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Sustainability of current GM crop cultivation

Effects of the cultivation of GM soybean, maize, and cotton in terms of People, Planet, Profit

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What is genetic modification?

A genetically modified (GM) organism is an organism in which the genetic material has been altered in a way that does not occur naturally by mating and/or natural recombination[1].

Genetic modification is a branch of biotechnology in which changes in the genetic make-up of plants or animals are generated without the use of crosses. This report is about crop varieties to which a trait has been added by inserting a gene encoding this trait into the plant's DNA.

Background of the study

The focus of this study is genetic modification in crop plants. In 2010, GM crops were grown on more than 140 million hectares worldwide, which amounts to more than 70 times the Dutch agricultural acreage. The main crop species with GM cultivations are soybean, maize, cotton and oilseed rape (canola). Worldwide, GM varieties are used on more than three quarters of the soybean acreage, half of the cotton acreage and a quarter of the maize acreage. In the EU, two genetic modification events have been allowed for cultivation, namely one conferring an insect-resistance in maize and one conferring an increased amount of a specific type of starch (amylopectin) in potato. In addition, 32 events in various crop species have been allowed for import and/or processing into food and/or feed products. GM crop cultivation is presently of minor significance in the EU, but GM crop products are imported in large amounts into the EU.

In the Netherlands, genetically modified (GM) crops are not commercially cultivated yet, but the country does import a large amount of GM crop products. The Dutch government aims at utilization of benefits offered by biotechnology in a responsible manner. A relevant question is therefore whether the cultivation of GM crops abroad for import in the Netherlands is in line with Dutch policy and societal aims striving for more sustainable forms of agriculture. To answer this question, we compared the sustainability of GM crops that are presently grown at a commercial scale, with their conventional (non-GM) counterparts. The study provides an overview of scientific knowledge about the extent to which the cultivation and processing chain of GM crops differ from those of non-GM crops with regard to sustainability. The full scientific review is published in a separate report[2]. This version provides a summary of the main results and conclusions.

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[1] Definition according to EU directive 2001/18/EC.

[2] A.C. Franke, M.L.H. Breukers, W. Broer, F. Bunte, O. Dolstra, F.M. d'Engelbronner-Kolff, L.A.P. Lotz, J. van Montfort, J. Nikoloyuk, M.M. Rutten, M.J.M. Smulders, C.C.M. van de Wiel, M. van Zijl (2011) Sustainability of current GM crop cultivation. Review of people, planet, profit effects of agricultural production of GM crops, based on the cases of soybean, maize, and cotton. Report 386, Plant Research International, Wageningen University and Research Centre, April 2011. http://edepot.wur.nl/166665.

The Netherlands' Ministry of Economic Affairs, Agriculture and Innovation initiated and provided funding for this study. The study was carried out by two Wageningen UR institutes, Plant Research International and LEI, and two research and consultancy agencies, CREM BV and Aidenvironment.

In the following sections we first present our methodology and subsequently the main findings and conclusions per crop species. Finally, we discuss a number of general trends that surfaced on the relationship between GM crops and sustainability.

Methodology

This study is focussed on three crop species: soybean, maize and cotton. The products of these crops are important for the Dutch economy. Outside of Europe, GM cultivations are increasing for these crop species.

The sustainability of GM crop production was compared to that of conventional crop production through a number of themes/indicators grouped under the main themes of *People*, *Planet*, *Profit*. In this review, we changed the sequence of these themes into *Planet*, *Profit*, *People*, because current GM crops show the most directly measurable impacts on the environment. Impacts of GM crop cultivations on people are to a large extent based on these environmental effects and on the economic effects. Thus, we discuss *Profit* aspects of sustainability before the *People* aspects. Food and environmental safety were not part of this study, as they are already part of the assessment for legal acceptance of GM crops for cultivation and/or import into the EU. For each main theme, a number of sustainability indicators were identified on the basis of existing schemes and international standards. The indicators are the starting point for the comparison between GM and non-GM crops.

