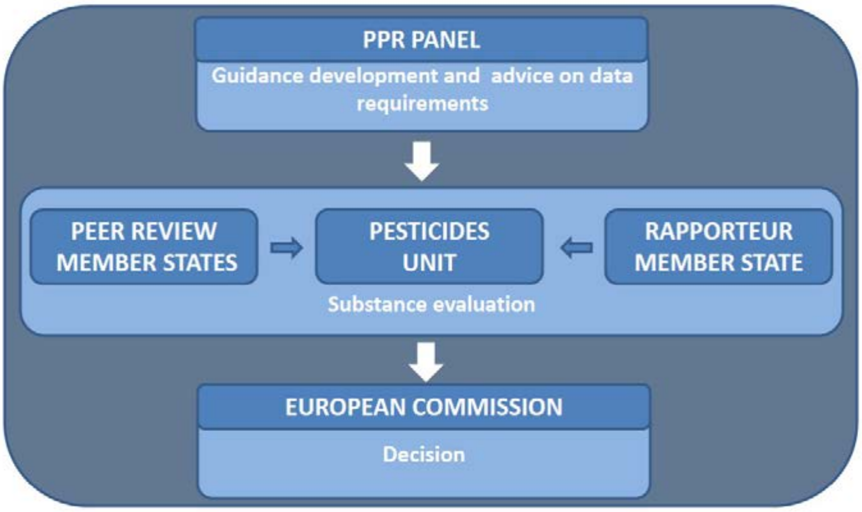

Figure 10 Risk assessment process in PPP regulation in EU (adapted from Hardy and Fontier, 2011)

The legislation establishes the data requirements for the active substance and a PPP, which should represent a typical use pattern. The requirements cover the following areas: physical and chemical properties, including methods of analysis; mammalian toxicology; residues; environmental fate and behavior; ecotoxicology and efficacy. The risk assessment methodology for the plant protection product and the authorization criteria (the so-called Uniform Principles) are developed and well described by EFSA's PPR Panel (Plant Protection Products and their Residues).

The description of the potential side effects is an important element of the testing and approval procedure for PPPs (Frische *et al.*, 2018). The direct effects of a PPP are described mainly on the basis of laboratory experiments in which indicator organisms -the so-called "non-target organisms"- such as algae, water fleas, beneficial insects, fish, earthworms, bees, birds, and rats are exposed to the active substance or the PPP. These studies are used to determine the acute and/or chronic toxicity of PPPs for those species. Generally speaking, all PPPs can be expected to have more or less severe side effects if the non-target organisms are exposed to relevant quantities. In other words: no effect (plant protection) without side effects (on organisms in the environment). However, PPPs became much more specific in the last decades. This means that because of a very specific mode of action, the PPPs are directed to specific harmful target species and do not evoke ecological deserts in the fields and surroundings anymore, which is in contrast to the broad spectrum PPPs of the '50s to '80s. Usually, the side effect profile usually corresponds to the intended effect of the PPP: herbicides are particularly toxic for algae and non-target plants that are relatives of "weeds". Similarly, insecticides are often more toxic for invertebrates like water fleas and bees.

The risk assessment of PPPs employs a tiered or stepwise approach, starting with relatively simple single-species tests carried out under worst-case exposure conditions in laboratory studies. If laboratory studies indicate an unacceptable risk, further testing under more ecologically realistic conditions is carried out, such as cage testing or field tests. Typically, lower-tier testing like lab tests are cheaper, easier to interpret and more conclusive than higher-tier testing in the field. Because of their set up, they represent a worst case scenario (maximum of exposure, …). As a consequence, the only conclusions which can be taken from these tests are 'acceptable risk' or 'needs further testing in higher-tier tests'. In the event of a negative assessment result at a lower tier based on standard data and conservative assumptions, the applicant can use a so-called "refined assessment" to show that no unacceptable environmental impacts of a PPP are to be expected under realistic application conditions. Care has to be taken that for each lower-tier test, the predictive ability of the laboratory (lower-tier) studies should be validated against PPP effects data obtained under more ecologically realistic (higher-tier) conditions (Jänsch *et al.*, 2006). Especially sub-lethal effects like e.g. the disorientation of bees should not be overlooked, as became clear after understanding some side effects of neonicotinoid insecticides.

Risk assessments are carried out to have an expert opinion whether the correct use of a PPP would lead to unacceptable risks for the user, the consumer or the environment and consists of the following main parts:

2.3.1 Toxicological and metabolism studies

Studies on absorption, distribution, metabolism and excretion in mammals, acute toxicity studies, short term toxicity, impact on genes (genotoxicity) studies, in vitro studies on cell lines, long term toxicity and carcinogenicity studies, reproductive toxicity studies, neurotoxicity studies and endocrine disruption (hormone mimicking) studies from the active substance but as well from its metabolites are included in the risk evaluation. It is important to notice that for new active substances no studies are executed on human beings (in contrast to pharmaceutical products). Nevertheless, for existing active substances which are already on the market, studies on humans like epidemiological studies, surveillance studies on workers in manufacturing plants or studies of poisoning incidents can be available and should be included in the risk assessment.

2.3.2 Residues on food or feed

To protect the consumer, residue studies have to be carried out on the consumable commodities of treated crops. Furthermore any animal produce (meat, milk, …) from animals potentially fed with treated plant(s) (parts) (e.g. poultry fed with cereal kernels, cows fed with non-commercialized apples, …) are investigated for the levels of active substance or metabolites thereof. Finally, the effects of food processing (baking, cooking, brewing, …) on the level of residue and the appearance of novel metabolites have to be investigated.

Toxicological endpoints like the Acceptable Daily Intake (ADI), derived from multiple generation chronic studies on animals, are compared to the residues which can occur on food after the intended use of the PPP as they are derived from multiple residue studies at least executed in 2 different years to include the impact of different climatological conditions. Based on those studies a European Maximum Residue Limit (MRL) and a Preharvest Interval (PHI) is established. No produce with residues above this MRL can be traded, imported or offered to the consumer. The farmer should not apply the PPP later than the Preharvest Interval, taken into account the intended harvest time of the produce, no matter whether the produce is immediately consumed after harvest or whether it is stored for a long time. Furthermore and in contrast to the US, the EU applies the ALARA (As Low As Reasonably Achievable) principle. This means that for the establishment of an MRL, the lowest value which is needed for the agronomic use can be limitative. For instance, an active substance which is applied before flowering against a pest or disease in apple orchards that doesn't exceed a residue level of 0.1 mg/kg apple whereas the toxicological acceptability could be at the level of 20 mg/kg apple. Hence, the EU will establish an MRL of 0.1 mg/kg, whereas the US would establish one of 20 mg/kg. As a consequence, the chance to exceed an MRL is higher in EU than in US, but does not necessarily mean that a toxicological threshold is passed.

To establish a Maximum Residue Limit, a default safety factor of 100 is used (more precisely in the setting of the Acceptable Daily Intake). This means that even if the level of active substance found on an edible commodity would be a 100 times higher than the MRL, no chronic effect is to be expected. One could compare this to other safety factors used in our daily life:

(1) After building engineers calculate the strength of the roof of a building, a safety factor of maximum 1.5 is used to select the thickness of the building material (steel, concrete, …);
(2) The recommended distance between 2 cars driving at 120 km/h over the highway is 60 m. A safety factor of 100 would necessitate a distance between vehicles on the highway of 6 km!

2.3.3 Fate and behaviour in the environment and ecotoxicological studies

This part includes the studies of the degradation and transport of the active substance and its metabolites in various compartments of the environment: in the soil, in water (surface water and groundwater), in river sediment and in the air with the primary goal to estimate the concentrations to which non-target organisms are exposed. Non-target organisms are considered for both the aqueous as the terrestrial compartments of the environment. For the aqueous compartment potentially occurring concentrations of active substances are tested on fish, invertebrates like the water flea, sediment dwelling insect species, algae and water plants. For the terrestrial compartments bees, beneficial arthropods (like predatory mites and parasitic wasps) and indifferent insects (springtails), earthworms and vertebrates like rodents and birds are studied. For many of these organisms both acute as chronic (including sub-lethal) effects are investigated. Non-target organisms like water fleas and algae are in particular very important as they constitute the primary level of the ecological pyramid, which means that an unintended impact on those organisms would affect all higher trophic levels in nature.

