Herbicide resistant soybean in Argentina
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Summary

Soybean currently is the most traded agricultural product in the world, both with regard to volume and value. Because of its high protein content and the rising demand for protein-rich animal feed, soybean acreage has increased spectacularly in South American countries such as Brazil and Argentina.

Soybean is moreover the crop that has undergone the most noticeable changes over the last 16 years as a result of the introduction of genetically modified soybean. Of all the genetically modified crops, herbicide resistant crops and particularly glyphosate resistant soybean have received the most attention. Argentina was one of the first countries to produce biotech crops commercially and, as an emerging economy, it is the main producer of herbicide resistant soybean.

Herbicide resistant soybean is an example of a first-generation GM crop which offers a direct advantage to the producer. Its cultivation goes hand in hand with efficient and flexible weed control, which results in a significant reduction in the production cost. In addition, the production of glyphosate resistant soybean has had a positive effect on the environment over the past 16 years. On the one hand, herbicide use has undergone a shift from more to less damaging products, while on the other hand glyphosate resistant soybean has had a highly stimulating effect on the use of no-tillage agriculture. No-tillage agriculture improves the soil structure and results in lower fuel consumption and reduced CO₂ emissions.

Contrary to what is commonly claimed, there is no direct link between the large-scale production of glyphosate resistant soybean and deforestation in Argentina. Other factors play a much more significant role, including changing economic conditions and increased rainfall in the Argentine dry forests.

Weed control is complex and glyphosate resistant soybean should not be regarded as a miracle solution. Indeed, the crop appears to have become a victim of its own success. Glyphosate has been used too exclusively and without a plan for sustainable agriculture, and this has resulted in a large increase in glyphosate resistant weeds. This undermines not only the efficiency of glyphosate resistant crops, but also the future use of glyphosate itself.

Herbicide resistant soybean should mainly be regarded as an aid to increase the cost efficiency of present-day commercial soybean production. If it is grown in a responsible manner, herbicide resistant soybean can help achieve a more environmentally friendly and sustainable soybean production.
In 1996 Argentina, alongside the United States and Brazil, introduced the large-scale commercial production of genetically modified crops. In 2012, almost 24 million hectares of genetically modified soybean, maize and cotton were grown in Argentina, making it the third largest producer of GM crops on the global market.

The production of herbicide resistant GM soybean in Argentina has increased spectacularly from 370,000 hectares in 1996 to more than 19 million hectares in 2012. By 2004, genetically modified soybean accounted for 100% of Argentina’s soybean acreage.

In Argentina, the cost of producing glyphosate resistant soybean is approximately 10% lower than the cost of conventional culture.

Partly due to the introduction of glyphosate resistant soybean, 80% of Argentine fields are cultivated using the no-tillage method.

The less intensive ploughing stimulated by the production of herbicide resistant soybean resulted in 2011 alone in an estimated saving of more than 260 million litres of fuel in Argentina and consequently reduced CO₂ emissions by almost 700 million kg. The no-tillage method also has the advantage of improving soil structure and preventing soil erosion.

Since its introduction in 1996, the economic benefits to Argentina of herbicide resistant soybean amount to 65 billion US dollars. Approximately 3 billion was economised by the reduced need for selective herbicides and by reduced fuel consumption. The remaining 62 billion comes from the extension of the cultivated area. 72.4% of this profit went to the producers, 21.2% to the government in the form of export and other duties and 6.4% to technological development, seed production and herbicide use.

A study carried out by the Argentine non-profit organisation ArgenBio shows that the current international soybean price would be 14% higher if herbicide resistant soybean hadn’t been introduced in Argentina.

Soybean and soybean-derived products account for more than 20% of Argentina’s exports.
The thriving soybean-based agriculture of Argentina

Argentina is one of the world’s largest food producers, with 33.2 million hectares of agricultural land. The production of soybean in particular has undergone unprecedented changes over the past 20 years. In 2012, approximately 19 million hectares of soybean were produced. Compared to 1990, this represents a quadrupling of acreage. This increase can largely be attributed to the introduction of herbicide resistant soybean. Genetically modified soybean offers producers simple flexible weed control and its production goes hand in hand with no-tillage agriculture, Argentina’s most popular cultivation method.

Despite the highly favourable growing conditions, agricultural production in Argentina remained low for most of the 20th century. Agriculture was heavily taxed and subsidies went to industry rather than agriculture. Fortunately, the political situation changed in the early 1990s. The recession led the government to reduce import duties on fertilisers, pesticides, agricultural machinery, etc., while at the same time the export of agricultural products was stimulated. The government also became interested in genetically modified crops and saw these as an opportunity to boost Argentine agriculture. In 1991, the Ministry of Agriculture created the necessary framework to enable the production of genetically modified crops. The first genetically modified crop produced on a commercial scale in Argentina was glyphosate resistant soybean. Glyphosate is the active substance in herbicides such as Roundup. This glyphosate resistant soybean was introduced during the 1996-1997 growing season. This introduction coincided with the global commercialisation of genetically modified (GM) crops and meant that Argentina, as an emerging economy, was one of the first countries to produce GM crops.

According to official FAO figures, during the 2009-2010 growing season 18.1 million hectares of soybean were produced in Argentina. This represents 55% of Argentina’s agricultural acreage. In 2010, Argentina was the third largest producer of soybean in the world with a record production of more than 52 million tonnes. This is a spectacular increase compared to the 1990-1991 season, when 10.8 million tonnes were produced on slightly less than 5 million hectares. In 1980, soybean production was only 3.5 million tonnes on 2 million hectares.

4 Food and Agricultural Organization of the United Nations
5 FAOSTAT http://faostat3.fao.org/home/index.html#VISUALIZE_BY_AREA
Production figures after 2010 vary depending on the source, but the general trend is that Argentine soybean acreage is continuing to increase. For the 2010-2011 growing season, the FAO reports the planting of 18.7 million hectares, which is an increase of 3% as compared to the previous season. For 2011-2012, the figures vary between 17.5 and 18.8 million hectares. If the predictions for 2012-2013 are correct, a new absolute record will be set: the production of 19.1 to 19.7 million hectares of soybean, which represents 57 to 59% of Argentina’s agricultural acreage.6

As glyphosate resistant soybean was mainly developed for more efficient and simple weed control, its effect on the yield per surface area is limited or non-existent in most cases. The average yield between 1990 and 1999 was 2.2 tonne per hectare. Between 2000 and 2010, this varied from 2.2 in 2003-2004 to 2.9 tonne per hectare in 2009-2010. In 2009, there was a dip in yield due to the severe drought in the 2008-2009 season, while in 2012, production was disappointing due to high rainfall. In 2012-2013, Argentina again may come close to the record yield of 52.7 million tonnes in 2009-2010. Barring important problems, a yield of 51 million tonnes is expected, which would represent 2.64 tonnes per hectare.7,8

There is no doubt that the introduction of herbicide resistant GM soybean has given Argentine agriculture a huge boost. Weed control became more flexible and simpler. Instead of using complex cocktails of expensive and environmentally damaging herbicides, one single herbicide can be used that causes less damage to people and the environment. In addition, unusable land that was overgrown with weeds could be cultivated again. Yet the main advantage is that herbicide resistant crops support a form of agriculture based on no-tillage (see page 18). Reduced tillage or no-tillage is very popular in South America as this cultivation method improves the soil structure and, among other things, helps prevent soil erosion. As a result of these benefits, following the introduction of GM soybean the soybean acreage increased by an average of 9.4% per year, while between 1971 and 1996 (prior to the introduction of GM soybean) it increased by only 3.5% per year.9 Based on these figures, Eduardo Trigo of the Argentine non-profit organisation ArgenBio calculated that soybean production would be 54% less today if genetically modified soybean had not been introduced.

However, the success story of the Argentine soybean-based agriculture cannot be attributed to the new biotechnological developments alone. When the commercially viable cultivation of glyphosate resistant soybean became possible, soybean was already an important crop in Argentina and production was increasing every year even before 1996. The land was cultivated more efficiently with the use of a rotation system with maize and wheat, production cost fell and the market price of soybean rose.3 Consequently, between 1980 and 1990 soybean acreage more than doubled.5 Moreover, the growing global demand for soybean also contributed to this increase in acreage. China and Europe in particular have been importing large amounts of Argentine soybean since 2001 (see page 35).
Weeds, herbicides and herbicide resistant crops

Anyone who is concerned with nature deplores the use of chemical weed killers in agriculture. However, weeds compete with the crops and therefore have to be removed. Herbicides help the producer keep his field free of weeds in an economically viable way.

Herbicide resistance is not a biotechnological invention

Weeds are, in the broadest sense, plants that grow at a certain moment in a certain quantity in a certain place where for some reason or another they are not desired by humans. It is necessary to control weeds in crops to prevent economic damage. Weeds are in competition with the crop: they take up water and nutrition, but also sunlight so that the crop does not grow as well. In addition, weeds may also cause problems at harvest time and in some cases may spread diseases and pests. If a producer wants to guarantee his harvest and income, he therefore has to remove the weeds from the field.

For centuries, weeds were mainly removed by manual or mechanical means of cultivation. For example, by ploughing a field before sowing it, the germinating seeds of weeds can be buried under the soil. However, this form of weed control has no long term effect. Other weed seeds present in the soil are not destroyed. They can continue to germinate and come back causing problems the following day. Scale also plays a role in mechanical weed control. In vegetable gardens, weeds can easily be removed by hand or by hoe, but with an average size of 784 hectares per production unit in Argentina in 2007, or 170 hectares in the US, this is not feasible in commercial agriculture (see Box section ‘Weeding versus herbicides’). As an alternative there are highly specialised machines on the market to remove weeds. These machines are GPS-controlled and even recognise plant rows so that damage to the crop is minimised. They are, however, expensive to buy, consume a lot of fuel, take up more of the producer’s time and are globally considered to be less cost effective than the use of herbicides.

Herbicides such as glyphosate, atrazine, imidazoline, etc., are weed killers. These are chemical compounds that can be used to eliminate unwanted plant growth (= broad-spectrum herbicide) or to remove specific weeds from in between the crops.
crops (= selective weed control). Dozens of such substances have been developed over the past 60 years. If the weeds (e.g. grass) and the crop (e.g. soybean) belong to different plant families, in most cases selective herbicides can be used that act specifically on the weed without affecting the crop. An example of this kind of herbicide are ACCase inhibitors. These are chemical substances that block the action in the plant of acetyl-coenzyme A carboxylase (ACCase), an enzyme in the fatty acid synthesis.12 As the ACCase of grasses is much more sensitive to these inhibitors than the ACCase of dicotyls,14 ACCase inhibitors can be used to kill specific grasses in a soybean field.13 The herbicide 2,4-D, on the other hand, can be used to selectively remove dicotyls from a field with grasses.15

However, if the weed is too similar to the crop, spraying will also affect the crop, resulting in damage and reduced yield. To make weed control easier, plants have been bred to become resistant to specific herbicides since the 1970s. Herbicide resistant plants are plants that survive spraying with a specific herbicide, while all the other plants (weeds) in their vicinity die. There are various ways to make plants less sensitive to a product (see Box section ‘Glyphosate resistance using CP4 EPSPS of Agrobacterium’). The most commonly used strategy is the random modification of plant DNA in the hope that the plant suddenly becomes resistant to the product. In practice, this is done by radiating seeds or treating them with chemical substances. This traditional selective breeding has made maize and rice resistant to imidazoline,16, 17 rapeseed to triazine18 and soybean to metribuzine19.