Under *Planet*, the following indicators were assessed:
- Production efficiency (use of land, water, biocides, nutrients and energy)
- Soil conservation
- Water conservation
- Biodiversity
- Climate change

Under *Profit*:

- Farm income
- National income
- Economic welfare distribution
- Financial and other risks

Under *People*:

- Labour conditions
- Land rights, rights of indigenous people and community rights
- Freedom of choice
- Competition with food production
- Contribution to livelihood of producers and local communities

This study is based on data from literature. We used peer-reviewed publications from scientific journals and supplemented these with information from other sources, such as reports from academic institutes, international institutes such as FAO, farmers organizations, biotechnology companies and non-governmental organizations (NGOs).

By using the abbreviation GM (genetically modified), we refer to all variants of GM crops. Many sustainability aspects are related to the type of trait that has been introduced through genetic modification and thus, where necessary, we distinguish herbicide-tolerant (HT), e.g. Roundup Ready (RR) soybean, and insect-resistant, e.g. Bt cotton.

Presently, herbicide tolerance and insect resistance are increasingly combined in new varieties, the so-called stacked varieties. In the future, GM crops with other types of traits, such as improved drought tolerance or a changed fatty acid composition, are expected to be commercialized. These new GM traits have not been addressed in this review, because they are not yet cultivated at a larger commercial scale.

Main findings per crop

Soy

General

Soybean is the most important oil and protein crop worldwide. The global soybean acreage has increased enormously in the last 20 years, partly to the detriment of natural areas. The largest soy producers and most important providers of soy to the EU are Brazil, Argentina and the US. The EU imports about 15 million tonnes of soybean and 24 million tonnes of soy meal annually. By far the greater part of this import is consumed by the feed industry.

A large part of the soybean grown in the Americas is comprised of GM varieties. In 2009, 65%, 99% and 92% of the soybean in Brazil, Argentina and the US, respectively, was GM. Thus of these three countries, only Brazil still has a large acreage of non-GM soybean.

Untill recently, only one type of GM soybean was cultivated: Roundup Ready (RR) soybean, which is tolerant for the herbicide glyphosate (Roundup). Since glyphosate is a non-selective herbicide, the RR soybean grower does not need to use various combinations of more selective herbicides or to execute additional mechanical weed control. In this way, weeds can be controlled more effectively, with more ease and/or at lower costs.

Planet

Our review of the literature showed that herbicide usage drastically changes with the transition to RR soybean. Glyphosate replaces the various herbicides used in non-GM soybean. The total amounts of herbicide used can decrease as well as increase. Glyphosate has a relatively low toxicity and, hence, a lower environmental impact than the herbicides used in non-GM soybean. Therefore, RR soybean offers an opportunity to diminish the environmental impact of herbicide usage in soybean cultivation. Several studies have shown that this indeed has happened after introduction of RR soybean. However, the exclusive use of glyphosate in soybean and in consecutive crops of the rotation resulted in the development of glyphosate-resistant weeds in many soybean cultivation areas. In this

way, glyphosate loses its efficacy in weed control. It appears that in some areas farmers have reacted by increasing the dose of glyphosate used or by using other herbicides. In this manner, the original environmental advantage of glyphosate-tolerant crops was lost in such areas. Development of glyphosate-resistant weeds can be slowed down by diminishing the reliance on glyphosate as the sole option of weed control in the soybean crop rotation, for instance, by alternating with herbicides with a different mode of action. In principle weeds could also be controlled mechanically in soybean. However, this does not appear to be a broadly applicable option in the Americas because of soil erosion risks, costs or labour constraints.

There are only minor differences in water and nutrient use efficiency between GM and non-GM soybean. There are reports that glyphosate use in RR soybean affected nitrogen fixation or micronutrient (manganese) uptake, but this has not led to problems in agronomic practice. Yields (per hectare) of GM and non-GM soybean are similar. The availability of RR soybean facilitated the use of soil conservation tillage systems in the Americas. Conservation tillage systems often suffer from higher weed pressure, which can be relieved by the broad spectrum herbicide glyphosate. Conservation tillage enables soil conservation by diminishing erosion. Soil erosion as a result of agricultural activities has serious consequences for the environment and economies worldwide. Conservation tillage is also helpful in increasing soil organic matter. In combination with decreased energy use as a result of the reduction in tillage operations, this increased carbon sequestration may lead to a lower emission of greenhouse gases. To what extent this is being realised is yet unclear, among others because soil carbon may be released at later stages, depending on soil usage. There were no reported differences in agrobiodiversity between GM and non-GM soybean. The loss of natural areas, e.g. in the Amazon and Cerrado of Brazil, can not be related directly to the GM trait. The strongly expanding soy production in central Brazil, near the Amazon, is based on conventional soy.