Risk assessment studies have to be executed by certified bodies under stringent quality schemes and government supervision. Good Laboratory Practices (GLP) are the recognized rules governing the conduct of non-clinical safety and risk assessment studies and are based on Organization for Economic Cooperation and Development (OECD) principles to ensure the quality, integrity and reliability of the study data. Such studies are as much outsourced as executed by the industry itself, evidently under the same quality criteria and supervision.

Sometimes people wonder why the crop protection industry is paying for risk assessment studies as they assume that results might be infringed by this kind of involvement. One has to consider however that the costs for those studies are extremely high for the tax payer as the cost of risk assessment studies per active substance raised from 41 m$ in 1995 to 71 m$ nowadays (+ 80.4 %) and are meanwhile 25% of the total development cost of a PPP[2] (Fig. 8). Of all R&D expenditures of the crop protection industry, 60.8 % is dedicated to the development and launch of new PPPs. It is also important to notice that authorities often oblige the crop protection industry to monitor their active substances post registration. In total the cost of these product monitoring and stewardship programs yet amounts to 8.7% of the total R&D budget of the company. Due to the increasing demand of studies, development time increased from 8.3 years in 1995 to 11.3 years in 2010-2015[3]. Not only the increasing costs or the prolonged time for development and registrations, especially in Europe, influences decisions of phytopharmaceutical companies to omit Europe for developments and final market entrance. Also the uncertainty of always further going of requirements contribute to such decisions of the multinational companies.

Based on the required extensive risk assessments, plant protection products and their active ingredients are one of the best-studied and safest products worldwide.

3 How do PPPs contribute to higher yields?

3.1 Crop losses and yield

Oerke (2006) has extensively studied crop losses in agriculture and is considered as the reference in this field. Crop losses can be due to weeds, pathogens, viruses and animal pests. The total crop loss without any crop protection is called the potential loss. In practice losses will be lower due to the use of synthetic PPPs (conventional agriculture), biopesticides (organic and conventional agriculture) and other cultivation measures, such as mechanical weed control, crop rotation, biological control (e.g. pheromones, biological control organisms,…) and resistant cultivars. The actual losses are those that occur when plant protection was carried out by PPPs and/or by other cultivation measures. Actual losses can be high by non-efficient crop protection or low by adequate crop protection. Crop protection becomes more important at high potential yields. Under these conditions the impact of PPPs is high and will substantially decrease potential crop losses and increase crop yield (Aktar *et al.*, 2009).

Worldwide potential and actual crop losses differ considerably according to crops (Fig. 11) but also according to regions. Potential losses vary between around 80% (rice and potato) to 60% (soybean) and 55% in wheat. Weeds are the most dominant contributor to the losses. Actual losses are around 40% in rice and potato, 30% in wheat and 26% in soybean. Considerable losses are as well caused by animal pests and diseases.

Potential and actual losses differ also between regions: potential losses are 71% in N-W Europe, 63% in S-W Europe, 52% in both N-E and S-E Europe, while actual losses are 18%, 25%, 30% and 32% respectively (Oerke, 2006). The considerable reductions in food losses in Western Europe can be attributed to the more intensive use of PPPs. The lower yields in Eastern Europe are due to a substantial yield gap (Foley *et al.*, 2011), and less input of PPPs and fertilizers (Our World in Data, 2019, FAOstat, 2019). Here, a more or better optimized use of PPPs will contribute to improved crop yield. However, it doesn't make sense to invest in PPPs when other factors are sub-optimal: fertilizers, adapted varieties, irrigation, other culture techniques (e.g. soil management).

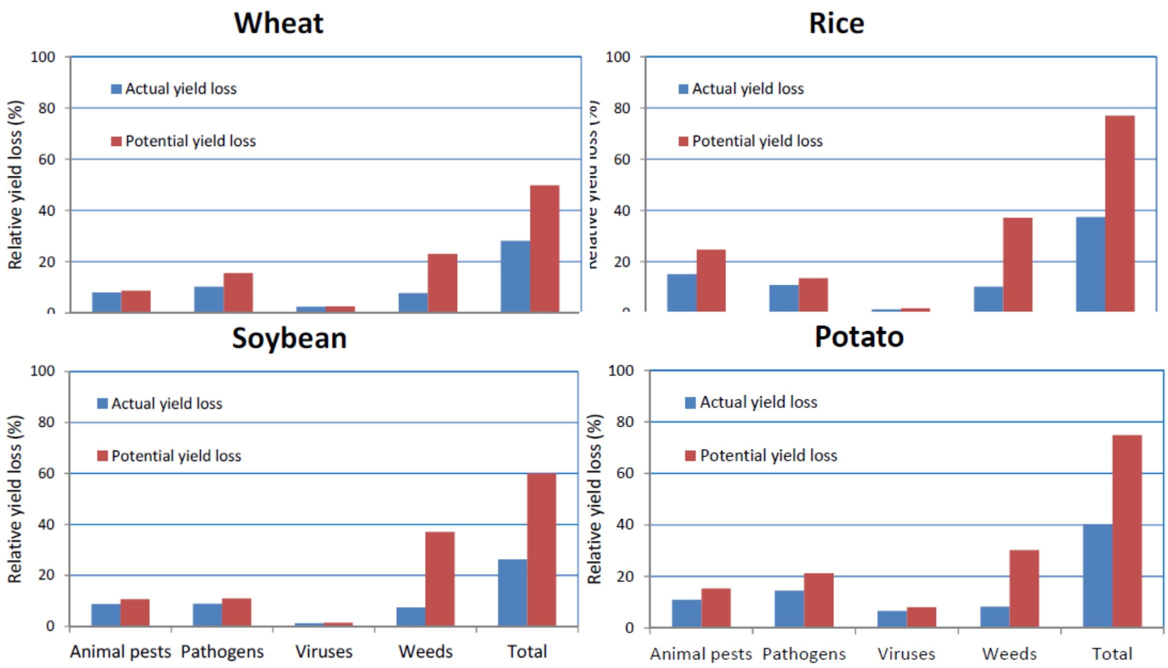

Figure 11 Effect of weeds, diseases, animal pests and viruses on worldwide potenial crop losses and actual losses in different crops *(Oerke, 2006).*[4]

It is expected that climate change will result in a temperature rise of 1.5-2 °C and in more irregular precipitation with more rainfall in some regions (e.g. Eastern Europe) and more drought periods in other regions (e.g. South Europe). According to Deutsch *et al.* (2018), global yield losses are projected to increase by 10 to 25% per degree of global mean surface warming. Crop losses will be most acute in areas where warming increases both population growth and metabolic rates of insects. These conditions are centered primarily in temperate regions, where most grain is produced. Moreover, it is likely that new pest and diseases will threaten crops in the future, at least at the local scale. More and new infestations will stress an adequate crop protection with (new) PPPs, unless alternatives can be developed.

Meite *et al.* (2018) demonstrated the export of fungicides, herbicides and heavy metals (Cu and Zn) from agricultural soils by different rainfall patterns. Export was in a decreasing order: fungicides, herbicides, copper and the lowest run-off for zinc. Heavy rain patterns and a longer rain period have most effect. These patterns are more expected in the case of climate change. The effect depends on soil type and compaction of the soil.