The first herbicide resistant plants were already being grown in the field before the introduction of genetically modified crops. Herbicide resistance can therefore be obtained using a variety of methods and was not invented by the biotech sector. It should rather be seen as the plant breeding companies responding to the needs of the producers.

Instead of causing random mutations (e.g. by treating seeds with chemical substances20 in the hope that a plant becomes resistant to a specific herbicide), biotechnology can create herbicide resistance very quickly and specifically in a certain crop. An example of herbicide resistance is glyphosate resistance.
Weeds are often a significant restriction at harvest time. In global soybean cultivation, for example, 37% of production is threatened by weeds. For many centuries, weeds could only be removed manually and a large part of the population, sometimes up to 90%, had to be employed in the field. Because of this high dependence on manual labour, in 1830 the work and production of four farm workers only fed five persons. In 1930, with the start of the first green revolution, this ratio changed and one farm worker quickly became able to feed 10 mouths. Due to the rapid production increase and due to agriculture becoming less dependent on manual labour (with herbicides playing an important role in this), the world today is fed by the work of only 2% of the population. This is a ratio of one farm worker to 50 non-farm workers.

In developing countries, the current ratios are still similar to those in the industrialised countries of 200 years ago. An average of 46% of the population work on the land in developing countries. Figures from African countries are therefore interesting to estimate the labour intensity of weeding if no mechanical or chemical weed control were to be used. Nigerian researchers have demonstrated that in Northern Nigeria 309 man hours are required to keep one hectare of maize weed free, and 324 hours to efficiently weed one hectare of sorghum (a grain crop). Herbicide treatment can reduce the manual labour required to 100 and 91 man hours, respectively. In Ghana, the manual weeding of a rice field was compared with herbicide treatments. Manual weeding required 211 man days, which cost 500 euros/ha, while for the chemical treatment only 86 man days were needed as well as 8 litres of herbicides per hectare, amounting to a total cost of 256 euros/ha, a halving of the costs.

It is clear that the use of herbicides greatly reduces the need for manual labour in agriculture and thus reduces the cost price of agricultural products. It is therefore not unexpected that more than 90% of the cultivated area in the United States, Europe, Japan and Australia is treated with herbicides. According to the NCFAP (American National Center for Food and Agricultural Policy), the use of herbicides in wheat, maize and soybean cultivation during the peak times of weeding is equivalent to 1.1 billion hours of manual labour. If herbicides were not available, 7.2 million workers would be required.

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Glyphosate is a broad-spectrum herbicide that inhibits a specific vital reaction in the plant. Glyphosate affects the shikimic acid pathway: it specifically inhibits the 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSPS). EPSPS catalyses the reaction between phosphoshikimic acid and phosphoenolpyruvate (PEP) (Figure 3). The chemical structures of glyphosate and PEP are very similar, but glyphosate binds more tightly to EPSPS than PEP does. In this way, PEP is no longer able to react to phosphoshikimic acid. Blocking the EPSPS action results in an accumulation of shikimic acid and a shortage of the aromatic amino acids tryptophan, phenylalanine and tyrosine. However, the precise mechanism responsible for the death of the treated plants is not completely clear yet. Many people think that the plants die because of the shortage of aromatic amino acids. These are in fact necessary for the formation of all kinds of vital proteins. But plant hormones and lignin (cell wall component that strengthens plant cells) are also produced via the EPSPS pathway. Other people think that the disruption of the shikimic acid pathway itself is the cause. Each pathway is checked by positive and negative feedback mechanisms. The inhibition of EPSPS results in reduced negative feedback within the shikimic acid pathway and therefore an accumulation of shikimic acid. This results in increased carbon consumption, causing a shortage of carbon in other vital pathways and a blockage.27

EPSPS is present in all plants and glyphosate inhibits the EPSPS enzyme of all higher plants. This means that glyphosate is non-selective for one specific plant group and is therefore a broad-spectrum herbicide. In addition to plants, bacteria and mould also produce the EPSPS enzyme. They too use it for the same purpose: the creation of aromatic amino acids.28 However, EPSPS is not found in animals28, they have to obtain the necessary amino acids from their diet. Glyphosate was first synthesised by Henri Martin of Cilag, a small Swiss pharmaceutical company, but Cilag did not test or patent the product as a herbi-cide. John Franz of Monsanto had a more specific plant group and is therefore a broad-spectrum herbicide. In addition to plants, bacteria and mould also produce the EPSPS enzyme. They too use it for the same purpose: the creation of aromatic amino acids.28 However, EPSPS is not found in animals28, they have to obtain the necessary amino acids from their diet. Glyphosate was first synthesised by Henri Martin of Cilag, a small Swiss pharmaceutical company, but Cilag did not test or patent the product as a herbicide. John Franz of Monsanto had a more entrepreneurial spirit and after testing glyphosate as a herbicide in 1970, it was patented by Monsanto and put on the market in 1974.29 It took a few more years before Steinrucken and Amrhein discovered that glyphosate inhibits EPSPS.30 The many advantages of glyphosate mean that it is the preferred and most widely used product in the production of herbicides. Glyphosate is absorbed easily through the leaf, but what is much more interesting is that it is transported throughout the plant. Because of this systemic effect, glyphosate reaches the growth points in the root and thus literally tackles the ‘root cause’ of the weed problem. Additional advantages of glyphosate are its low toxicity to humans and animals31 and its limited impact on the environment (see below). The World Health Organisation (WHO) classifies chemical agents into various classes according to their toxicity.32 This classification is mostly based on the LD50 value: this is the amount of product per kg of body weight that kills 50% of the test animals. Class I is known as very toxic, class II moderately toxic, class III slightly toxic, while class U is used for products unlikely to cause damage if used correctly. Glyphosate is classified in class III toxicity and therefore scores better than herbicides such as glufosinate, 2,4-D or dicamba that have a class II label.33 To view this classification in the correct context, we can compare glyphosate to kitchen salt. With an LD50 value of 3000 mg/kg body weight34, kitchen salt would also come under class III.

Glycophosphate resistance via CP4 EPSPS of Agrobacterium

Because glyphosate has a non-selective effect, its use in the first 20 years after its commercialisation was limited to weed removal before the crop was sown, or to the removal of weeds on pavements and other public places where there are usually no other plants. After all, the crop itself was sensitive to the product. To enable glyphosate to be used after crop germination too, the crop had to be made resistant to the herbicide. Traditionally this is done by causing spontaneous (and therefore random) modifications to the plant’s DNA (mutations). Seeds are radiated or treated with chemical substances that induce mutations. The seeds are then germinated in the presence of the herbicide in the hope that one of the many seeds treated has become resistant. Various attempts were made on the model plant Arabidopsis thaliana, but a glyphosate-resistant plant was not found.35 The place where glyphosate binds with the EPSPS enzyme is most probably too close to the binding place of PEP.36 In other words, if the EPSPS enzyme could be modified so that glyphosate can no longer bind, this would also have a negative effect on the binding between EPSPS and PEP. Another method to obtain a resistant plant is to grow plant cells in the presence of low concentrations of glyphosate and then to build up the concentration. However, this selection method results in plant cells that contain more EPSPS genes. As more EPSPS is present, plants can withstand a higher dose of glyphosate, but all the EPSPS proteins remain sensitive to glyphosate.37 The resistance obtained by this method was, however, not significant enough for commercial use. Instead of this trial-and-error method based on pure chance, biotechnology can be applied in a targeted and much more efficient manner. Many attempts were made to modify the plant EPSPS so that it could no longer bind with glyphosate. The mutations made, however, also meant that the modified EPSPS reacted less well with PEP.38, 39

31 Herbicides are classified according to the way in which they work, with the most commonly known being contact herbicides and systemic herbicides. Contact herbicides kill the plant tissue which they come into contact with, for example the leaves. Systemic herbicides are absorbed through the leaf and transported throughout the whole plant, after which the whole plant dies.
32 People and animals have no EPSPS enzyme and therefore its action cannot be disrupted by glyphosate.
The chloroplasts are cell organelles in the plant cell and all photosynthetic reactions are carried out there.

A small protein sequence that contains the information to transport a protein to a certain place in the cell. For the commercially available glyphosate-resistant soybean, this is the EPSPS transit peptide originating in Petunia.

Nucleotides are the building blocks of DNA and form the genetic letter code.


There was, however, another obstacle to overcome in order to obtain glyphosate-resistant plants. The shikimate acid pathway is active in the chloroplasts of the plant cell, while bacteria such as Agrobacterium have no chloroplasts. The CP4 EPSPS therefore lacks the necessary information to be transported to the chloroplast. A transit peptide from plants that does contain this information was therefore added to the CP4 EPSPS protein and the composite was expressed in agricultural crops. When these plants are treated with glyphosphate, the plant EPSPS is inhibited but, as this function is taken over by the resistant Agrobacterium CP4 EPSPS, there is no longer a negative effect on the transgenic plant (Figure 4).

Figure 4. The strategy to produce a glyphosate resistant plant

Whereas no success was achieved with soybean in modifying the plant EPSPS to make it resistant to glyphosate, there was more success with maize. Using a targeted mutagenesis (adding of mutations), 2 nucleotides of the maize EPSPS gene were modified. These 2-point mutations resulted in 2 amino acid changes making the new protein resistant to glyphosate. Apart from these 2 mutations, the modified EPSPS protein (mEPSPS) is identical to that of the endogenous EPSPS. The genetically modified maize that expresses the mEPSPS is marketed under the name GA21.

Because of molecular know-how and knowledge of plant biotechnology, plant breeding today is no longer limited to the extant genetic diversity of the plant kingdom. A search outside the plant world for EPSPS proteins that are resistant to glyphosate came up with the EPSPS gene of the bacteria Agrobacterium sp. strain CP4. The gene codes for an EPSPS protein with a slightly different amino acid composition than that of plants, which means that glyphosate is unable to bind with it. The bacterial EPSPS is, however, still able to bind PEP so that all the necessary reactions can continue. The gene was called CP4 EPSPS.
Another way to make plants glyphosate resistant is the expression of certain proteins that break down or ‘detoxify’ the absorbed glyphosate. GOX, or glyphosate oxidoreductase, is a bacterial protein that breaks down the absorbed glyphosate into AMPA (aminomethylphosphonic acid) and glyoxylate. Although no plant-specific GOX genes have been identified yet, it appears that some plants such as soybean are able to break down glyphosate into AMPA themselves. It is therefore expected that these plants create enzymes similar to GOX or have other breakdown mechanisms at their disposal. Rapeseed, however, does not appear to have this information enabling it to break down glyphosate. To make rapeseed even more glyphosate resistant, a glyphosate resistant variety was recently developed in which a modified GOX protein (goxv247) from the soil bacteria Ochrobactrum anthropi was expressed together with the CP4 EPSPS enzyme.

In addition to GOX, the glyphosate N-acetyltransferase (GAT) was also isolated from bacteria. Acetylation or the adding of an acetyl group to a molecule controls the biological effect of the molecule. N-acetylation detoxifies glyphosate and expression of optimised GAT enzymes creates an efficient glyphosate resistance in plants. This strategy was also used for soybean: soybean event 356043 expresses a modified form (gat4601) of the GAT protein of Bacillus licheniformis.