Profit

RR soybean has a positive effect on farm income due to savings in herbicide costs and/or labour, which generally outweigh an increase in seed costs. Other benefits for farmers are greater flexibility in crop management and lower production risks. The latter are often important considerations for a farmer. Greater flexibility in combination with conservation tillage enabled farmers to grow a second crop in the same year in some parts of Argentina.

Several model studies indicated that the introduction of GM soybean has led to net welfare gains at the global level. There are shifts in the spatial distribution of soy production. Global production increases at lower prices, from which most, but not all, countries benefit. The welfare distribution across the production chain (seed producers, growers, processing industry and consumers) depends amongst others on the protection of intellectual property (IP). In countries with weak IP protection of RR soybean, e.g. Argentina, farmers benefitted more than in other countries, where the seed industry benefitted more.

Uncertainties regarding (future) approval of GM soybeans create considerable institutional risk for soy producers and downstream industry. An important example is the risk of being held liable for low level presence of GM varieties that have not or not yet been approved in the EU, in shipments destined for the EU. Such risks may lead to a reluctance in adoption of GM varieties in soy-exporting countries and to higher production costs for the processing and livestock industry in importing (EU) countries.

People

The reduced labour input needed for GM soy production could result in fewer on-farm employment opportunities. For a farmer this means lower costs and/or saving time that could be used for other activities. The presence of child and/or forced labour is related to the local comprehensiveness of the national law as well as the efficiency and effectiveness of the legal system. While child and forced labour occur in the soy sectors of some countries, on the basis of available literature no difference between GM and non-GM production could be observed in this regard. Nor could scientific studies be found on the issue whether exposure of local communities to agrochemicals is more common in GM production than in non-GM. There are reports of aerial spraying in the neighbourhood of villages. There is a court judgment on indiscriminate glyphosate spraying in Argentina. The increased exposure as a result of the use of aerial spraying is related to large-scale cultivations and both GM and non-GM soybean are grown in large-scale operations.

The large-scale expansion of soybean cultivation in Latin America during the last few decades is also an important cause of land rights conflicts and violations of the rights of indigenous people. The availability of GM soybean is, however, not a likely primary driver of this expansion. In the same period, expansion to larger scale of agriculture also occurred on the basis of conventional soy varieties, for instance in the state of Mato Grosso in Brazil.

In the main soy-producing countries, farmers are in principle free in their choice between GM and non-GM varieties. This freedom of choice is influenced by, among others, availability of the various types of seeds, intellectual property arrangements for the seeds, market demand, and the presence of a functional segregation system between GM and non-GM production chains. No link between the transition to GM soy production and any change in food security has been observed from the available scientific literature. Adoption of GM soybean most likely had a positive effect on income security for farmers who adopted GM soybean. It did not become clear from the literature how this carried over to local communities. Such carry-over effects will strongly depend on local socio-economic and institutional arrangements.

Maize

General

In maize two types of GM varieties are widely cultivated, namely herbicide-tolerant and insect-resistent variants. With regard to herbicide tolerance (HT), Roundup Ready (RR) maize based on glyphosate tolerance is the most widely used one. With insect resistance, different variants exist that confer resistance to some seriously damaging insects, corn (stem) borers (caterpillars of moth species) and the corn rootworm (larvae of a beetle species). These GM variants contain so-called Bt genes, which originate from the bacterium *Bacillus thuringiensis.* This bacterium produces proteins that are toxic to specific groups of insects. By transferring a gene encoding such a protein into the DNA of maize, the maize acquires resistance against these specific groups of insects, including the corn borer or corn rootworm mentioned.