3.2 PPPs and their effect on yield

Quantitative scientific studies on the effect of PPPs on yield quantity and quality are limited. Exact relations between yield and PPP use is difficult to prove with experimental data. Effects are based on simulations, assumptions and/or interpretations of PPP application schemes by experts. Rough estimates of the reduction in yield losses are around 80% of the potential loss when PPPs are banned and crop protection is carried out by other cultivation measures. This percentage depends to a very large extent on crop, region and potential yield. Japanese research simulated the effects of PPPs and fertilizers on wheat yield and quantity (Kawasaki and Lichtenberg, 2015). In all fields studied over

[4] https://inra-dam-front-resources-cdn.brainsonic.com/ressources/afile/416601-2607f-resource-crop-losses-conference-keynote-willocquet.pdf

the period 1995-2006 fertilizers and PPPs were used, but in different amounts. This research revealed that fertilizers had the highest impact on wheat quality and quantity, followed by fungicides and insecticides and herbicides .

Based on available data we estimate the yield gain by use of PPPs between 19% for wheat to 42% for potato; while rice, maize and soybean have comparable yield gains by PPPs, around 30% (Table 1). These numbers are based on global data and it is expected that gains are higher in high productive cropping systems compared to low productive systems, where other culture measures are growing conditions like soil or climate are often sub-optimal.

Table 1. Potential food losses, food losses with and without PPPs, and gains by using PPPs for 5 major crops. Losses are calculated at the global scale and are caused by pathogens, pests, viruses and weeds. Crop protection without PPPs include crop rotation, biological control, soil management, resistant varieties…

Crop	% losses with PPPs*	% losses without PPPs ** (own estimation)	% potential losses ***	Yield gain by PPPs
Wheat	21% (10.1-28.1)	40%	50%	19%
Rice	30% (24.6-40.9)	62%	77%	32%
Maize	22% (19.5-41.1)	55%	69%	33%
Potato	18% (8.1-21)	60%	75%	42%
Soybean	21% (11-32.4)	48%	60%	27%

*: Savary *et al.*, 2019; **: estimated at 80% of the potential losses; ***: Oerke, 2006

In Denmark, farms specialized in potatoes, sugar beet and grass seeds lose 270 Euro/ha when PPPs are banned, but the study also pointed out that in general the use of PPPs can be substantially reduced without dramatic economic losses, e.g. by including crop rotation and adapted cultivation systems[5].

According to Lechenet *et al.* (2014) low PPP use will not reduce high productivity or high profitability of arable crops in France in 77% of the farms, included in their study. In 59% of the farms there is 42% reduction of total PPP treatments (treatment frequency index) possible without negative effects on profitability and productivity: 37% herbicide reduction, 47% fungicide and 60% insecticides. Most reduction is possible in farms with high PPP use. For the production of industrial crops, the reduction of PPPs become in some cases negative (23% of the farms). Also according to Jacquet et al. (2010), a reduction of PPPs in French field crops is possible by 30% without reducing farmer's income. For the US, Pimentel *et al.* (1993) suggested that a reduction of PPPs by 50% in the US is achievable without crop losses. To reach this goal, crop fields needed to be much more controlled for pest and diseases by adjusting the PPP schemes. In rapeseed it was suggested that the herbicide dose might be cut by at least 50% in order not to jeopardize negative effects on production and economic performances. But although the income reduction from 812 to 748 euro/ha was not significant, it is still substantial.

It remains an open question if a reduction in PPP use is achievable in all crops and all circumstances without negative effects on yields, crop quality and farmers income. Many studies show inconsistent

[5] https://ageconsearch.umn.edu/bitstream/6957/2/cp02or02.pdf

results of the effect of PPP reduction and productivity or profitability, especially when organic (lower use) and non-organic farmers (higher use) are compared (Seufert *et al.*, 2012; Lechenet *et al.*, 2014).

We can conclude that agriculture without PPPs, including biopesticides, can considerably reduce crop yields and increase yield instability. Food quality will decrease as well as food safety (increase in e.g. mycotoxins). All these aspects will have a negative impact on farmers income and food security and banning PPPs is therefore unrealistic. Food production reduction is unacceptable when we have to feed more than 11 billion people by the end of this century.

On the other hand the reduction of PPP use needs more attention. First results indicate that this seems promising, but solid data over a sufficient long period are lacking to advise farmers to do so. We have also to consider that production systems become more complex and more difficult to manage when PPPs are reduced. The latter will increase the risk while the gain is unclear. On top adequate monitoring and good prediction models are needed. In §6 we will consider alternatives or additional measures to reduce pesticide use (e.g. precision farming, resistant varieties, improved monitoring and prediction models).

A ban on PPPs will reduce crop yield by around 20-40%, depending on the crop. PPPs are a risk insurance for the farmer. Therefore, reduction of PPP use needs more research and will depend on the actual management scheme of PPPs and the crop.

4 Humans and their relation with PPPs

4.1 Are PPPs 'per definition' bad for human health?

It is an understatement that intensive agriculture and PPP use is a high concern of the general public. Recent issues as the suspected carcinogenicity of glyphosate and the concern about the neonicotinoid insecticides contributing to bee decline do have a serious negative impact on the general public's opinion on the use of PPPs in modern agriculture (see box 1[6,7]; Lins and Staes, 2018 and box 2; Steinhauer *et al.*, 2018). Moreover, some NGO's oversimplify the message and make the general public believe that PPPs are 'by definition' bad for the human health and the environment whereas their use can easily be avoided without losing quality or quantity of the agricultural produce. As a consequence, the general public doesn't understand why PPPs are not yet forbidden. This provokes a political reaction as can be noticed by the installation of a special committee to comment on the Union's procedures for authorization of PPPs (Lins and Staes, 2018), which was voted on 16 January 2019 with 88.4% of the EU parliament members in favour of substantial improvements of the current procedure.

[6] EPA's Office of Pesticide Programs (2017). Revised Glyphosate Issue Paper: Evaluation of Carcinogenic Potential. 216 p.

[7] De Standaard (2017). Nog snel Roundup of toch maar azijn of javel?, http://www.standaard.be/cnt/dmf20170607_02914850

Box 1: Confusing news on carcinogenicity of glyphosate

In 2002 glyphosate was included in Annex I of Plant Protection Directive (91/414/EEC) with Germany as a rapporteur member state. In 2015 the International Agency for Research on Cancer (IARC) classified glyphosate as probably carcinogenic to humans (which is a classification comparable to the one of red meat). After reviewing the available information and the IARC conclusions, the European agencies EFSA and ECHA concluded that no classification as carcinogenic was warranted. Whereas IARC based its conclusion on published literature, EFSA and ECHA additionally used unpublished studies submitted by Monsanto. Several other competent authorities around the world, including those of US, Canada, New Zealand, Australia and Japan, have subsequently finalized a new assessment of glyphosate and concluded that the herbicide is not carcinogenic (EPA, 2017 - *footnote 6, page 14*). Over one million EU people meanwhile called on the Commission to ban glyphosate. In parallel to this call, Belgian citizens were hoarding glyphosate-based products to continue weed control in their gardens after its ban (De Standaard, 2017 - *footnote 7, page 14*).

Box 2: The role of neonicotinoids on bee decline

Honey bee colonies are collapsing in many parts of the world at a worrying speed. Most specialists currently agree that the major driver for this decline is caused by parasitic mites, of which Varroa is the most important and best known one. More recently, it was found that viruses contribute as well to the decline. Moreover, certain viruses like the Deformed Wing Virus act synergistically and increase the hazard caused by Varroa mites. Furthermore, American and European foulbrood (bacteria) weaken colonies as well. Land use changes and loss of biodiversity cause malnourished colonies which can rapidly collapse. Whereas ancient insecticides usually caused an acute poisoning, neonicotinoids have sub-lethal effects like disorientation, reduction of queen fecundity, … Effects of PPPs synergize with nutritional stress. Finally, bee-hive survival strongly depends on the beekeeper competence and management practices. Who is at fault?