Like glyphosate, glufosinate, the abbreviated name of glufosinate ammonium, is a non-selective systemic herbicide. However, glufosinate ammonium works in a completely different way. Whereas glyphosate blocks the proper working of EPSP synthase, glufosinate disrupts the function of the glutamine synthetase. Glutamine synthetase plays a vital role in the nitrogen metabolism by detoxifying ammonia. It catalyses the reaction between glutamic acid and ammonia with the formation of glutamine. The blocking of this reaction by a glufosinate treatment results in an accumulation of the toxic ammonia and a shortage of glutamine, so that photosynthesis stops. Plants that have been treated in this way become red/brown in colour and die within 2 weeks after the treatment. Contrary to EPSPS, the action of which is blocked by glyphosate, animals do have the glutamine synthetase enzyme. According to the WHO, glufosinate comes under class II toxicity, one class less safe than glyphosate.

Glufosinate ammonium is the active substance in herbicides such as Basta and Liberty. Following on from Monsanto, which launched the first glyphosate resistant crops on the market, the company Bayer CropScience developed transgenic crops that are resistant to treatment with glufosinate. These crops are better known as Liberty Link crops. As in most glyphosate resistant plants, a bacterial gene was expressed to obtain resistance to the herbicide. For glufosinate resistance, this is the pat gene of Streptomyces viridochromogenes or the bar gene of Streptomyces hygroscopicus. Both genes code for the PAT protein (phosphinothricin acetyl transferase). As the GAT protein does for glyphosate resistance, the PAT protein ‘detoxifies’ the glufosinate absorbed by the plant through the addition of an acetyl group. Because of this acetyl group, the herbicide can no longer act on the glutamine synthetase and the transgenic plant becomes glufosinate resistant.

In this Fact Series we will focus mainly on glyphosate resistance. From 1996 to 2011, this was in fact the only herbicide resistant characteristic of genetically modified soybean in Argentina (see page 41).
3. Unprecedented adoption of glyphosate resistant soybean

The cultivation of herbicide resistant soybean in Argentina started with a modest 370,000 hectares. Only 8 years later, however, genetically modified soybean accounted for 100% of the soybean acreage. Today, herbicide resistant soybean is cultivated on more than 19 million hectares in Argentina.

From 0 to 100% in 8 years

Argentina and the cultivation of soybean have gone hand in hand for several decades. Soybean was already an important crop even before it became possible to grow glyphosate resistant soybean on a commercial scale. The production and importance of soybean increased in the early 1980s and soybean started to become the dominant crop in the fertile Pampas. The land was cultivated more efficiently through use of a rotation system with wheat, the production cost fell and the market price of soybean rose. Although conventional production of soybean was very successful, herbicide resistant soybean made a big impression on Argentine producers.

The production of glyphosate resistant soybean started in 1996 on 370,000 hectares. This acreage had increased almost fivefold by the next growing season and by 1998-1999, there were almost 4.9 million hectares of glyphosate resistant soybean crops. In the 2001-2002 season, the acreage of genetically modified soybean crossed the threshold of 10 million hectares, representing an adoption of 91%. Remarkably, the production of genetically modified soybean continued to rise, and in the 2004-2005 growing season it ultimately accounted for more than 14 million hectares, fully 100% of soybean acreage. An adoption rate of this magnitude is unprecedented. Herbicide resistant soybean in Argentina has managed to convince almost all producers over a period of 8 years. It took much longer even to win the support of producers when hybrids were introduced in North America in the 1930s.

A variety of factors have played a role in the early rapid adoption of genetically modified crops in Argentina. Herbicide resistant soybean did not only meet the requirements of producers and produced a positive economic and ecological effect, the government also played a vital role. It was prepared to give the technology a chance. The government attracted scientists from the public and private sector and this resulted in flexible, rational and scientific regulations. Moreover, in the nineties Argentina held a special position, as companies were not able to claim any patent rights to glyphosate resistant soybean.

Argentina and the cultivation of soybean

![Graph](image_url)

**Figure 6.** In the course of eight years, Argentine soybean production switched completely to genetically modified soybean.
No extra costs for patent

An additional advantage that Argentine producers had over all other countries, was the special situation with regard to patent rights. In the mid-1980s, Asgrow International, a large Argentine agrotechnological company, entered into an agreement with Monsanto to include Monsanto’s glyphosate resistant technology in their soybean selection program. Shortly after, however, Asgrow was taken over by Nidera, which with this takeover also obtained the production rights to all the plant material produced by Asgrow. Monsanto terminated their agreement and consequently Nidera no longer had free access to herbicide resistant technology. However, the existing plant material, including the glyphosate resistant soybean varieties, had become the property of Nidera.

Nidera navigated its genetically modified soybean through the Argentine biosafety procedures and in 1996 was the first company to launch herbicide resistant soybean varieties on the Argentine market. Monsanto and other companies followed suit over the next few years. By 2001, 7 companies offered more than 50 different glyphosate-resistant soybean varieties. When Monsanto applied for a national patent in 1995, it was refused by Argentina, probably because the technology could no longer be regarded as new. Nidera decided to sell its glyphosate resistant soybean seeds without the special contracts that Monsanto normally presents to producers. One of the consequences was that producers could keep seeds from their own harvest as sowing seed for subsequent years. Because of its pioneering role, Nidera rapidly became the main player in the Argentine seed industry. The other companies (including Monsanto) therefore had little option but to adopt the same strategy. The National Seed Institute in Argentina (INASE) estimates that only 35% of soybean seed is purchased directly from seed companies. Approximately 30% of the sowing seed is produced by the producer himself and 35% of the seeds are made available illegally on the black market.

This exceptional position has undoubtedly played a role in the rapid adoption of glyphosate resistant soybean in Argentina.

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Flexible weed control

The advantages of the first-generation of genetically modified crops are mostly important for the producer. Glyphosate resistant plants enable simple and flexible weed control. Firstly, glyphosate is a broad-spectrum herbicide that kills many different kinds of weeds. Secondly, glyphosate resistant crops are not affected by the product, which means that the producer can use it on the whole field and has greater flexibility with regard to the time of application. Whereas previously the timing of spraying was crucial to avoid damaging the crop, glyphosate can also be used after germination and, in principle, throughout the growing cycle of the herbicide resistant crop without damaging the crop.

Lower production cost

Various sources state that the production cost of glyphosate resistant GM soybean is approximately 20 US dollars per hectare lower compared with conventional soybean.\textsuperscript{55,56} Whereas the production was estimated at approximately 245 US dollars per hectare prior to the introduction of GM soybean in Argentina, this fell in 1997 to 220 US dollars per hectare.\textsuperscript{56} This was mainly due to two factors. Firstly, the production of glyphosate resistant soybean stimulates a shift in herbicide use away from the more expensive selective herbicides and to the cheaper glyphosate. Secondly, glyphosate resistant soybean stimulates the use of no-tillage or no-ploughing agriculture (see following section). These less intensive soil treatments enable fuel and labour savings, which is confirmed in surveys carried out among GM soybean producers. In 1999, the Argentine National Institute for Agricultural Technology (INTA) held a survey among 80 Argentine farmers in a region where adoption increased from 23\% in 1998 to 80\% in 1999. Ninety three per cent of the farmers cited reduced production cost as the reason, while 71\% also indicated a time saving.\textsuperscript{57}

Support for no-tillage farming

Soil compaction and soil erosion represent a serious problem for sustainable agriculture. Agriculture based on no-tillage, which does not use ploughing, improves the soil structure, protects the soil against erosion and reduces production costs and fuel consumption. However, the adoption of no-tillage agriculture in Argentina was a slow process because of the lack of a compatible weed control. Herbicide resistant crops have encouraged the breakthrough of no-tillage. In Argentina today, more than 78% of the fields are cultivated without ploughing and for soybean fields this figure rises to almost 87%.

Breakthrough of no-tillage agriculture

For centuries, producers have cultivated their land intensively, using the plough to bury crop residues and weed seeds underground and to loosen the soil. Depending on the climate, ploughing can have both advantages and disadvantages. In areas with wet winters, for example, ploughing can dry out better in the spring, making it possible to sow earlier. The disadvantage, however, is that ploughing also causes extra compaction of the deeper soil layers and this has a negative effect on plant growth. In dry areas, bringing the wet subsoil to the top implies extra evaporation and thus the soil retains even less water.

Depending on soil type and field condition, however, ploughing may also have another effect. The soil structure of compacted soil can be partly restored by ploughing, but ploughing also results in smaller soil aggregates. This makes soil particles less resistant to wind and water and as a result a ploughed field becomes more susceptible to erosion.

Moreover the moisture in the soil evaporates less quickly and the soil releases less CO$_2$.

There are different kinds of no-tillage treatments. No-tillage generally means that the soil is not turned but merely loosened. The soil is broken up and crumbled using tines drawn through the soil, without displacing it. The term reduced tillage is often used for this. A more extreme form is the direct-sowing method or no-tillage in the strict sense of the word. In the latter case, no form of tillage is used at all, so that the soil is permanently covered either with a crop or with residues from previous crops. Only a narrow trench is dug in the earth to sow the crop. The soil is left completely undisturbed. For the sake of simplicity, we will hereinafter refer to the two methods together by the term no-tillage, unless stated otherwise.

In spite of the many advantages of no-tillage agriculture, it is not all good news. It is true that no-tillage methods are often associated with a higher density of weeds. In traditional agriculture, many weeds can be removed mechanically by creating a false seedbed.68 If the soil is not ploughed, weeds germinate simultaneously with the sown crop and the producer has to resort to the use of chemical weed killers.

However, herbicides that kill the weeds but do not affect the crop have always been scarce. Additionally, more and more herbicides are being taken off the market.

If weeds are not controlled adequately, more weed seeds grow in the field year after year and the use of the no-tillage method comes under pressure. As a consequence, genetically modified soybeans that is tolerant to the herbicide glyphosate has become very popular with no-till producers. It enabled them to make and keep their fields free of weeds without ploughing and without damaging the crop.
South America, the United States and Canada led the field in the use of no-tillage methods. This is logical as these countries are also the main producers of herbicide resistant crops. In Argentina, the first steps in no-tillage agriculture were taken in the early seventies. It was, however, not a great success as, due to the lack of knowledge and effective weed control, many producers quickly gave up. However, this lack of know-how was rectified by AAPRESID. This Argentine association of no-till producers waged an intense public information campaign and was able to convince more and more producers to switch to no-tillage.

But the mass switchover only happened when glyphosate resistant soybean was introduced. Simple weed control based on only one herbicide which allowed to control even the most stubborn weeds without the need for ploughing gave the Argentine soybean industry a huge boost. Recent AAPRESID figures indicate that almost 87% of Argentine soybean fields are cultivated using no-tillage methods (Figure 7).

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**Figure 7. Sensibilisation of the public together with the introduction of glyphosate resistant soybean stimulated the use of no-till methods in Argentine soybean production.**

Source: AAPRESID 2012.