Planet

The main environmental impacts of RR maize are similar to those of RR soy and are likewise related to a change in weed management and the use of soil conservation techniques. In important maize producing countries such as the US, maize is often rotated with soybean and thus the relationship in impacts is even closer. However, RR crop adoption rate has been slower in maize than in soy, since efficiency advantages were smaller at the start than with RR soybean. In RR maize too, any positive impacts from the accompanying use of the relatively low-toxic glyphosate could be nullified in the longer run by development of herbicide-resistant weeds. A relationship of growing RR maize with the use of soil conservation techniques could less clearly be established than with soy, which was also partly due to fewer studies in the scientific literature.

The main impacts of Bt maize are related to either an increase in yield while other inputs remain essentially the same, or to lower insecticide usage while yield remains the same. With the Bt system against the European Corn Borer (ECB), these changes were generally less dramatic than with cotton (see below for the latter). This is due to the irregular occurrence of the pest insect and the difficulty in the application of insecticides against it, as the caterpillar is hiding within the stems most of the time. Thus, many non-GM farmers do not use insecticides against the corn borer and accept a

chance of yield losses, leading to smaller differences in insecticide use between GM and non-GM cultivation. With other pest insects, such as the corn rootworm, decreases of insecticide use and effects on yields can be larger, depending on local conditions. The wide cultivation of Bt maize has led to advantages for non-GM growers as well, since the overall population sizes of pest insects have gone down over the years. This has diminished pest pressure on non-GM cultivations in the vicinity of Bt maize cultivations too.

The biodiversity of various insect groups is generally higher in Bt maize than in non-GM maize treated with insecticides, since the insecticides usually affect a wide array of insect groups. No consistent effect on soil biodiversity outside a normal range of variation with cultivation conditions and varieties used were reported for Bt maize. In herbicide-tolerant (HT) maize, effects on agrobiodiversity were mainly related to the effectiveness achieved in weed control, since lower levels of weeds naturally lead to lower levels of organisms dependent on them for survival. As in soybean, there may be a difference in greenhouse gas emissions between HT and non-GM maize. Again, the net effect is not completely clear yet.

Profit

Herbicide-tolerant (HT) maize generally has a positive effect on farm income due to cost savings from reduced and more efficient herbicide use. However, the magnitude of this effect depends on the effectivity of herbicide use in conventional maize production and on herbicide prices relative to the extra seed costs. The increased cultivation efficiency of HT maize provides the farmer with extra time, e.g. for generating additional income outside of maize cultivation.

Bt maize also generally has a positive effect on average farm income, by reducing production costs (for corn rootworm resistant GM varieties) or increasing revenue (for both corn rootworm and corn borer resistant GM varieties). The magnitude of these benefits depends on pest pressure and the efficiency of pest control in conventional maize production. In addition, the very fact that pest populations strongly fluctuate makes Bt maize attractive for farmers as it decreases production risks.

Model analysis showed that the introduction of HT maize (together with soy) probably has led to net welfare gains at the global level, which increase as more countries adopt the technology. These welfare gains are experienced by practically all countries, whether or not they produce GM maize themselves. The distribution of welfare across the production chain depends on IP protection arrangements.

GM maize exporters to regions with a more restrictive policy on the introduction of GM varieties face the risk of being held liable for low level presence of GM crops not (yet) admitted. This may lead to higher production costs for processing industries dependent on import of maize, because the higher risks are discounted in the price for export to countries with the more restrictive GM admittance policies.

During and after cultivation, conventional maize may become admixed with GM maize and, as a result, the conventional maize cannot be sold as non-GM anymore. In order to eliminate this risk as far as possible, the EU has drawn up a coexistence framework. In this context, a maize farmer must take measures to diminish GM pollen flow to a neighbouring non-GM maize to a level that the harvest can still be sold as a conventional or organic product. An example of such measures is the implementation of isolation distances between GM and non-GM cultivations. These measures could lead to additional costs for farmers and other parties in the production chain, depending on the way they are implemented in individual Member States.

People

Bt maize cultivation is likely to require less labour input, also on small-scale farms. Whether this has led to reduced labour opportunities of farm workers or movement of workers to other jobs and regions in both developed and developing countries could not be established. There is a positive impact from reduced risks of exposure of farm workers to insecticides harmful to human health. Bt maize mostly has positive impacts on producers' livelihoods. Child labour occurs in maize production in developing countries, particularly on small farms. The few available reports did not show that lower labour requirements of GM maize (HT or Bt) at small-scale farms, e.g. in South Africa, led to a decrease in child labour.