4.2 Information, opinions and perception

Various stakeholders have unilateral and often biased opinions. Mass media rarely change existing attitudes but rather reinforce messages and strengthen public perception by repetition. Accuracy, objectivity and sourcing are identified as problems. However, a more balanced message of academics is neither understood nor appreciated by the general public. A 1999 study in 5 different countries divulged that 40-60% of the consumers trusted NGO's messages about food safety, which was higher than the percentage of consumers trusting scientists (29-49%) and considerably higher than consumer's belief in the message of the authorities (9-27%). Not surprisingly, the industry was least trusted (2-6%) (Poortinga *et al.*, 2000).

This results in an apparent paradox. Most toxicological and epidemiological studies demonstrate that in the European Union people live ever safer and more secure lives and enjoy a higher average life expectancy than any previous generation[8]. Apart from old-age diseases like dementia, people are suffering from fewer life-threatening and chronic diseases than their ancestors. Most people in Europe, however, feel that risks to life and health have steadily grown over time and that in particular environmental health risks caused by chemicals and pollutants have increased in volume and intensity. Nowhere is this discrepancy more evident than for the risks associated with food production and nutrition. Giving credence to popular surveys, food scares top the list of fears and

[8] https://www.sapea.info/wp-content/uploads/SS-PPP-for-publication-June.pdf

worries shared by the European public. People are highly sensitive to health hazards associated with alimentation and have a keen interest in real and perceived risk assessment. More than 70 % are convinced that the dangers associated with food will increase in the future[6]. From all potential risks in the house, PPPs are appointed by 70% of the Europeans as the most risk bearing chemicals in the home (Eurobarometer, 2009) illustrating the chemofobia of Europeans.

More specifically, the public's ranking of risks from food consumption is diametrically opposed to the ranking by food scientists as is shown in Table 2 (Whitford F., 1993).

Table 2: Perception of risk from food consumption (Whitford, 1993)

Public Ranking	Food scientist ranking
Food additives	Microbial contamination
PPP residues	Nutritional imbalance
Naturally occuring toxicants	Environmental contaminants
Environmental contaminants	Naturally occuring toxicants
Nutritional imbalance	PPP residues
Microbial contamination	Food additives

4.3 Risk communication

Communicating risk of food and agriculture bears obstacles for policy makers, stakeholders and consumers. Multiple actors are involved in risk communication, resulting in conflicting messages that make it difficult to build trust and transfer reliable information. Cultural differences, including the language, between those seeking for information and risk managers cause additional problems that need to be addressed by risk communicators. Different channels of communication are used by different social groups, enforcing perception biases in society. While social media have become increasingly important nowadays, many groups still rely on traditional media. As a result of different information from different sources, researchers are not considered impartial, but are often seen as biased members of different parties. Some researchers are framed as ideology-driven and others are suspected to work on demand for non-governmental organizations (NGOs) or the chemical industry. This makes it even more difficult to build a trustful relationship between risk managers and the targeted audiences. The greatest obstacle for trust in risk communication seems to be uncertainty, but it was learned that the challenge the society is setting for those involved in risk assessment is to ensure more transparency, on input data quality, assessment procedures and on resulting uncertainty (Wilks *et al.*, 2015).

Successful risk communication needs clear messages. Communicators should engage trust by focusing on benefits, without ignoring the uncertainties. Being more honest with perception goals seems to be more useful, than to elaborate on uncertainties. The goal is to influence human behavior with action-oriented, illustrative risk communication methods, not lengthy comprehensive reports. Successful risk communication has to acknowledge that risk perception is an essential part of handling risk in society and has a strong influence on how a society copes with uncertainty and ambiguity. Risk communicators put risks in context, include different perspectives on how to interpret risk assessment results, and focus on benefit-oriented, empowering messages. Most importantly, risk communication has to show the boundaries between what is possible, likely, certain or definitely wrong or absurd. The worst that could happen would be that people believe that risk assessments are arbitrary and their results depend on who pays for them[6].

Successful risk communication needs clear messages. Communicators should engage trust by focusing on benefits, without ignoring the uncertainties. The worst that could happen would be that people believe risk assessments are arbitrary and their results depend on who pays for them.

4.4 Farmers and PPPs

Farmers consider PPPs as a necessary, but also expensive input of their production systems. One has to admit that –though insights are broadened every day- agronomists, advisors or farmers are usually not able to exactly determine the timing of appearance or infection, the level of population of pests or pathogens or the severity of final damage or diseases of the crops. This is caused by a lack of fundamental knowledge of the biology of the diseases or pests, the exact impact of local influencing circumstances (pest pressure, presence of natural enemies like predators and parasitoids, microclimate, cultivar sensitivity, …) and a reliable weather forecast for the next 2–3 weeks. A strict implementation of IPM principles which allow the use of chemicals only as a last resort (when biological or physical control measures have failed), does also have a back side of the medal. Chemical treatments, if necessary, are applied shorter to harvest and could lead to a higher exposure of the consumer. PPPs are often used as an insurance for the farmer to reach a close-to-perfect product. In certain cases, PPP use can afterwards certainly be shown to be redundant. In other cases their non-use or reduced use would result in damage going from small imperfections to a total loss of the final produce.

4.5 Consumers and PPPs

This brings us to another discrepancy: consumers generally expect the minimization or avoidance of the use of PPPs but still, they expect agricultural products as fruits and vegetables to look perfect. This translates in the price a farmer gets for any imperfect product. As this is usually below the production cost, a considerable part of PPs is used to avoid any imperfections, even if they are just cosmetic and do not cause any human health risk or any impact on taste, flavour or shelf life. Research showed that suboptimal products can be sold but only when consumers receive a discount that fits the sub-optimality (de Hooge *et al.*, 2017). Reduced PPP use, which would be feasible according to §3.2, might convince consumers to accept imperfections, but the only determinant to realize a shift in willingness to buy is information (Bunn *et al.*, 1990).

Measuring the value consumers put on PPP reduction is of interest in order to assess the variation of surplus in welfare analysis and to evaluate the potential market for farmers who could take advantage of the growing demand for PPP-free products. Bazoche *et al.*, (2014) showed that consumer's behavior in this respect is quite similar throughout Europe. After being informed on the PPP use, consumers are willing to purchase more organic products, but taste is always a more important determinant of choice. In Europe market prices of organic products are generally twice as high as prices of their regular counterparts. This gap is larger than the average consumers are willing to pay, which is the main reason for the small market shares of organic products in Europe (< 5%). The same study also indicates that clear labelling is key to valorize this organic produce and that retailers are not seen as a trusted third party to guarantee this effect. If an independent body certification under governmental control is executed and familiar for consumers, the value of initiatives for PPP reductions in IPM products is often close to organic products. Importantly, it could also be shown that communication on the presence of PPPs on regular produce does not necessarily increases the buying of organic fruit and vegetables, but could result in a lesser buying of fruits and vegetables (Huang *et al.*, 2016).

The agricultural product without imperfections, which the average consumer is looking for can often only be produced by using PPPs. Only prices commensurate to this 'perfect' product quality cover the production cost. However, the consumer expects this product to be produced without PPPs.

4.6 Most recent evolutions in the market

Currently, prices that farmers receive for their produce is often too low to have a decent income. Many farmers show recently a lot of eagerness to switch to organic production in order to obtain better prices. However, one has to realize that rules of supply and demand play in this market as well. Though annually increasing, still a limited percentage of the consumers is willing to pay the extra price for organic products. If the supply for this niche market is fulfilled, prices will drop to levels which do not compensate for lower yields and higher waste, a scenario which is feared by the current organic farmers.

PPPs have contributed since the 60s to high yields and affordable food prices in a way that in countries like Belgium only 12% of the income is in average spent on food. When PPPs use is prohibited, it is to be expected that food prices will rise again. This will influence the buying of fruits and vegetables by lower income classes of the population as this part of the population might switch from fruits and vegetables to cheaper high fat and sugar food products (Huang *et al.*, 2016). As the risk of PPPs for human health is considered to be much lower than the health risk by a nutritional imbalance of sugar and fat and a reduced uptake of anti-oxidants, vitamins and fibers which are typically present in fruits and vegetables. As a consequence, the prohibition of PPPs might indirectly lead to more health problems related to obesities, diabetes, cancer and neurodegenerative diseases as Parkinson, Multiple Sclerosis and Alzheimer.