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Improved soil structure

More and more agricultural studies show that ploughing has more disadvantages than advantages. A meta-analysis surveying 35 different field experiments tested physical soil properties, water management, nitrogen availability and yield. The examined fields were widely distributed throughout the Argentine Pampas region and consequently included a good range of climate and soil types and rotation systems. The researchers found that the penetration resistance of a field under no-tillage was significantly greater than with ploughing. Soil that has not been ploughed is therefore more resistant to the structural destruction of tractors and other agricultural machinery. The average diameter of soil particles of a ploughed soil was also much smaller than that of a non-ploughed soil. This grain diameter is a measure of soil stability. The larger the grain, the more resistant it is to water and wind erosion.

Throughout the experiments, Alvarez and Steinbach found that ploughed soil is 70% less stable than no-tillage soil. No-tillage soil on average held 13 to 14% more water than ploughed soil, both at the time of sowing and at the time of flowering. A field that retains a lot of water is desirable during dry periods, but in wet periods the excess water is a disadvantage. Interestingly, while non-ploughed soils contained more than 10% extra water than ploughed soils, this difference in water content was much less pronounced in wet conditions. The infiltration rate of water in non-ploughed soils is significantly higher than in a ploughed soil.

The meta-analysis also indicated that in non-ploughed soils the amount of nitrate nitrogen is in general less than in a ploughed field. There is also less nitrogen release in a no-tillage soil. The main reasons for this are the higher temperature of a non-covered field, the reduction in size of soil particles and organic material by ploughing, and faster composting and nitrogen release in a ploughed soil. Depending on the crop, this may have an effect on the yield. Nitrogen-fixing plants such as soybean are less affected by this and soybean yield therefore does not vary significantly on a non-ploughed or a ploughed soil.

Irrespective of whether a farmer has to modify the nitrogen content of the soil or not, there appears to be a large consensus that soil properties improve when a field is tilled less.

75 Dorts K et al. (2006). C and N mineralization of undisturbed and disrupted soil from different structural zones of conventional tillage and no-tillage systems in northern France. Soil Biology & Biochemistry 38, 2576-2586.
Glyphosate resistant soybean has resulted in the mass adoption of no-tillage agriculture in Argentina. In this way, it has indirectly contributed to a noticeable ecological improvement in Argentine agriculture. As herbicide resistant crops allow effective weed control without ploughing the fields, less fuel is required and therefore CO₂ emission is also reduced. According to the English agricultural economists Graham Brookes and Peter Barfoot, 27.12 litres less fuel is required to cultivate one hectare per growing season in no-tillage and 10.39 litres less in reduced tillage as compared to conventional ploughing systems.⁷⁶

Based on these figures, Brookes and Barfoot have calculated that in Argentina 262 million litres of fuel were saved in 2011 alone by the change in ploughing mentality. Based on the fact that the consumption of 1 litre of fuel is equivalent to an emission of 2.67 kg CO₂, the fuel saving resulted in 699 million kg less CO₂ emission. To more readily visualise these figures, Brookes and Barfoot calculated that in 2011 alone the effect was comparable to taking 310,000 cars off the road for one year.⁷⁷

If we take a general look at the various crops and countries, no-tillage is assumed to have resulted in about 14.69 million tonnes less CO₂ being emitted due to the 5.471 billion litres less fuel that was used over the period from 1996 to 2011. This is equivalent to taking almost 6.5 million cars off the road for 1 year.

**No-tillage agriculture and the anchoring of CO₂ in the soil**

No-ploughing or no-tillage agriculture is often linked to the increase in organic carbon in the soil, called CO₂ anchoring or CO₂ sequestration.⁶⁷,⁷⁶ Not disturbing the soil prevents the stored carbon to get released into the atmosphere in the form of CO₂. One kg of organic carbon corresponds to 3.67 kg CO₂.⁷⁶ In addition to reduced CO₂ emission due to reduced fuel consumption, no-tillage methods therefore further reduces CO₂ emission by increasing CO₂ sequestration in the soil. Graham Brookes and Peter Barfoot estimate that in 2011 almost 2 million tonnes of carbon was stored as the result of no-tillage in the Argentine fields. This CO₂ sequestration would have prevented the emission of more than 7 million tonnes of CO₂.

However, the effect of no-tillage on CO₂ sequestration is increasingly being qualified. Most meta-analyses continue to show that no-tillage agriculture on a global level results in an increase in CO₂ sequestration,⁷⁹ but in many cases the increase in organic carbon under field conditions is limited or non-existing.⁸⁰,⁸¹,⁸² These studies give different results because the presence or absence of increased organic carbon appears to depend on the sampling method. No-tillage soil holds more organic carbon in the top layers, but this increase is not found in the lower soil layers. In certain cases, the lower layers of undisturbed soil in...
Success has a down side

Despite the fact that herbicide resistant crops have been more ecological over the past 16 years than conventional production, we have to keep asking ourselves what the impact is if certain crops are produced on very large acreages. In this respect it appears that herbicide resistant soy in particular has become the victim of its own success. Driven by the reduced production costs of genetically modified soybean cultivation and the constant demand for soybean-related products, Argentina has experienced an extreme scaling up of production. Mathematical models estimate that the availability of genetically modified soy has resulted in more than 8.6 million additional hectares being planted.\textsuperscript{9} This gives rise to concerns about the negative effects of monoculture. The continuous planting of soybeans in Argentina has been observed to result in the loss of nutrients in the soil. Between 1996 and 2010, more than 14 million tonnes of phosphate from the soil were depleted.\textsuperscript{9} To keep achieving the same yields, more crop rotation is needed or – more probably – the soybean fields will have to be fertilised with phosphate. The latter not only causes additional environmental pollution, but also involves additional cost so that the net yield of soybean production will be reduced.

In addition to using up certain nutrients, the huge soybean acreage in Argentina also means that very large areas are treated with the same herbicide (in this case glyphosate). If the guidelines for the production of herbicide resistant crops are not followed, sooner or later this will result in glyphosate resistant weeds (see box section Superweeds), which will make these crops less efficient in the future.

\textsuperscript{83} Mishra U et al. (2010). Tillage effect on soil organic carbon storage and dynamics in Corn Belt of Ohio US. Soil and Tillage Research 107, 88-96.
Victim of its own success

Unlike insect resistant crops, which reduce the need for insecticides, glyphosate resistant plants were not developed with a view to using fewer herbicides. They were brought on the market to provide farmers with a flexible way to control weeds. The cultivation of glyphosate resistant crops has also ensured a shift in herbicide use. What effect does this have on the environment and on the health of humans and animals?

A shift in herbicide use

Glyphosate is a broad-spectrum herbicide that is harmful to a wide range of plants, including crop plants such as soybean. Until the introduction of glyphosate resistant crops, glyphosate could therefore only be used in the absence of the crop or before the germinating crop emerged. As a result, the use of glyphosate was spontaneously curtailed. However, this restriction was lifted when glyphosate resistant crops came on the market. Whereas farmers used three to four different selective herbicides to keep a field of non-GM soybean free of weeds, a field of glyphosate resistant soybean could be successfully treated with glyphosate alone. Naturally then, the use of glyphosate increased in Argentina from 1996 onwards. Qaim and Traxler estimate that there was an 11-fold increase in the use of glyphosate was also observed. However, the increased use of glyphosate is just one part of a comprehensive change in herbicide use. Herbicides as well as other pesticides are categorized according to their toxicity (see page 12). The World Health Organization (WHO) uses an international classification system for pesticides, whereby class Ia indicates the most toxic products and class II the next most toxic. Glyphosate is categorised in class III. Qaim and Traxler have calculated on the basis of surveys that the rising use of glyphosate in Argentine soybean fields has entailed a spectacular growth in the use of the less toxic herbicides of class III, while the use of herbicides in class I and II fell considerably (Table 1). The surveys were conducted at the end of 2001 in three different Argentine provinces. A total of 52 farms were surveyed in Buenos Aires and Santa Fe and 7 interviews were done in the province of Chaco.

There has also been a progressive shift in herbicide use outside Argentina since the introduction of glyphosate resistant crops, with the use of most herbicides falling and the use of glyphosate rising (Figure 8). On the basis of surveys, the USDA has kept records of pesticide use in the United States over several years. Due to a lack of resources, this is only available for soybean crops until 2006. The percentage of soybean acreage treated with glyphosate rose from 20% in 1995 to 96% in 2006. At the same time, the use of imazethapyr, pendimethalin and trifluralin fell significantly from 44% to 3%, from 26 to 3% and from 20 to 2% respectively. The same trend is observed in the herbicides alachlor and metribuzine.
**Table 1. Glyphosate resistant soybean led to a shift in herbicide use in Argentina.**

Data based on surveys carried out in 2001.

Source: Qaim and Traxler (2005), adapted according to the new WHO classification system.33

* In 2009 the WHO classification system for pesticides was amended: class I became Ia, class II became Ib, class III became class II and class IV is the current class III.

<table>
<thead>
<tr>
<th></th>
<th>Conventional Soybean</th>
<th>Glyphosate Resistant Soybean</th>
<th>%</th>
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</thead>
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<tr>
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<td>2.30</td>
<td>16.8</td>
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<td>5.57</td>
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<tr>
<td>**Herbicides class II (l/ha) **</td>
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<td>**Herbicides class III (l/ha) * **</td>
<td>1.58</td>
<td>5.50</td>
<td>248.1</td>
</tr>
</tbody>
</table>

**Table 1.** Glyphosate resistant soybean led to a shift in herbicide use in Argentina. Data based on surveys carried out in 2001. Source: Qaim and Traxler (2005), adapted according to the new WHO classification system.33

* In 2009 the WHO classification system for pesticides was amended: class I became Ia, class II became Ib, class III became class II and class IV is the current class III.

**Figure 8. The introduction of glyphosate resistant crops in 1996 has resulted in a shift in herbicide use in the US. Presented here is the percentage of agricultural soybean acreage treated with a specific herbicide. No data are available for the year 2003 and after 2006.**

Source: USDA National Agricultural Statistics Service.84
An increase in the use of herbicides in glyphosate resistant soybean crops

No single aspect of genetically modified crops has been so fiercely debated as the use of herbicides in the cultivation of glyphosate resistant GM crops. Calculating and estimating the effect of a new technology is anything but simple. Firstly, herbicide use depends on a number of parameters, such as crop, weed suppression, soil and climate, which makes it difficult to make generalisations. Secondly, the glyphosate resistant GM crops tend to be used by innovative farmers who usually have large areas of land which makes comparison with a smaller organically grown crop difficult. Thirdly, the impact of the GM crops must be compared with a situation without herbicide resistant GM crops. Given the extent of the adoption of glyphosate resistant soybean in Argentina and elsewhere, the limited reference fields available often fail to give a true picture, so that the effect of herbicide resistant crops is either underestimated or overestimated. But the biggest problem in making comparisons is the limited data available.