Next to the usual limitations imposed by market demands, freedom of choice for farmers depends on institutional arrangements, which may vary considerably between countries depending on their legal systems. For example, co-existence of GM and non-GM crop cultivation may be enabled by measures aimed at prevention of cross-pollination and other types of admixture, and by consultation of neighbouring farms with the introduction of GM cultivation, including the proper enforcement of such measures when necessary. As mentioned above, there is a *Profit* aspect here as well, since lack of a functioning legal basis for coexistence can lead to economic loss from the admixed products.

Particularly maize is grown by indigenous people in South and Middle America, where it was originally domesticated. Several publications discuss possible inroads from GM maize introduction to the rights of these people with regard to traditional cultivation of local landraces of maize. As a particular example, our study has reviewed the way indigenous people and local communities in Mexico and Colombia were faced with GM maize. In Mexico, GM admixture was found in landraces. This was most likely a consequence of import of GM maize seeds that were approved for consumption but not for cultivation. As no permit was provided for cultivation, no consultation had been deemed necessary prior to the introduction. In Colombia, indigenous local communities were not engaged during the process of approval of GM crop cultivation, despite the existence of national regulations and international treaties that require this. These cases could be regarded as violating indigenous peoples’ rights. They indicate a need for improvement of public consultation and prior information as well as risk management procedures based on the participation of local communities, in order to enable their freedom of choice in regard to the introduction of GM varieties.

Cotton

General

Cotton is worldwide the most important fibre crop. The largest cotton producers are China, India, the US, Pakistan, Brazil and Uzbekistan. In the EU, there is only a minor production in the South. The production chains are often highly complex, as they involve many participants. Particularly China, India and Pakistan are important processors of cotton and exporters of cotton products. Cotton production has various sustainability issues worldwide. Cotton production often involves the use of insecticides such as organophosphates and pyrethroids that are relatively harmful to human health and the environment in comparison to other crop protection agents. Moreover, cotton cultivation and processing require considerable amounts of water. There are also problems with the *People* dimension of cotton cultivation. Cotton and cotton seed production is sometimes associated with child labour and there is exposure of farmers and farm workers to the already mentioned insecticides and chemicals used in cotton processing.

Insect-resistant Bt cotton is a GM crop popular with farmers outside of Europe. Small-scale farmers in countries such as China, India, Pakistan and South Africa, as well as large-scale farmers in e.g., the US, Australia and Brazil, grow Bt cotton. Bt cotton produces a protein that is toxic to caterpillars of certain species of moths. Bt cotton is mainly used to control damage by the cotton bollworm (which is the caterpillar of a moth).

Planet

Various studies indicate that the introduction of Bt cotton resulted in higher yields and/or a lower insecticide use in cotton production worldwide. There could be a bias in the levels of benefits in some of the reports if early Bt cotton adopters already had higher yields with lower insecticide inputs before the arrival of Bt cotton, while the farmers with less resources would not have adopted GM. However, also when these management factor differences are filtered out, Bt cotton cultivation in India shows higher yields per hectare than conventional cotton cultivation and thus an improved land usage. The reduction of insecticide usage in Bt cotton as compared to non-GM cotton can lead to a

higher diversity of non-targeted insects and to a lower impact on soil and surface water. As in Bt maize, no significant impacts of Bt plant residues on soil organisms have been reported. Cases of insects developing resistance to the Bt toxins in the field have been rare so far. Although energy use in Bt cotton cultivation may have been diminished as a consequence of a decrease in insecticide spraying, it is not clear what this means in terms of greenhouse gas emission.

Profit

Bt cotton on average increases farm income, through an increase in revenue and/or a decrease in pesticide costs. The benefits of Bt cotton may vary considerably, due to differences in insect pest pressure and local differences in cultivation conditions, e.g. with regard to water availability. The higher seed costs of Bt cotton may reduce the benefits for farmers and may also increase financial risks for small-scale farmers. Using model analysis, the introduction of GM cotton is projected to have positive welfare effects worldwide, and this effect increases as more countries adopt the technology. Also non-GM-adopting countries generally experience positive welfare effects. Distribution of welfare across the production chain varies among countries and depends on intellectual property (IP) protection arrangements, as described for soybean and maize above. Bt cotton may contribute to poverty reduction and rural development, provided that it is usable and accessible by smallholders. The yield strongly depends on the availability of reliable sowing seeds of locally adapted varieties.