Another recent development of concern are the extralegal requirements for PPP residues put forward by retailers. Very stringent procedures are in place to establish a Maximum Residue Limit (MRL). However, some supermarkets started a commercial strategy of differentiation from competitors by including extra standards such as a maximum of 33% of this MRL, a maximum of cumulative residues expressed in % of MRL or a restriction of the number of residues, … At first sight, it could be commendable to minimize extra exposure of consumers, however this hype needs further consideration. If farmers do not fulfil these extra requirements, they are excluded for supplying these (often important) retailers. As supermarkets count for 70% of fruits and vegetables buying, most farmers try to satisfy these extralegal requirements. However, this phenomenon implies some ethical and agronomical drawbacks. Firstly, the risk is 100% at the farmer's side. If for instance fruits are not treated for storage diseases, a huge percentage of fruit risks to be infected after several months of storage, for which the farmer is not compensated. E.g. in the case of apple this can add up to > 50%. Secondly, these requirements trigger the repeated use of always the same PPP because this will not increase the number of residues. Moreover, a minority of PPP is used over and over again because they are not found by the current multi-residue analyses, which gives a false perception to the consumer. Moreover, the risk of development of resistance of pests and pathogens against these frequently used PPPs cannot be overestimated and is against recommendations of the phytopharmaceutical industries and IPM experts. As Europe follows the Alara-principle (As Low As Reasonably Achievable), a further reduction of dose rates in most cases conflicts with the proposed use pattern, the latter is only approved after spending millions of euro on expensive studies to support these conclusions.

It is all about the acceptance of risk. Scientifically a 'zero risk' doesn't exist and therefore conclusions are often categorized as 'acceptable risk'. People who target zero risk in life will never accept the use of PPPs. But shouldn't those people avoid as well the risk of crossing the street, the risk of eating food because of potential microbiological contamination and the risk of drinking alcohol or eating sugars and fats? Shouldn't they avoid wearing clothing, touching surfaces or using cosmetics which all can contain biocides? Should those people expose themselves to the sun? Isn't risk inherent in life?

People who aim at zero risk in life will never accept the use of PPPs. However, isn't risk inherent in life? Even staying in bed will have a significant negative health effect in the meium to long term.

5 Can we reduce the use of PPPs to increase biodiversity and reduce environmental impact?

In this paragraph we will focus on which strategies can be followed to reduce the use of PPPs and will evaluated their impact on biodiversity and other environmental sustainability factors. These strategies will include integrated pest management (IPM), organic farming and other alternative production methods as well as the implementation of novel breeding technologies and precision agriculture.

5.1. PPPs and biodiversity

The use of PPPs negatively influences biodiversity. However, this should be put in a correct context. The main impact on reduction of biodiversity is the altered land use, habitat loss and fragmentation, which counts already for 80% of the biodiversity reduction. A study of Sánchez-Bayo and Wyckhuys, (2019) confirms the high impact of land use change on biodiversity loss, but they claim that a major driver of biodiversity loss is the intensification of agriculture. The latter conclusion is not well supported by solid quantitative data. They mention as other important drivers for biodiversity loss biological factors (e.g. parasites and pathogens, sometimes due to invasive species), climate change and pollution. For the latter their study is biased in favor of organic agriculture as they state that synthetic PPPs in intensive agriculture contribute directly to biodiversity losses by toxicity and by their contribution to more eutrophication and acidification than organic agriculture does. When natural PPPs work properly, one would expect the same effect as for synthetic PPPs, although other but less efficient measures for plant protection can be implemented in organic farming. But the statement that the choice for organic farming will reduce eutrophication and acidification in comparison to conventional agriculture is not correct, the opposite is true, as was demonstrated with quantitative data by Clark and Tilman (2017) in their metastudy.

Another metastudy showed that species richness could be 30% higher in organic production, but this is rather due to differences in fertilization than to PPP use (Tuck *et al.*, 2014). Amongst academics an intensive debate whether land sharing (more extensive low yield agriculture, inclusion of more biodiversity in production systems) or land sparing (intensive agriculture with high yields next to maximal biodiversity areas) is most beneficial for biodiversity is kept. However, the outcome of this debate will depend on various factors like the local situation, the scale and the crops considered (Egan and Mortensen, 2012; Valin *et al.*, 2014). Most researchers agree that more extensive agriculture around nature reserves can act as a buffer for biodiversity. A more detailed comparison of biodiversity in organic and conventional production systems is presented in §5.3.

Land use for agriculture is inevitably related to loss of biodiversity. Management techniques such as use of PPPs have by definition a negative impact on biodiversity, but this loss is by far surpassed by the higher land use in extensive production systems.

5.2. Integrated Pest Management

Another important EU regulation within crop protection includes the implementation of Integrated Pest Management (IPM) which is compulsory in EU since 2014. In general IPM is defined as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep PPPs and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms. For technical reasons, IPM is much more advanced in some crops (i.e. fruiting vegetables, fruit, …) compared to others (arable crops, leafy vegetables with short production cycles, …). However, since the implementation of Directive 2009/128/EC, most crops have established IPM practices and most EU countries have drawn up National Action Plans to implement the range of actions set out in the Directive. In contrast to what policy makers or consumers assume, IPM measures do not always lead to lower PPP use (expressed as number of applications or as kg active ingredient per hectare) for two reasons. Firstly, broad spectrum PPPs, which are active against a whole range of organisms and which are not selective for beneficial or indifferent organisms, make it possible to target several harmful organisms in once at specific timings of the cropping season. Their side effects on non-target organisms do not allow their use in IPM and therefore more selective PPPs are used, urging repeated applications or tank mixes of selective PPPs when multiple pests appear at the same time. Secondly, former PPPs were rather persistent and could cover a longer period of protection. Unfortunately, the persistence continues in the environment and causes long lasting effects on non-target organisms and/or accumulation in the environment. Nowadays, PPPs degrade much faster, which in particular situations necessitates to retreat at shorter intervals. Changes in characteristics of PPPs over the last decades are shown in Fig. 12. In conclusion, IPM incorporates a large range of practises but does not explicitly state the degree of PPP reduction at farm level. This is why producers have not yet been able to send a clear signal about IPM to consumers in contrast to the organic producers, which made from 'organic' a very strong brand, for which the perception is stronger than the promises. Indeed, consumers generally are convinced that organic produce is not treated with PPPs, which is not the case albeit that it is only treated with non-chemical PPPs. Biological PPPs can be as toxic for human health or for the environment as chemical ones, but degrade usually much faster (except minerals like copper, sulphur, …).

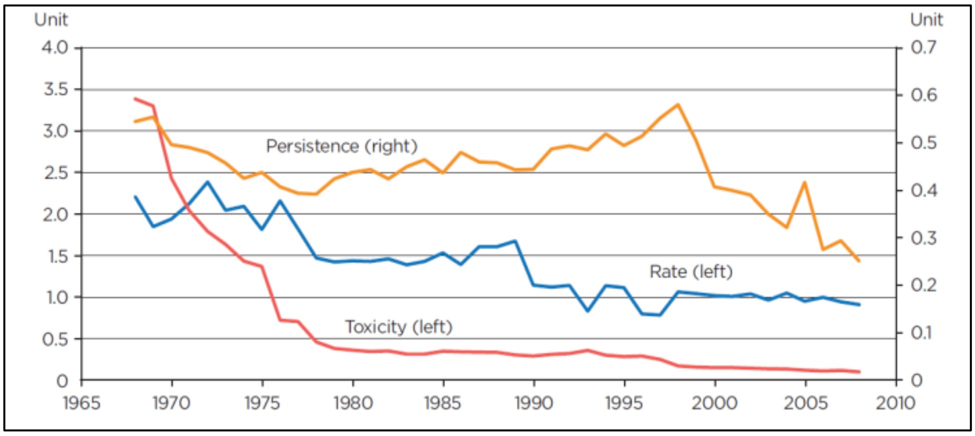

Figure 12 Average quality characteristics of PPPs applied to four major US crops, 1968-2008. *Datasource*[3] **.** (Fernandez-Cornejo *et al.*, 2014) ***Rate, pounds of active ingredient per acre times the number of applications per year. Toxicity index is the inverse of water quality threshold and serves as the environmental risk indicator for human drinking water. The persistence indicator is defined by the share of PPPs with a half-life less than 60 days.***

The implementation of Integrated Pest Management, compulsory in the EU since 2014, aims to reduce or minimize risks of PPPs to human health and the environment. However, IPM does not always lead to lower pesticide use.