Due to a lack of data for Argentina, we will extend this discussion to North America. Agricultural economist Charles Benbrook from Washington State University recently studied the evolution of herbicide use in the US from 1996 (introduction of glyphosate resistant crops) to 2011. A similar investigation was undertaken by the French research institute INRA (Institut National de Recherche Agriculture). Both studies made use of the USDA NASS data and established two remarkable trends. In the period shortly after the introduction (1996 to 2001) herbicide use in glyphosate resistant crops fell, but from 2002 use increased again (Figure 9). Due to budgetary constraints there are no more available public data for soybean crops from 2006 from the government. However, so as to be able to evaluate herbicide use after 2006, Benbrook used extrapolations and estimates, while the French study made use of the GfK Kynetec figures. The latter data are collected by a private institution and are not freely available.
In his study, Benbrook concluded that herbicide use continues to increase and that since the introduction of glyphosate resistant soybean in the US, an additional 167 million kg pesticides have been used over the period from 1996 to 2011 in comparison to conventional soybean crops. However, these figures are disputed by economist Graham Brookes. He points out that extrapolations and estimates do not present a reliable picture. Moreover, Benbrook’s figures must be an overestimate because they take no account of the increase in the amount of land dedicated to soybean crops. Yet, Brookes also reports a rise in herbicide use in soybean crops. After all, erroneous cropping schemes and excessive use of glyphosate in relation to surface area have logically paved the way for the emergence of herbicide resistant weeds in North and South America (see text box “Superweeds”). This is one of the main reasons why farmers are using more glyphosate and have also returned to alternative and more toxic herbicides. The GfK Kynetec figures also show that herbicide use in the herbicide resistant soybean crops is higher than in conventional soybean crops. On the basis of these figures, up to 30% more herbicides were used in the period between 2003 and 2009 in the glyphosate resistant soybean crops.


Figure 9. During the first years after the introduction of glyphosate resistant soybean, the use of herbicide in the US fell, but it has risen again since 2002. Source Bonny (2011).
In order to benefit from the advantages of herbicide resistant crops (both GM and non-GM) in the longer term, these crops must be cultivated wisely. All farmers know that crop rotation is extremely important, not only because it prevents crop-specific pests and stops the soil from being exhausted by a crop-specific demand for nutrients, but also so that crop-specific pesticides can be used in alternation. If the same pesticides are used year after year in a certain field, the selection pressure on the pest increases. As the result of a natural selection process by which organisms try to adapt to a changing environment, insects can evolve that are resistant to certain insecticides, fungi that are no longer affected by fungicides and weeds that are tolerant to certain herbicides. In the latter case, the weeds remain in the field after herbicide treatment and the efficiency of the herbicide resistant crop deteriorates significantly. However, these are not ‘superweeds’ that can no longer be destroyed by any product. These are weeds that can no longer be removed by the herbicide to which the crop was made resistant, e.g. glyphosate.

To prevent this from happening, farmers should avoid growing one specific herbicide resistant crop in the same field year after year. It is also sensible to alternate glyphosate resistant crops with glyphosate sensitive crops within one particular crop year. If these rules are not respected, the selection pressure on weeds increases and herbicide resistant weeds can evolve. By alternating herbicides, weeds that may have built up a slight resistance to a certain herbicide can be destroyed by another herbicide and will not get the chance to propagate.

In North and South America, the introduction of glyphosate resistant crops was such a success and everyone was so overwhelmed by the ease with which weeds could be destroyed, that almost every farmer began growing glyphosate resistant crops. In 2012, 93% of all soybean in the United States was herbicide resistant GM soybean. In Argentina it took only 8 years for all farmers to trade in their conventional soybean for glyphosate resistant soybean. The emergence of resistant weeds is induced by the massive adoption of the glyphosate resistant soy but cropping schemes are as essential in this process. Glyphosate resistant soybean was alternated with glyphosate resistant corn in both North and South America, which flies in the face of good farming practices. By relying too heavily on glyphosate as the only herbicide and not respecting essential cropping rules, gigantic areas of land were being treated year on year with the same herbicide. The results, therefore, were hardly unexpected. Less than a decade after the introduction of glyphosate resistant crops, the first glyphosate resistant weeds appeared, both in Argentina and in the United States.89

90 www.weedscience.org

However, the reason for the emergence of glyphosate resistant weeds is not exclusively the introduction of herbicide resistant crops. After all, all weeds are capable of developing resistance to any herbicide and resistance for certain herbicides had been observed in the field long before the first GM plant was developed. Glyphosate resistant weeds (Conyza bonariensis and Conyza sumatrensis) have been observed in Greece,90 a country that forbids the growing of GM crops and where glyphosate resistant crops have never been cultivated. The same is true of France, where glyphosate resistant rye-grass (Lolium rigidum) has been reported. In other words, glyphosate resistant crops are not exclusively to blame for glyphosate resistant...
weeds. However, the large-scale use of glyphosate in North and South America has facilitated and accelerated their evolution locally. One example illustrating that the cultivation of herbicide resistant plants doesn’t necessarily result in herbicide resistant weeds is the cultivation of glyphosate- and glufosinate resistant oil seed rape in Canada. Here, herbicide resistant oil seed rape is grown in rotation with wheat and rye, with the result that it only grows in the same field every four years. Moreover, the farmers are able to alternate glyphosate- with glufosinate resistant GM oil seed rape. In 2010, 6.5 million hectares of oil seed rape were grown, of which 47% was glyphosate resistant (GM), 46% glufosinate resistant (GM), 6% imazamox/imazapyr resistant (non-GM) and 1% conventional oil seed rape. As a consequence of the crop rotation and the alternation of the type of herbicide-resistance, there has been no abnormal rise in the emergence of herbicide resistant weeds since the introduction of herbicide resistant GM crops. The number of herbicide resistant weeds in Canada is comparable with a country in which no herbicide resistant plants are cultivated. Therefore, when herbicide resistant crops are managed correctly, there is no increased risk of resistant weeds developing.

Notwithstanding the fact that the historic overuse of glyphosate reflects a lack of understanding about weed management, not all the blame can be laid at the door of the farmers. Producers of herbicide resistant applications should also have monitored and documented the use of herbicides and the cropping situation, and intervened where necessary. Plant biotechnology can accomplish many things, but the introduction of a GM crop should not mean discarding the basic rules of good farming practices.

More glyphosate, but a lower environmental impact

Introducing resistance to a particular herbicide in a crop stimulates the use of that specific herbicide. However, now that it appears that total herbicide use is higher than for conventional crops, herbicide-resistance would seem at first glance to be bad for the environment. Yet that depends on the properties of the herbicide. Depending on the mechanism of action, possible side effects and biodegradability, every herbicide has a different effect on the environment. A shift in herbicide use caused by herbicide resistant crops, doesn’t immediately have to lead to greater pressure on the environment.

Glyphosate is one such example. According to the WHO, glyphosate is categorized in toxicity class III. It therefore scores better than other herbicides such as 2,4-D and dicamba. Glyphosate also has no carcinogenic properties and without wishing to trivialize the use and impact of chemicals, its acute toxicity is lower than that of kitchen salt. When it is used correctly, glyphosate binds to soil particles, which means less of it filters through to the groundwater.

When monitoring the effect of glyphosate resistant crops on the environment, it is important to take into account the ecological as well as the toxicological impact of the herbicides. There are various formulas for doing this and depending on which one is used, different factors weigh more heavily in the result. The most widely accepted method seems to be the ‘Environmental Impact Quotient’ (EIQ). The EIQ model determines the environmental footprint for every pesticide and takes into account the three most important steps in the farming production chain: the risk for the farmer, the risk for the consumer and the ecological impact. The higher the EIQ, the more harmful the product. The EIQ of the most common herbicides ranges from 8 to 47. With an EIQ of 15.33, glyphosate scores quite well. The herbicides imazethapyr (19.57), trifluralin (18.83) and pendimethalin (30.17) whose use has fallen since the introduction of glyphosate resistant crops, score less well than glyphosate. The same goes for alachlor (17.86), metribuzine (28.37) and atrazine (22.85). For an even more representative picture of the impact of herbicides, the EIQ value is often multiplied by the quantity of active ingredient used per hectare. This facilitates a comparison of the herbicide programmes of GM soybean with those of non-GM soybean.

When this is taken into account, there is a remarkable drop in the EIQ rate coinciding with the introduction of glyphosate resistant soybean (Figure 10). In the United States, the change in herbicide use brought about by the introduction of glyphosate resistant soybean resulted in the EIQ falling by 29% between 1996 and 2005 (Figure 10). In Argentina too, the EIQ of soybean crops fell by 21% during the same period.
At the same time, it is striking that from 2006, the year in which the first herbicide resistant weeds appear, the EIQ rises along with total herbicide use (see also Figure 9).

However, according to Brookes and Barfoot who use the non-publicly available GfK Kynetec figures, the EIQ in conventional soybean crops also rises. Notwithstanding the fact that the EIQ is gradually rising, the average EIQ of a GM soybean field in the US was 37% lower than the average EIQ of a conventional soybean field both in 2009 and in 2010. That difference was less significant in Argentina. From 2008 to 2010, the average EIQ/ha in Argentine glyphosate resistant soybean crops was 41.38 compared to 43.64 for conventional crops. According to these figures the glyphosate resistant soybean crops in Argentina therefore only scored 5% better than conventional crops in the area of environmental impact.

However, the question is whether this environmental advantage will last. We are increasingly seeing more glyphosate used per hectare or farmers using other products in addition to glyphosate. The most obvious reason is the emergence of glyphosate resistant weeds (see text box ‘Superweeds’). Compared to 2010, the quantity of active ingredient in the Argentine glyphosate resistant soybean crops in 2011 rose from 2.68 to 3.02 kg/ha and the EIQ/ha from 41.38 to 47. Given the lower EIQ of glyphosate, the glyphosate resistant soybean crops still only perform 2% better than conventional crops in the area of environmental impact (EIQ/ha=48). But forecasts for 2012 show that the increase in herbicide use will continue, thereby completely eradicating the already limited environmental benefit of glyphosate resistant crops (as concerns herbicide use). A similar trend is also being seen in the US. The quantity of active ingredient per hectare rose from 1.63 kg/ha in 2008 to 1.9 kg/ha in 2011, reducing the environmental benefit from 37% in 2010 to 18% in 2011. These calculations are of course only looking at the shift in herbicide use.

The major environmental benefit of glyphosate resistant crops in Argentina but also in the US is that they have stimulated the trend towards no-tillage farming. This benefit remains even when herbicide use increases.

**HERBICIDES: ACTIVE INGREDIENT VERSUS FORMULATION**

When glyphosate is mentioned as a herbicide, it is the active ingredient that is being referred to. Glyphosate is a chemical ingredient that impairs the action of the EPSPS enzyme (see page 11). The herbicides that are available in the trade, and which can be used directly where necessary after making up a solution or dilution, are prepared or formulated beforehand in a specific way. These formulations (such as RoundUp) render the active ingredient (glyphosate) suitable for a particular application. During formulation, all kinds of components are added to the active ingredient. Solvents to dissolve the active ingredient, stabilisers to prevent the active ingredient from being broken down by sunlight, dyes, anti-foaming agents but also surfactants and wetting agents to ensure that the active ingredient binds to the weed and is more easily taken up by the plant. When we talk about the (eco-)toxicity of glyphosate in this article, we mean the toxicity of the active ingredient. The herbicide that is ultimately used contains countless other chemical ingredients. Like the active component, these substances must also undergo toxicity analyses before the complete formulation is allowed on to the market by the competent authorities.