There are reports that liability risks in the absence of biosafety laws have withheld large international seed companies from selling their products in some developing countries. Important motivations for this are the risk of liability in case of problems encountered with GM cultivations and the undermining of IP rights by illegal GM seed sales. On the other hand, in some countries, e.g. in India, GM varieties are successfully marketed due to arrangements between local seed companies and farmers.

People

Bt cotton has led to significant reductions in exposure to harmful pesticides of farmers and farm workers. Next to cost savings and/or yield increases, ‘peace of mind’ about bollworms (cultivation risk reduction) is an important benefit of Bt cotton. Farmers need to worry less about monitoring cotton bollworm populations in their fields.

Child labour occurs in conventional and GM cotton. Insufficient evidence was found to conclude that Bt cotton was positively or negatively related to child labour as compared to non-GM cotton. Many farmers can afford the extra investment necessary for buying Bt-cotton seed. Since the extra investment in buying Bt-cotton seed can only be returned after the harvest, some resource-poor small-scale farmers were not able to afford the Bt-cotton seed in, for example, India. Nevertheless, an Indian study showed that when looking at income, all types of households, including those below the poverty line, benefitted considerably more from Bt than from conventional cotton. This was a result from more employment for hired female workers (resulting from increased harvests) and from higher returns to agricultural family labour that became available for alternative employments as the number of pesticide sprayings was reduced. No evidence was found that wages in cotton production were higher when comparing Bt to non-GM cotton production.

There are NGO reports for Pakistan and South Africa indicating that (the profitability of) Bt cotton crops incidentally may have led to land rights conflicts. One study in South Africa showed that market demand from a cotton processor that also was the financer for the same cotton farmers, posed a limitation to the farmer’s freedom to choose non-GM cotton seed. Whether and to what extent intellectual property rights impacted on the availability of non-GM cotton seed and the freedom to choose non-GM seed could not be established based on the studies available.

On a micro-level in local communities in China and Africa Bt cotton may compete with food production for own consumption. However, model studies indicate that an increased income as a result of growing Bt cotton will also allow farm families to increase their budgets for food purchases and education, and that food security thus is not diminished.

Summarizing conclusions

The sustainability of the presently cultivated GM crops depends on the GM trait and varies with crop species, region, institutional context and time. This is not unique to GM crops, but applies to agricultural systems and innovations in general. Together, all factors mentioned determine whether any cultivation, GM or not, fits in a policy aiming to improve agricultural sustainability. Although universally applicable conclusions on GM crop sustainability cannot be drawn, our study provides a systematic framework of sustainability aspects and their interrelationships that can be used for future case-by-case assessments of second and subsequent generations of GM crops.

The first generation of GM crops was developed for several purposes. Bt varieties were engineered to be resistant against specific pest insects, whereas herbicide-tolerant varieties are meant to offer the farmer a higher flexibility in weed control. Bt crops generally improve sustainability with regard to *Planet* aspects. For both types of GM crops sustainability depends to a large extent on their use together with good agricultural practice (GAP), based on the best of agronomic and agro-ecological knowledge available. When GM crops are not cultivated according to such GAP, for example, when weed control becomes dependent on a single herbicide to the extent that weeds develop resistance against the herbicide, any improvements in sustainability will be lower or may turn into the opposite.

With regard to *Profit* and *People* themes, the contribution of GM crop production to sustainability is also highly dependent on local legal and institutional systems.

Reflection

This study showed that the sustainability of the presently cultivated GM crops varies with crop species, GM trait, region and institutional context, and also depends on other factors, such as time since first introduction and year-to-year variability.

This study focussed on relative differences between GM and non-GM crops and not on absolute levels of sustainability. Our conclusion that there are few differences in sustainability effects between GM and non-GM crops, does not automatically mean that the crop production system in general is sustainable. For instance, loss of natural vegetation and accompanying biodiversity is only indirectly related to GM soy in Brazil. However, the strong expansion of the overall soybean acreage, GM and non-GM, does contribute to this phenomenon.