5.3. PPPs and organic agriculture

By intuition most people perceive organic agriculture as a more environmental friendly production system. Several publications claim a reduction of the environmental impact by organic agriculture because no use of PPPs (e.g. Muller *et al.*, (2017) and publications therein), the latter is not completely correct. Biopesticides are increasingly used in organic agriculture and account in 2016 for 5.6% of the total PPP sales (§2.2).

Since it is generally accepted that biopesticides have less toxic effects for both target and non-target organisms than synthetic PPPs applied in conventional agriculture, it seems logic that they have less impact on biodiversity and water pollution. But biopesticides in organic agriculture seems somewhat mysterious since there are little solid quantitative data on their application in practice. Moreover, some active ingredients in biopesticides are toxic to organisms and environment, such as copper, a heavy metal that is widely used as a *biofungicide* in organic agriculture, but also, to a lesser extent in conventional agriculture (Box 3, Lamichhane *et al.*, 2018). Some active ingredients are the same in biopesticides and synthetic PPPs e.g. the Bt protein from *Bacillus thuringiensis*.

Box 3: The success of copper-based antimicrobial compounds (CBACs) is raising concerns about the long-term sustainability of copper-based production systems.

CBACs have been widely used in both organic and conventional farming. The relatively high toxicity to plant pathogens, low cost, low mammalian toxicity are major benefits of these compounds. However, reliance on CBAC, as the sole means of disease management, which is often the case for organic agriculture, poses serious threats to sustainable agricultural production due to the high level of copper contamination in soils and water, potential contamination of food and the increased occurrence of copper-resistant strains. Therefore, EU introduced legislation limits the use CBACs (EC no. 473/2002). EFSA recently reconfirmed the toxicity of CBACs. However, the current authorization of CBACs expired on 31 January 2019 but no decision has been made yet. Very little alternatives for CBACs exist in organic farming and no confirmed authorization could seriously impact organic farmers.

Bahlai et al. (2010) compared organic and synthetic PPPs in soybean and found that some synthetic are more toxic than organic and vice versa. They concluded: "These data bring into caution the widely held assumption that organic PPPs are more environmentally benign than synthetic ones. All PPPs must be evaluated using an empirically-based risk assessment because generalization based on chemical origin do not hold true in all cases". Therefore, a natural product is per se not less toxic than a synthetic one. As was mentioned there is little data on the effectiveness of biopesticides compared to traditional ones. Bahlai *et al.* (2010) mention that choosing natural PPPs over synthetic PPPs may not effectively mitigate environmental risk in soybean.

Maybe the lower effectiveness of some biopesticides contribute to the lower yields (20-25% on average, figure 13) that are obtained in organic. It is hard to relate the yield reduction of organic only to PPPs, since yield is the result of many management measures, including variety choice, fertilizers, soil management,… , and these measures are very different between both cultivation systems.

Seufert (2019) mentions 4 main reasons for this yield reduction: less efficient application of nutrients, difficulties with weed control, inadequate pest management and non-adapted varieties in organic farming. Important drivers for this reduction are related to plant protection products for weed and pest management. Differences related to PPPs are also dependent on the crop: e.g. disease incidence and severity is lower in maize than in fruit species. Concerning the latter considerably high losses are due to post-harvest disease like this the case in apple and pear, where sometimes up to 50% of the harvest is lost during fruit storage.

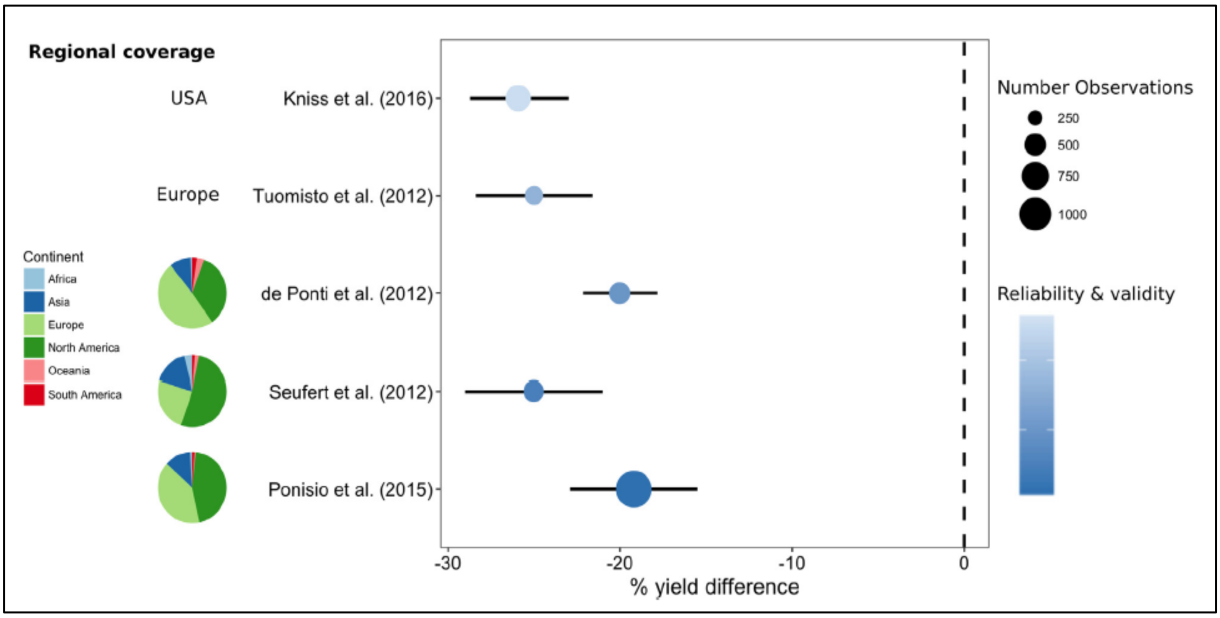

Figure 13 Differences in yield of organic compared to conventional agriculture in different metastudies. The yield reduction of organic varies between 20-25% (Seufert, 2018).

Several publications mention good results for pest, diseases and weed control in organic agriculture. Muneret *et al.* (2018) demonstrated that organic agriculture has a better potential for overall pest control compared to conventional agriculture. They showed lower pathogen infestation, similar animal pest infestation but more weed problems in organic agriculture. However, the authors did not compare the yield of both systems. In a study on triticale, Krauss *et al.* (2011) proved that natural control by predators in organic farming have comparable effects on aphids than PPP control in conventional agriculture. But here also no data on yields were presented. Seufert *et al.* (2012) came in a meta-analysis (316 publications) to the conclusion that a lower production in organic (on average about 20-25%) is obtained even when fertilizers are applied in higher doses than in conventional agriculture, and in all irrigation situations or soil and management conditions. This suggest that a considerable part of the yield differences are related to weed, pest and diseases control. We can conclude that biopesticides or biocontrol organisms have potential but in many crop systems at the expense of a reduction in yield.