The introduction of glyphosate resistant crops has brought about a shift in herbicide use. This shift has drastically increased the amount of glyphosate used in worldwide weed control. The question is whether it is wise always to rely so heavily on the same pesticide. The answer is a resounding no. Deciding to put all your eggs in one basket may be lucrative in the short term, but in the long term it is untenable. Excessive use of one herbicide flies in the face of farming logic. The emergence of herbicide resistant weeds (see text box ‘Superweeds’) is proof of the fact that glyphosate resistant crops have become a victim of their own success. If we want to continue to provide farmers with herbicide resistant crops, then alternatives must be developed that can be cultivated alternately with glyphosate resistant crops. Oil seed rape cultivation in Canada demonstrates that with the use of good farming practices in combination with different kinds of herbicide resistance, sustainable farming can be combined with herbicide resistance. By implementing crop rotation with crops that are non-herbicide resistant and by alternating glyphosate and glufosinate resistance, the development of tolerant weeds has not been stimulated in Canada over the years (see text box ‘Superweeds’). The EIQ value of Canadian oil seed rape therefore remained stable between 2008 and 2011, while that of oil seed rape in the US has been increasing in recent years. In the space of two years, the environmental benefit of glyphosate resistant oil seed rape in the US has halved (Table 2).

The ability to alternate crops with different herbicide resistance (glyphosate and glufosinate) is a very efficient way to prevent the emergence of herbicide resistant weeds. However, it must always be verified that the environmental impact is thereby reduced. In recent years, GM crops have been developed that are resistant to other herbicides such as 2,4-D, dicamba or imidazolinones. The 2,4-D and dicamba resistant crops will be marketed in the coming years. In Argentina, the cultivation of GM soybean resistant to imidazolinones has been approved since 2013. By being able to treat crops with 2,4-D, dicamba or imidazolinones, the glyphosate resistant weeds can be destroyed. According to the WHO, imidazolinones are less toxic than glyphosate, which could be a step in the right direction. The EIQ value (which takes account of far more parameters) of most imidazolinones is, however, higher than that of glyphosate. For dicamba, the situation is even worse.Dicamba is not only more toxic than glyphosate according to WHO; but with an EIQ value of 26.33 it has a far bigger ecological footprint than glyphosate. This is obviously not the right way to attain sustainable agriculture. 2,4-D in turn is a very volatile product, more easily carried by the wind to neighbouring plants and residential areas. One of the companies that wants to sell 2,4-D resistant crops claims that they have created a less volatile variant of this molecule. However, there is a very real danger that farmers will use the cheaper generic form which doesn’t have these properties and which is therefore much more harmful to the environment. A responsible choice is therefore crucial if the sustainable aspect of farming is to prevail.

Table 2. Average EIQ values per hectare of oil seed rape crops in Canada and the United States between 2008 and 2011. Glyphosate, glyphosate resistant GM oil seed rape; Glufosinate, glufosinate resistant GM oil seed rape; Conventional, non-GM oil seed rape.

<table>
<thead>
<tr>
<th></th>
<th>CANADA</th>
<th></th>
<th></th>
<th>UNITED STATES</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GYLFSATE</td>
<td>GLUFOSINATE</td>
<td>CONVENTIONAL</td>
<td>GYLFSATE</td>
<td>GLUFOSINATE</td>
<td>CONVENTIONAL</td>
</tr>
<tr>
<td>2008</td>
<td>10.68</td>
<td>7.07</td>
<td>11.52</td>
<td>9.95</td>
<td>7.78</td>
<td>25.70</td>
</tr>
<tr>
<td>2009</td>
<td>10.68</td>
<td>7.07</td>
<td>11.52</td>
<td>9.95</td>
<td>7.78</td>
<td>25.70</td>
</tr>
<tr>
<td>2010</td>
<td>10.68</td>
<td>7.07</td>
<td>11.52</td>
<td>15.64</td>
<td>10.97</td>
<td>25.53</td>
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<tr>
<td>2011</td>
<td>10.68</td>
<td>7.07</td>
<td>11.52</td>
<td>17.60</td>
<td>9.70</td>
<td>25.90</td>
</tr>
</tbody>
</table>

Source: Brookes en Barfoot.46, 99-101

References:
X2 http://www.aghsvirtualmeetings.com/24d_about.html
X3 http://www.aphisvirtualmeetings.com/dicamba_about.html
X4 The imidazolinones are a group of herbicides that inhibit the action of acetolactate synthase, so preventing the production of amino acids. This group also includes imazaquin, imazapyr, imazapic, imazethapyr and mazamox.
X6 http://msdssearch.dow.com/PublishedLiteratureDAS/dh_07ea/0907b603807e6e837.pdf?&type=pdf&fromPage=010-42296.pdf&fromPage=GetDoc
X7 http://www.aphisvirtualmeetings.com/24d_about.html
X8 http://www.aphisvirtualmeetings.com/dicamba_about.html
X9 By being able to treat crops with 2,4-D, dicamba or imidazolinones, the glyphosate resistant weeds can be destroyed. According to the WHO, imidazolinones are less toxic than glyphosate, which could be a step in the right direction. The EIQ value (which takes account of far more parameters) of most imidazolinones is, however, higher than that of glyphosate. For dicamba, the situation is even worse. Dicamba is not only more toxic than glyphosate according to WHO; but with an EIQ value of 26.33 it has a far bigger ecological footprint than glyphosate. This is obviously not the right way to attain sustainable agriculture. 2,4-D in turn is a very volatile product, more easily carried by the wind to neighbouring plants and residential areas. One of the companies that wants to sell 2,4-D resistant crops claims that they have created a less volatile variant of this molecule. However, there is a very real danger that farmers will use the cheaper generic form which doesn’t have these properties and which is therefore much more harmful to the environment. A responsible choice is therefore crucial if the sustainable aspect of farming is to prevail.
Monsanto

In 1996, Monsanto came on the market with genetically modified crops that were resistant to glyphosate. The herbicide is better known as Roundup and the crops are called RoundupReady. It was perhaps not the best choice of application for introducing a new technology. With incorrect use it allows for more herbicide products (providing the crop is resistant), has no direct benefit for the consumer and can only be used in combination with a herbicide from the same firm. This issue continues to feed the negative debate around genetically modified crops. And this despite the benefits that herbicide resistant crops can offer the environment in comparison with other conventional methods for weed control.

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From day 1, multinationals have been wise to the possibilities of GM technology and they certainly do have a massive impact on the biotech and seed industry. At present the 10 biggest seed companies control 73% of the global trade in sowing seed. Over the last century, the seed product industry has undergone various structural changes, the most significant of which happened in the 1980s. With a strong wave of strategic mergers and takeovers, certain companies wanted to maintain and expand their presence in the agrochemical sector. The fusion of biotechnological knowledge and access to sowing seeds was important in this respect. GM technology has therefore certainly not attenuated the ‘oligopolisation’ of the seed market, but neither can it be blamed for it. The change has more to do with economic strategies than with a particular technology. As an illustration, not all major seed companies develop GMOs and, furthermore, GM crops are also developed by governments and small biotech firms.

Multinationals are generic to any high-tech and capital-intensive sector. The computer industry is in the hands of IBM and Apple, more than half the automobile industry is owned by Toyota, General Motors and Volkswagen, and multinationals such as Johnson & Johnson or Pfizer dominate the pharmaceutical industry. All these sectors make use of patent laws to protect their innovations and to earn back their huge investments. Things are no different with genetically modified crops.

The development and registration procedure for these crops is very costly, a financial investment that is hardly feasible for the public sector. There is also a lack of product marketing know-how in the public sector. ‘Golden rice’, a genetically modified form of rice containing more provitamin A, is a wonderful example of this. This GM rice was developed by the public sector and can prevent a shortage of vitamin A in Asian children. The ‘Golden Rice Initiative’ was however obliged to enter a public-private alliance with Syngenta. In their licensing agreement both parties agreed that the company Syngenta would mass-produce and sell the GM rice on condition that it would be made available free of charge in developing countries for humanitarian purposes.

In order to stay economically viable, companies have to recoup their investment costs. Patents enable companies to protect their development. For as long as the patent protection is valid and only in countries where the patent is recognised, the owner can prohibit other parties from producing, using, selling and importing the product. The patent gives the patent-holder exclusivity and once a product is approved for the market, he can decide the conditions (e.g. at what price) under which this will proceed. This gives him the chance to earn back his investment costs during the period of protection. Without such protection, companies would not invest in innovation, or if they did, to a lesser degree.

On top of that, the ‘GMO and multinational’ picture is a little more complicated. First of all, no farmer is obliged to use glyphosate resistant or other genetically modified seeds. Yet more and more farmers do, because benefits like greater ease of cultivation, a greater certainty of harvest, and/or an increase in income carry more weight than the higher purchase price of the seed. Ultimately, the free market plays a role here.

Secondly, small and medium-sized seed companies also profit from the success of genetically modified crops. The herbicide resistant and insect resistant plants may be generated by the multinationals, but they are licensed to smaller companies who insert the properties into their local varieties (see text box ‘2 GM events, 368 soybean varieties’). The same goes for the herbicide Roundup. The Monsanto patent expired in 2000, and many other companies are now producing glyphosate. In addition, farmers are not contractually obliged to buy herbicide from Monsanto.113

Thirdly, not all GM crops are developed by multinationals. The high development and registration costs meant that the first generation of genetically modified crops could only be brought on the market by capital-rich companies. These days, however, that argument doesn’t hold water anymore. More and more countries are developing genetically modified varieties independently of the biotech industry. In Argentina too, individual research centres have developed drought resistant corn, wheat and soybean varieties using a drought resistant gene from sunflowers.115 These genetically modified crops should come on the market in the next few years and the 20-year licence remains in Argentine hands.

Elsewhere too, the public sector is not standing idly by. In the 1990s, a virus resistant genetically modified papaya was developed in Hawaii. The University of Hawaii and Cornell University transferred the patent rights to the local papaya industry.115 Recently, the Brazilian research institute EMBRAPA has developed virus resistant beans. These GM beans will be made available to local farmers in the coming years.

113 http://thefarmerslife.files.wordpress.com/2012/02/scan_doc0004.pdf
114 http://ipsnews.net/news.asp?idnews=107065
6. And what about deforestation?

The debate about genetically modified crops is often fed with incorrect information and misleading anecdotes. For instance, it is often claimed that the introduction of herbicide-resistant soybean has led to deforestation in Argentina. The scale increases in soybean crops are certainly real, but there are no direct indications that the introduction of glyphosate-resistant soybean is the reason for deforestation in Argentina.

A rising demand for soybean

On a global scale, soybean is the fastest growing crop. In the last 25 years, global soybean acreage has more than doubled, while the area planted with soybean in Argentina has risen from 36,000 hectares in 1971 to more than 18 million hectares in 2011. This spectacular increase clearly has an effect on the use and division of land. One of the underlying reasons for the increase in soybean acreage is the constant and rising demand for soybeans and soybean-related products. China and the European Union are now the biggest importers of soybean in the world. What is remarkable, however, is that they have both been importing more soybean products since the beginning of this century. Soybean imports in Europe have remained relatively stable over the years (Figure 11) and represented 14.4% of soybean trade in 2010. The import of soybean flour in contrast has risen by 50% over the last 10 years (Figure 11). In 2010, half of the almost 30 million tonnes of imported soybean flour came from Argentina. Europe remains the biggest importer of soybean flour, mostly in the form of cattle fodder cakes.