Bengtsson *et al.*, (2005) also found in a meta study that organic agriculture has 30 % higher species richness, but in 16% of the studies negative effects were observed. The most positive effects were found for birds, insects and plants. These positive effects were present at the field scale, but were much lower and more variable at the farm scale, especially in more divers landscapes with high biodiversity. Also the abundancy was higher than in conventional systems, but also here the differences were much lower in more diverse landscapes. The conclusion was an overall positive effect of organic farming, but differences were highly landscape dependent and much lower at the farm level. Also Gabriel et al. (2013) compared biodiversity in organic and conventional agriculture. Their results indicate that the higher biodiversity in organic was at the expense of a reduction in yield. They explained the negative correlation not by the differences in management as such, but by the bigger share of non-crop plants in organic fields, attracting more insect species. So biopesticides seem to have a minor effect on insect biodiversity in organic fields. Lichtenberg et al. (2017) studied from a meta-dataset the biodiversity of arthropod pollinators, predators, herbivores and detritivores. They found as a general tendency more biodiversity expressed as species richness but a lower species evenness. Biodiversity increase was negatively correlated with yield and also influenced by landscape elements. Rundlöf *et al.* (2016) confirmed the 30% increase in biodiversity found by Bengtsson et al. (2005) but mentioned that the yield reduction in organic could offset the biodiversity benefits. They confirmed that a substantial increase of the biodiversity comes from pollinator insects as this was also found by Gabriel *et al.* (2013). Hole et al. 2005 concluded that the reduction/prohibited use of chemical PPPs is an important driver for the increase of biodiversity in organic agriculture and they also remark: "It remains unclear whether a holistic whole-farm approach (i.e. organic) provides greater benefits to biodiversity than carefully targeted prescriptions applied to relatively small areas of cropped and/or non-cropped habitats within conventional agriculture (i.e. agri-environment schemes)".

The conclusion is that organic has around 30% more biodiversity than conventional agriculture at the field level but this gain is very context-dependent, lower at the farm level and overruled at the global level because the reduced yields of 20-25% in organic (Seufert, 2019). In the latter meta-study a comparable or in most cases a lower yield stability was obtained in organic agriculture.

According to Bourn and Prescott (2002), organic products have likely less residues from PPPs (because less different PPPs are used), but there are little quantitative data available. They mention also that organic products are not more susceptible to microbiological contaminations than conventional food and there are no differences in nutritional value or organoleptic quality.

Concerning chemical residues, including PPPs, and micro-pollutants, Dervilly-Pinel *et al.* (2017) found these compounds, below the regulatory limits, in meat from organic and conventional farms. Most of the environmental contaminants (dioxins, PCBs, HBCD, Cu, Zn, Cd, Pb, As) were found in organic samples. Possible explanations are the fact that livestock from organic farms raised more outdoors, that they are in most cases older and heavier and/or that their feed includes more PPP residues such as Cu. One mycotoxin (OTA) was found more frequently in organic meat.

The lower yield in organic farming is partially due to less adequate plant protection, including the use of PPPs. Applications of biopesticides have no clear advantages compared to chemical ones concerning toxicity or effectiveness.
It is not clear whether the higher biodiversity in organic farming is due to biopesticide management or to lower yield.

5.4. Agroforestry, Agro-ecology and CSA

Community Supported Agriculture (CSA) and urban faming are two new, at the moment experimental, production systems. Most CSA farms produce vegetables and fruit according to the organic principles (see § 5.3). Urban farming systems are very intensive. In open air, some small scale initiatives use bio-PPPs. Another type of urban farming is a high tech controlled system in growth containers or greenhouse-like structures. Because high value horticultural products are cultivated in a controlled environment, pests and diseases are of minor importance and can be controlled like in greenhouses, based on biocontrol. In urban farming there is no urgent need to use PPPs.

Agroforestry is a very extensive production system were agriculture and tree production are combined. In most cases agroforestry is based on organic principles with reduced use or PPPs. Since agroforestry has little contribution to food production, we don't discuss this system, as we will not do with agro-ecology. There are very different definitions of the latter production system according to the different groups of adepts. Therefore it is difficult to incorporate agro-ecology in the policy of governments. Some consider agro-ecology as principles for production, some as a scientific concept, others as a practice and some as a movement for more justice in agriculture (Wezel *et al.*, 2009). Agro-ecology can be considered as the study of ecological processes applied to agricultural production systems. Bringing ecological principles and agro-ecosystem services in agro-systems suggest novel management approaches. One problem arise from the extent, how and which ecological principles are integrated; another arise from the duality whether agro-ecology is a separate, independent production system or can be integrated in existing systems such as the conventional agriculture or organic farming. Organic growers organizations claim agro-ecology as their production system. Since there are no solid data at the moment concerning agro-ecology and PPPs, we assume little differences with organic agriculture.

There is a lot of information available on principles of these production systems but no quantitative data on effect of PPPs on yield or reduction of their usage. It is accepted that they resemble with respect to PPPs to organic agriculture.

Because of the confusion and claims about agro-ecology it seems more realistic to integrate agro-ecological principles in organic and conventional production systems rather than to consider agro-ecology as a separate production system.

5.5. Conclusions on biodiversity and environmental impact of PPPs

It is clear that PPPs have a negative effect on biodiversity and other environmental factors, however these impacts are overruled at the global scale by the historical changes in land use of all agricultural systems. The positive effect of organic farming on biodiversity is present at the field level, less at the farm level but not at the global level due to the need for more arable land. The loss of biodiversity in farmland still continues but rather slow. Crop production, especially in mono- or oligocultures, and biodiversity are difficult to combine since high biodiversity is not only impossible to realize in production systems but it includes also often more but less severe pests and a higher weed pressure with a reduction in yield as a consequence. This is also the basic reason for the use of PPP. The contribution of PPPs to other environmental sustainability factors such as eutrophication and acidifications are minor compared to those of nutrients and these impacts are lower in conventional agriculture compared to organic farming. In any case a reduction in PPP applications will contribute to a more sustainable agriculture. It seems more promising to implement more sustainable practices as reduced uses of PPPs in IPM production systems and in organic farming, as was concluded in the extended study of (Dicks *et al.*, 2019) for the UK.

6. Novel technologies and their impact on pesticide use

6.1. Genetically modified organisms and resistant cultivars

In order to reduce the amount of PPPs, the implementation of resistant cultivars is extremely important and fits within the preventive measures included in IPM. Depending on the crop, many cultivars and varieties exist that confer resistance to specific pests and disease. However, in the past, domestication of crops mainly focused on securing specific agronomic traits that occurred at random, either spontaneously in nature or as a result of classical mutagenesis induced by radiation treatment or treatment with mutagenic chemicals (Palmgren *et al.*, 2015). The main traits that have been selected for in these breeding programs were easy harvest, high yield and low toxicity. As a consequence, traits that protect crops against environmental stress including abiotic and biotic stress have often been lost or not been selected for, also because PPPs came available. Nowadays, active breeding programs focus more and more on the identification and incorporation of specific resistance genes, and even on stacking multiple resistance genes. This strategy will be very important to reduce PPP use and to reach this goal, original traits that are important for plant survival under biotic stress need to be re-introduced, while at the same time other traits obtained through breeding for food quality and yield need to be preserved (Fig. 14). Resistance traits are often present in wild cultivars.

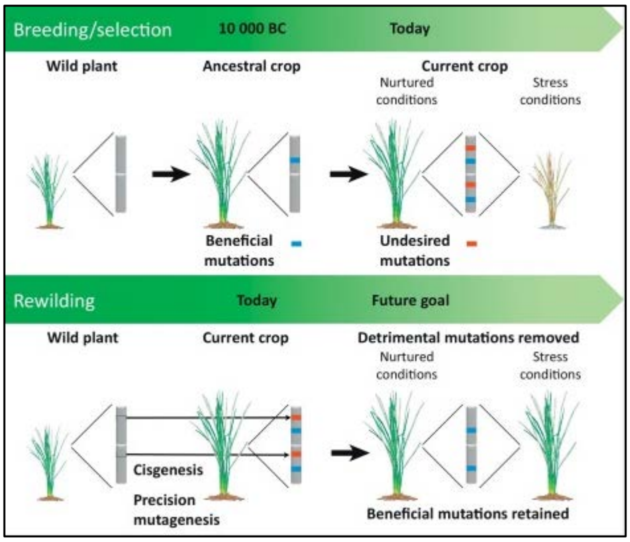

Figure 14 Rewilding maintains beneficial mutations while eliminating undesired mutations (Palmgren et al., 2015)

As a scientist it is a very fascinating era to study plant-pathogen/pest interactions in order to provide solutions for the development of more resistant crops. For example, the fungal-like pathogen *Phytophthora infestans* causes late blight disease of potato and led to the Irish famine in the 19th century. Nowadays it is still a devastating disease affecting more than 3 million hectares of cultivated potato and causing economic losses due to difficult chemical control and yield loss are estimated at $6.7 billion per year[9]. Potato breeding for resistance against *P. infestans* is not straightforward but recent biotechnological advances have provided tools (e.g. Renseq) to systematically identify resistance genes in wild potato relatives (Jupe *et al.*, 2013; Witek *et al.*, 2016). The identification of those genes together with genetic engineering technologies to stack multiple resistance genes will create durable resistance to late blight in potato, significantly reducing PPP use. This brings us of course to the very important discussion on whether implementation of genetically modified crops (GMOs) can aid in the reduction of PPP use. In general, literature often provides contrasting results on this topic. This is mainly due to the GMO crops currently on the market including the most cultivated herbicide-tolerant (GMHT) crops. Improper use of herbicides (mainly glyphosate) and the cultivation of GMHT monocultures led to the appearance of glyphosate-resistant weeds which resulted in a rise in the use of glyphosate and other herbicides (Bonny, 2016). Another important GMO crop on the market are the insect-resistant Bt crops (GMIR) such as e.g. maize, cotton and eggplants. These GMO crops contain a toxin derived from *Bacillus thuringiensis* which is harmful to some caterpillars of moths and butterflies or larvae from other insects. The cultivation of GMIR maize and cotton resulted in 2016 in 82% and 56% less active ingredients used respectively when compared to the cultivation of non-GMO crops. It has been estimated that the environmental

[9] http://2blades.org/projects-and-technology/projects/late-blight-potato-africa/

impact of GMIR maize and cotton has lowered by 58% and 32%, respectively (Brookes and Barfoot, 2018). Often GMIRs are blamed for the decline of butterflies e.g. the monarch butterfly. However, it has been recently shown that the monarch decline started around 1950, prior to the introduction of GMIRs (Boyle *et al.*, 2019). Since GMOs are strongly debated in Europe, very few GMOs are on the market and we are convinced that expanding the range of GMO crops resistant to pests and diseases will have a tremendous impact on PPP use. Moreover, new genome editing tools such as CRISPR/Cas9 allow to specifically modify your gene-of-interest, avoiding time consuming traditional plant breeding techniques using classical mutagenesis. Adopting this precision breeding technology resulted in many examples of disease-resistant crops (Jaganathan *et al.*, 2018). Unfortunately, the court of Justice of the European Union (ECJ) ruled that organisms obtained by these new breeding technologies are not exempt from the EU GMO legislation. Consequently, genome edited organisms must comply with the strict conditions of the EU GMO legislation. In our opinion, Europe is missing out a great opportunity to implement these technologies to reduce PPP use.

6.2. Smart farming

Reducing the use of PPPs not only depends on the breeding of resistant cultivars but requires an integration of several management strategies, which is also the aim of IPM. Here, we touch upon two additional aspects that are highly researched and will be key to further develop sustainable agriculture namely (1) decision-support systems (DSS) to predict disease and pest outbreaks and (2) precision agriculture. DSS are not new to plant pathology e.g. weather –based disease forecasts have already been implemented since the 1970’s. Since then interactive computer-based models, including data on e.g. location, weather, cultivars, growth period, high-tech monitoring tools for fungal spore release or insects etc., are constantly improving to better predict disease and pest outbreaks and should be widely adopted by farmers as part of their IPM practices (Gent *et al.*, 2013; Shtienberg, 2013).

Walter *et al.* (2017) recently stated that agriculture is undergoing a fourth revolution triggered by an exponential increase of information and communication technology. In that sense, the speed at which remote sensing with lightweight and powerful hyperspectral cameras combined with unmanned aerial vehicles (UAVs) are developing offers great potential in disease detection and site-specific PPP management. Two recent papers e.g. showed that researchers were able to detect with remote sensing UAV *Sclerotinia sclerotiorum* on oilseed rape in leaves (Cao *et al.*, 2018) and sheath blight on rice (Zhang *et al.*, 2018).

Implementation of novel technologies such more accurate decision-support systems, breeding of resistant cultivars using the recently developed genome editing tools and precision agriculture with remote sensing combined with UAVs will significantly decrease the use of PPPs.

7. General conclusions

- Crop yield cannot decrease but has to increase to close the yield gap and to feed 11 billion people in the future in a sustainable way.
- Increase in yield within the sustainability borders of the planet implies, besides other measures, no further land use changes and adequate crop protection.
- Crop production in the EU without PPPs is not realistic at the moment, but there are indications that reductions are possible without or with acceptable yield losses; the (financial) risk for the grower is however an important aspect to consider.
- Modern PPPs are more specific towards target pests. As a consequence, more PPPs are needed in some crops.
- There is a considerable loss of biodiversity by the applications of PPPs, both synthetic as well as natural, but this loss is surpassed by changes in land use (expansion of arable land).
- The lower yield in organic farming is partially due to less efficient crop protection compared to conventional farming.
- Therefore, organic production should be higher priced than conventional production. However, if all food were produced in organic systems, lower income classes would switch to cheaper and unhealthy food. The potential negative health effects thereof (obesitas, …) are more important as a risk than the exposure to PPPs.
- There is no clear indication that natural PPPs are better for biodiversity or the environment.
- Assuming that a fixed amount of food should be produced to feed the world population, the higher land use of organic production has a negative impact on the biodiversity at the global level.
- To improve the sustainability of crop production the sustainable intensification of the IPM system by pursuing sustainability targets is the most promising. They include the reduction of PPPs by new technologies, precision farming, development of resistant varieties by both, classical and new breeding techniques. Organic farming, agro-ecology and agroforestry have on average less potential in this respect, but can be beneficial in a restricted number of specific situations, such as buffering nature reserves from intensive agriculture.
- New technologies in breeding, crop protection, precision farming, … will further decrease the use and dependence on PPP's.
- PPPs are amongst the best studied compounds in our life. Their risk is not zero, but acceptable and in accordance with current scientific insights. Re-evaluations every 10 years ensure regularly updated risk assessments.
- Safety factors in the evaluation of the risk of PPPs are much higher than safety factors used for other risks in our daily life.
- The perception of risk of PPPs by the general public is diametrically opposed to the risk classification of scientists.
- Multiple actors are involved in risk communication, resulting in conflicting messages. Scientists are considered less neutral than one could expect. Some actors are framed as ideology-driven and others are suspected to work on demand for non-governmental organizations (NGOs) or the chemical industry. Neutral key opinion leaders are however needed as the worst that could happen would be that people believe that risk assessments are arbitrary and their results depend on who pays for them.

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Plant Protection Products (PPPs) are often perceived by citizens as very harmful for human health and for the environment. The tendency in EU policy is to stimulate reduction in use of PPPs.

Can we maintain high yield while using less PPPs?

This paper presents the current state-of-the-art regarding the role of PPPs in securing global food production, preserving biodiversity and supporting farmers' income. The role various stakeholders play in the current perception of risk by the general public is explored, and the paper comments on promising alternative, and more sustainable, strategies to further reduce PPP use.

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