One explanation for the rising European demand is found in the fodder industry. Until 2001, up to 2% of animal protein in feed came from carcasses and cadavers. However, in the wake of the global outbreak of mad cow disease, the feed industry banned bone meal and began looking for an alternative source of protein. Animal proteins were mainly substituted by soybean flour. With imports of 37.2 million tonnes, the EU is today’s biggest consumer on the soybean market. As a result of the negative attitude in Europe towards GM soybean, only 1% of soybeans come from Argentina; 47% come from Brazil. It is however worth noting that almost half the soybean flour does come from Argentina. In addition, 43% of imported soybean oil comes from Argentina.

Figure 11. In the late 1990s, soybean flour imports increased in Europe, while there was a spectacular rise in demand for soybeans in China.

Source: FAOSTAT.

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118 Mad cow disease or the BSE crisis began in 1996 in the United Kingdom and spread throughout Europe. It arrived in Canada and the US in 2003. As BSE can be transmitted between animals if infected bone meal is incorporated in feed, the use of bone meal was banned in Europe in 2001.
However, the biggest demand for soybean comes from Asia. Economic and demographic developments in China have resulted in a considerable rise in demand for soybeans and soybean oil both for animal feed and human food in recent years (Figure 11). According to FAO data, China imported 57 million tons of soybean beans in 2010. In 1998 only 8 million tons of soybeans and soybean-related products were imported. In 2010, China alone was responsible for more than 58% of global soybean trade. Together with Japan, Taiwan and South Korea, they imported more than 62 million tons of soybeans, which translates into 66% of global soybean imports. 18% of soybeans are from Argentina.

Chinese import data for soybeans however must be set in the right context. In 1998 China imported 5 tonnes of soybeans and 3 tons of soybean flour. However, this ratio has changed completely in favour of soybeans (Figure 11). China currently has the second highest capacity for grinding soybeans16 and imports more beans than it needs. A considerable share leaves China in the form of soybean flour. Japan and South Korea are the biggest purchasers of this flour.16 However, China can no longer satisfy its own domestic need for soybean oil and remains the biggest importer of Argentine soybean oil.16
Increase in soybean acreage

The Pampas area, the central region of Argentina, has a long farming tradition thanks to its favourable climate. In this major agricultural region, the expansion of the soybean area was largely associated with a reduction in the cultivation of other crops such as grains and vegetables. Grain crops, for instance, were reduced between 1970 and 2009 from 44% to 25%.119

Soybean cultivation also expanded towards the north-western part of Argentina in areas outside the Pampas, more specifically in the Chaco region. The Chaco region is a large area of more than 1,200,000 km² spread over Paraguay, Bolivia and North West Argentina and consists of meadows and dry forests.120

Dry forests connect the rain forests with the savannahs and are characterised by an annual dry period. The composition of a dry forest is therefore quite different from that of a rainforest. In a rainforest, densely growing trees form a closed canopy, whereas in a dry forest trees are interspersed by dense shrubs and grasses. Tropical dry forests are one of the most threatened ecosystems in the world.121 In the Chaco region there was a scarce supply of farmland and for the last 30 years meadows and forests have been converted en masse into agricultural land.16,21

One of the main causes of the disappearance of tropical forests is the expansion of agricultural land. The disappearance of the Chaco forests is a clear example of this. The Chaco region has the highest absolute deforestation figures in Argentina with an average of 200,000 hectares per year. The five most heavily affected provinces are Santiago del Estero, Chaco, Cordoba, Tucuman and Salta. However, the question is whether deforestation is a direct result of the introduction of glyphosate resistant soybean and whether GM soybean has contributed more than conventional soybean to this shift in land use.

Argentine researchers Ignacio Gasparri and Ricardo Grau studied satellite images taken in 4 different periods between 1972 and 2007 over an area of approximately 90,000 km² in the Tucuman and Salta provinces (North West Argentina). During this period, 1.4 million hectares of dry forest disappeared. Deforestation in North West Argentina began in the early 1970s and increased gradually (Figure 13). The same observations were made in the provinces of Santiago del Estero, where between 1992 and 1999 more than 273,000 hectares of forest disappeared (5% per year), and North Cordoba, where between 1969 and 1999 about 12 million hectares of land was deforested (2.8% per year).

According to Gasparri and Grau, deforestation at this time was primarily the result of agricultural and technological changes. Herbicides and fertilisers were introduced during this period which meant that overcultivated and less fertile ground could be used. On the other hand, new soybean varieties that needed less water came on the market and as a result of climate change from the second half of the 20th century there was a simultaneous increase in annual rainfall. The result was that previously unusable drier areas could now be used to cultivate soybean.

However, the intensity of deforestation in Tucuman and Salta increased significantly from 2002 onwards (Figure 14). The most recent deforestation statistics available from UMSEF show that the trend in deforestation in the whole of Argentina continued even after 2007. According to Gasparri and Grau, this great increase in recent years is mainly attributable to changing economic circumstances. The global rise in prices in the primary sector and the devaluation of the local currency stimulated export, which in turn stimulated farmers to produce more soybean. The rising international soybean price also increased the value of farming land in the fertile Pampas area, causing many farmers to move onto cheaper ground in the Chaco region.
In addition to these economic changes, the availability of glyphosate resistant crops certainly also had an important effect on the expansion of soybean acreage. After all, from its introduction in 1996, glyphosate resistant GM soybean was a crop that cost less to produce, and was therefore more economically viable. Eduardo Trigo calculated that without glyphosate resistant soybean, there would be 9 million hectares less Argentina soybean acreage.\textsuperscript{9} It is perfectly feasible therefore to conclude that glyphosate resistant soybean stimulated deforestation. However, researchers at the University of Cordoba noticed that in the wetter north east region of the Chaco forest, there was more deforestation than in the drier north-western region, notwithstanding the fact that the availability of glyphosate resistant soybean seed was equal in all parts of Argentina.\textsuperscript{10} In a recent study they checked the correlation between deforestation and changing rainfall and came to the conclusion that the increased rainfall in the Cordoba province played a dominant role in the conversion of forest to farming land. In the more humid regions, forests were replaced by crops, while in the dry regions there was no link found between deforestation and farming activities. In another study area in Cordoba as well as in the province of Salta more intense deforestation was also reported in areas with more rainfall.\textsuperscript{56,126}

The consensus of many deforestation studies is that there are various factors behind the disappearance of tropical forests. These can be climatological and socio-economic or global factors such as technological change and a rising global demand for soybean. Depending on the geographical and historical context, various combinations of these factors are regarded as the cause of deforestation.\textsuperscript{123} Whereas weed control was the limiting factor for the expansion of soybean crops, glyphosate resistant soybean facilitated the use of meadows and certain nature reserves such as forests. The lower production costs of GM soybean also made soybean crops more economically appealing. The introduction of glyphosate resistant soybean in Argentina is therefore jointly responsible for the scale of deforestation. However, every soybean variety – GM or non-GM – resistant to a broad spectrum herbicide would have a similar effect. So it is not fair to see GM soybean as solely responsible for the increase in deforestation in Argentina and in South America in general, as also the increase in rainfall cannot be held solely responsible.

\textbf{Figure 14. Cumulative deforestation between 1972 and 2007 at 6 different locations in the Argentine provinces of Tucuman and Salta.}
\textit{Source: Gasparri and Grau (2009).}\textsuperscript{124}
The paradox of sustainable intensification of farming

The global increase in demand for farming products for food, feed and fuel, puts massive pressure on the environment and on the land available for farming. If harvest yields didn’t increase, then land use would have to increase in proportion with population. Between 1965 and 2004, the world’s population doubled and as if that wasn’t enough, there was an average 10% increase in consumption per person (Table 2).128 Yet farming acreage only increased by 2% and so higher production came principally from a higher yield per hectare. Nobel Prize winner Norman Borlaug, labelled the father of the Green Revolution, claimed that the intensification of farming between 1950 and 2000 prevented hundreds of millions of hectares from being converted into agricultural land.129 Increases in yields can therefore prevent deforestation and the use of protected nature reserves.

The effect of new technologies on land use is very difficult to study. On the one hand, the current situation must be compared to a situation which would have occurred in the absence of the technologies in question. On the other hand, socio-economic aspects also play a role. Higher productivity per hectare makes farming activities more financially attractive. This can in itself stimulate the expansion of farming acreage, whereby paradoxically new technologies can contribute to deforestation. The estimates of Borlaug, who took no account of this complexity, are therefore regarded by many experts as overestimates.

A more realistic model was created by economists Evenson and Rosegrant.130 By their calculation, in the year 2000 farming acreage would have been 3 to 5% bigger if there had been no genetic improvement in agricultural crops since 1965. This amounts to a saving of 9 to 12 million hectares of farming land in developed countries and 15 to 20 million ha in developing countries. This total saving of 24 to 32 million hectares due to technological developments between 1965 and 2000 corresponds roughly with recent data presented by James Stevenson of the FAO (Food and Agriculture Organization) and American colleagues. On the basis of a model that takes account of more parameters, they calculated that in 2004 there would have been between 18 and 27 million hectares of extra farming land in use if crops had the same yields as in 1965.128 Of these, 12 to 18 million hectares would have been saved in developing countries, thereby preventing 2 million hectares of deforestation.

These calculations give an indication that increased yields per hectare can lead to less pressure for deforestation. However, local socio-economic aspects can throw a spanner in the works. Increased productivity is a necessity if land expansion and deforestation are to be avoided, but it is not enough. Better monitoring combined with a well-thought-out strategy for forest expansion by the local authorities remains vital if deforestation is to be discouraged, so that ecologically responsible soybean production will become possible in the future.

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**Table 2. A comparison between population size, food demand and grain yield in 1960 and 2004.**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>1964-1966 (3-YEAR AVERAGE)</th>
<th>2003-2005 (3-YEAR AVERAGE)</th>
<th>% INCREASE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DEMAND SIDE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population (billions)</td>
<td>3.33</td>
<td>6.43</td>
<td>93</td>
</tr>
<tr>
<td>Food per capita (kg per capita per year)</td>
<td>311</td>
<td>344</td>
<td>10.6</td>
</tr>
<tr>
<td><strong>SUPPLY SIDE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area harvested (million ha of cereals)</td>
<td>669</td>
<td>680</td>
<td>1.6</td>
</tr>
<tr>
<td>Cereals yield (mt per ha per year)</td>
<td>1.53</td>
<td>3.25</td>
<td>112</td>
</tr>
</tbody>
</table>

Source: Stevenson et al. 2013.128

128 Stevenson JR et al. (2013). Green revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. Proceedings of the National Academy of Sciences USA
Natural variety - better known as biodiversity - is at the heart of evolution. For every species, both animal and plant, there are different varieties. In animals, the number of different varieties of dog is probably the most well known. But in horses too we have, for example, the Brabant draft horse, the Arabian and Icelandic horses. The same is true of plants. Through natural variation and mainly as a result of targeted breeding there are a great number of varieties for every crop, such as soybean, corn, cotton, potato, … These varieties differ in their outward appearance and in their DNA. They are adapted to specific, local conditions and/or have different purposes. In a country like Argentina, therefore, a great many different varieties of soybean are cultivated.

In the case of the development of a genetically modified plant, genetic information in the form of a DNA sequence is inserted in the plant DNA. This process is called genetic transformation. In one single transformation process, hundreds of plants are genetically modified, whereby every plant has the DNA piece inserted in a different place. One of these plants with an insertion in a specific place is called an ‘event’. The name of an ‘event’ is therefore linked to the feature (e.g. herbicide-resistance), the DNA sequence, and the place in which the DNA is inserted in the plant DNA as well as the variety used during the transformation.

After many analyses and tests in the lab and in the field often only one GM event (and therefore only one variety) is selected per transformation process. A cultivation licence must then be requested for this event. As a consequence, many of us think that the glyphosate resistant soybean in Argentina is only 1 soybean variety. So, one argument used a lot in the GM debate is that GM crops will lead to an attenuation in biodiversity: the number of soybean varieties would after all diminish if everyone switched to GM soybean. Nothing could be further from the truth.

If, on the basis of the analyses, a certain event was selected, this plant would be crossed with countless local varieties to introduce the GM characteristic to these varieties. If we take the example of soybean in Argentina, up until 2011 only one event was approved (Table 3). This 40-3-2 event was cultivated on about 16 million hectares, but in 2006 there were more than 368 different soybean varieties on the market with this specific GM characteristic.131

There are currently five different herbicide resistant genetically modified soybean events approved for commercial cultivation in Argentina (Table 3).131 For a long time, only the glyphosate resistant soybean from Nidera was available. Recently other companies have come on the market with similar products: glyphosate resistance combined with insect resistance but also resistance for other herbicides such as glufosinate and imidazolinone.

### Table 3. Approved GM events for soybean in Argentina

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Event</th>
<th>Company</th>
<th>Cultivation Licence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glyphosate resistance</td>
<td>40-3-2</td>
<td>Nidera</td>
<td>1996</td>
</tr>
<tr>
<td>Glufosinate resistance</td>
<td>A2704-12</td>
<td>Bayer</td>
<td>2011</td>
</tr>
<tr>
<td>Glufosinate resistance</td>
<td>A5547-127</td>
<td>Bayer</td>
<td>2011</td>
</tr>
<tr>
<td>Insect resistance + glyphosate resistance</td>
<td>MON87701xMON89788</td>
<td>Monsanto</td>
<td>2012</td>
</tr>
<tr>
<td>Imidazolinone resistance</td>
<td>CV127</td>
<td>BASF</td>
<td>2013</td>
</tr>
</tbody>
</table>

The economic impact of glyphosate resistant soybean

Argentina is the third biggest economy in South America. Glyphosate resistant soybean plays a significant role in this. Since its introduction in 1996, genetically modified soybean has contributed 65 billion US dollars to the Argentine economy.

A boost for the Argentine economy

In order to estimate the effect of glyphosate resistant soybean on the Argentine economy, INTA developed a dynamic model that can simulate the difference in production between the current situation (GM soybean crops since 1996) and the situation in which no GM soybean is cultivated. The adoption of GM soybean was accompanied by a reduction in production cost of about 20 US dollars per hectare (see page 17). With an estimated area of 18.65 million hectares in the season 2010-2011 this amounted to a saving of 373 million US dollars. If calculated from the introduction of GM soybean in 1996, this comes to a cumulative saving of more than 3.5 billion US dollars.

As mentioned earlier, soybean acreage also increased significantly with the mass adoption of glyphosate resistant soybean. While the cultivation acreage of soybean rose on an annual basis between 1971 and 1996 by an average of 3.5%, this increased in the period 1996-2010 by more than 9% per year. The Argentine non-profit organisation ArgenBio calculated that GM soybean has ensured that an extra 8.6 million hectares are being cultivated. This increase in soybean acreage translated into almost 12 billion US dollars in revenue in the 2010-2011 season. Over a period of 15 years, this led to extra revenues of almost 62 billion US dollars.

According to the model and calculations of ArgenBio, genetically modified soybean has brought economic benefits of more than 65 billion US dollars since its introduction in 1996. Of this income, 72.4% went to farmers, 21.2% to the government and 6.4% to technological development, seed production and herbicide use.

According to estimates, the Argentine economy, which experienced a boost due to the cultivation of genetically modified crops, created more than 1.8 million jobs between 1996 and 2010.
Soybean, the export showcase of Argentina

In 2012, about 80% of Argentine exports were raw materials. The most important export products were soybean (flour, beans, oil, pellets, ...), products from the automobile sector (cars and car parts), oil and gas, corn (grain, flour and oil), gold (raw nuggets and dust), iron and steel (iron ore, plates, tubes and pipes), copper (copper ore unrefined copper), fruits and fish. These nine categories counted for more than 60% of total exports in 2012 (Figure 15).

Plant farming products such as soybean, wheat and corn represented about 40% of Argentine exports in 2012. This amounts to 32 of the 81 billion US dollars. Of this, 18 billion US dollars or 22% comes from soybean and soybean-derivatives such as oil and flour. In comparison to the year 2000, when soybean exports represented 3.9 billion US dollars, this is more than a four-fold increase. Soybean pushed petroleum exports off the number one position and since 2001 has been the greatest share of Argentine exports. In 2011, Argentina exported 42.6 million tons of soybean.

Around the turn of the millennium, there was a remarkable rise in soybean exports (Figure 16). This increase was largely due to the rising demand from China and the sustained export to Europe (see page 35). Of the 18 billion US dollars of soybean export in 2012, China, Japan and India were responsible for 8.5 billion US dollars. Jointly they are the greatest importer of Argentine soybean, followed by the European Union with 3.8 billion US dollars and the Middle East with 1.4 billion US dollars.

Figure 16. During the late 1990s, soybean exports from Argentina increased. Source: FAOSTAT and www.indec.gov.ar

Herbicide resistant soybean outside Argentina

With more than 80 million hectares, GM soybean is by far the most frequently cultivated biotech crop in the world. The adoption of glyphosate resistant soybean is also remarkable: of the 100 million hectares of cultivated soybean in the world, 81% is GM soybean.69

11 countries cultivate biotech soybean

According to Clive James of ISAAA, almost 81 million hectares of herbicide resistant soybean were grown in 2012, spread across 11 countries.69 In comparison to 2011, this constitutes an increase of 5.3 million hectares or 7%. With 20.2 million hectares Argentina is the third biggest producer. The top 3 countries with the biggest GM soybean acreage are followed by the United States (29.5 million ha) and Brazil (23.9 million ha). Other countries are Paraguay (2.9 million ha), Canada (1.6 million ha), Uruguay (1.2 million ha), Bolivia (1.1 million ha), South Africa (450,000 ha), Mexico (7,000 ha), Chili (2,300 ha) and Costa Rica (2,400 ha). In 2011 alone, biotech soybean was responsible for an increase in the income for farmers of 3.9 billion US dollars.69

Of the GM-producing countries, Brazil is predominantly responsible for the continuing rise in global GM crop acreage. Compared to 2011, Brazil increased its GM surface by 6.3 million hectares in 2012 and accounts for 21% of the total 170.3 million hectares of GM crops worldwide. Biotech soybean thereby forms the biggest share with a rise of 15.4% compared to 2011 and an adoption of 88%.

It is remarkable that the majority of countries cultivating glyphosate resistant soybean have a very high adoption level. Alongside Argentina and Uruguay where 100% of all soybean is biotech soybean, the US, Paraguay, Canada, Bolivia and South Africa have an adoption level of 90% or more.69

In 2011, about 206 million ton of soybean was produced, of which 200 million ton was biotech soybean. A study by the Argentine non-profit organisation ArgenBio reveals that without the introduction of herbicide resistant soybean, the international soybean price today would be 14% higher.9

Glyphosate resistant soybean in Europe

Romania is one of the few European countries with favourable farming conditions for the cultivation of soybean.134 The first generation of glyphosate resistant soybean, event 40-3-2, was introduced in 1999 and reached an adoption level of 68% in 2006 (Figure 17). In absolute figures, this boiled down to 137,000 hectares of glyphosate resistant soybean.

Figure 17. After a slow start, biotech soybean acreage grew in 2006 to almost 140,000 hectares and disappeared completely the year after. Source: FAOSTAT and Otiman et al. 2008.134

Up until 1999, Romanian soybean crops suffered greatly from weeds, resulting in low yields and poor harvests. As a result of this suboptimal start-up situation the efficient weed control that accompanies the cultivation of glyphosate resistant crops had unforeseen benefits and biotech soybean became the most financially viable crop in Romania. In 2003, four years after the first commercial cultivation of glyphosate resistant soybean, soybean farmers active in the two most important soybean-producing regions of Romania were asked about their experiences. The farmers were then jointly growing 37% of all Romanian soybean (GM and non-GM). In contrast to other biotech soybean-producing countries who were rather neutral about the GM soybean yields, the Romanian farmers reported an increase in yield from 16 to 50%, which amounts to 0.4 to 1 ton per hectare extra. This increase in yield also persisted in subsequent years. In 2006, the average yield of glyphosate resistant soybean was 1.95 ton per hectare in comparison to 1.47 ton/ha for conventional soybean, which amounts to a difference of 33%. This is mainly the result of the weed problems encountered in conventional soybean cultivation. For the same reasons the Romanian soybean farmers also reported far greater cost savings compared to other countries. For Romanian companies with an acreage of up to 5,000 hectares, there would have been a saving of 32 to 91 euro per hectare in 2003 with an average of 61.5 euro per hectare. This would amount to a reduction of 29% in variable costs. The overall impact of the introduction of glyphosate resistant soybean in Romania was therefore overwhelming for local farmers. Not only did they obtain a 2% higher price due to the higher product quality (pure soybeans without weed residues), but there was also an average increase in yield of 30% and an average cost reduction of 30%. According to the surveys, this amounted in total to an average benefit in the magnitude of 200 euro per hectare. On a national level this amounted to a rise in farmers’ income of 28.6 million US dollars in 2006. However, with Romania’s entry into the European Union in 2007, the country was obliged to stop cultivating biotech soybean. Glyphosate resistant soybean can be imported into the European Union and can be used for animal feed and human food, but its cultivation is not allowed. The effect was immediately visible in the fields and the soybean acreage fell from 200,000 hectare in 2006 to 50,000 hectare in 2008, a decrease of more than 70% (Figure 17). Romania had succeeded in being a net exporter of soybean beans in 2005, and became an importer again in 2007 (Figure 18). The import of soybean flour also rose drastically as a result (Figure 18).

The discontinuation of biotech soybean cultivation had a significant effect on the balance of trade. Import costs for soybean flour increased in 2007 by 53 million US dollars compared to the previous year.
Herbicide resistant crops were never intended to do away with the need for chemical weed management in farming. However, they stimulate a shift in the use of toxic to less toxic herbicides. The biggest advantage of herbicide resistant crops is that they allow the use of no-tillage practices. This no-tillage farming offers many benefits for the environment: greater CO₂ storage in the soil, less fuel consumption, less CO₂ emissions, better soil structure and for erosion-sensitive soils less chance of wind or water erosion. Moreover, herbicide resistant crops enable much greater flexibility in weed control because the time of application is less strict.

The introduction of genetically modified crops should not however mean that good farming practices are thrown overboard. For every form of resistance, an effective resistance management strategy must be adopted to prevent problems in the long term.

Farming is a complex activity and it would be all too simple to see herbicide resistant crops as the only solution to weed management. However, if used in a broader context together with conventional cultivation methods, ecological insights and the latest mechanical techniques for weed control, herbicide resistant crops can be of added value for the environment, for farmers and for crop yields.