In addition, the study's design, *i.e.* based on a comparison between GM and non-GM crop cultivations, invoked the following observations:

1. The definition of the conventional, non-GM cultivation to compare the GM crop with, was not straightforward. Non-GM cultivations actually cover a wide range of practices, including forms of high-input intensive agriculture, integrated systems and organic agriculture. Differences between non-GM cultivations can be large, particularly when also local traditional systems are taken into account. Most reports used the common conventional systems in a region as reference. In a number of countries, GM crop adoption has been so extensive that it was barely possible to gather data on non-GM cultivations in the same region. For instance, in the US and Argentina, 92% and 99%, respectively, of soybean growers use GM varieties. Non-GM varieties are hardly grown anymore or only in specific regions. Information on non-GM cultivations thus only can come from the past or from other regions or countries, which may interfere with performing representative comparisons.

2. The study's design puts emphasis on any differences between GM and non-GM crops. Thus, it may insufficiently acknowledge the differences among agricultural practices and regions in general. However, the differences between GM and non-GM cultivations are mostly smaller than those among cultivations (GM and/or non-GM) in different regions. For instance, Bt cotton was reported

to increase yields, relatively to non-GM cotton, by 0 to 83%. However, national average cotton yields of main cotton producing countries in 2007/2008 varied 566%, from 367 kg/ha (Burkino Faso) to 2077 kg/ha (Australia) (USDA, 2009). This illustrates that for yield improvements, one needs to take into account a wide array of factors.

3. There is a wide array of agricultural developments in which the specific role of GM is difficult to disentangle from other drivers. For instance, GM soybean varieties fitted well in large-scale soy production, which expanded in Argentina and Brazil in the last decades. This expansion had quite a number of environmental and social-economic impacts. However, the main economic driver for this expansion was the worldwide increasing demand for soy products. At most, GM soybean has facilitated the expansion, for also large-scale cultivation of non-GM soybean has expanded enormously, e.g. in Brazil.

In the following, we will discuss three subjects that often surface in the debate on GM crops, in the context of the results from this study.

Intellectual property

Intellectual property of conventional plant varieties is usually protected by Plant Breeders' Rights (PBR). For breeding companies this is the return on the investment into development of new varieties. The development of GM crops is particularly costly and this has been one of the drivers of consolidation in the breeding industry. GM traits are often protected by patents, which is a stricter form of protection than PBR. The simultaneous trends of consolidation in the breeding sector and the use of patents may lead to re-distribution of welfare gains in the direction of the patent holders. In a competitive market, welfare gains are more equally distributed and the value of a patent is determined by the benefits of the patented product. GM traits are only successful in the long term if they are clearly beneficial for the farmers, for instance, by improving their flexibility, reducing their production risks, and/or improving yield and quality of the product. Indeed, farmers pay different 'technology fees' for GM seeds, which appears to be related to expected profits under local conditions. For instance, prices for Bt seeds in Spain varied between regions, seemingly in line with local infestation levels of the targeted insect, the European corn borer.

The comparison of Plant Breeders' Rights with patents is a complex issue. Patents on seeds came with restrictions on seed saving by farmers. However, this is not an entirely new development for farmers, as also the choice for hybrid varieties is accompanied by losing the option of seed saving because the original high yields are lost in subsequent generations of seed multiplication. Breeding companies are also seeking patent protection for other innovative breeding methods and non-GM traits. Therefore, we expect that the discussion about patents in relation to plant variety protection will continue, also outside the realm of genetic modification.

Technical lock-in

One risk of adopting new technology is that of a technical lock-in: if everybody absorbs a new technology and uses it under exclusion of other options, existing valuable knowledge on previous technology may be lost. In the Netherlands part of the mechanical weed control expertise was lost upon the introduction of herbicides in the 1960s and 1970s. Likewise, a technical lock-in could be envisaged for weed control in large-scale herbicide-tolerant GM crop production, especially if farmers do not use alternative weed control methods in the crop rotation anymore. This can lead to problems when weeds develop resistance against the herbicide. In this way, the development of weeds resistant to glyphosate has been observed for example in the US, where three glyphosate-tolerant crops may be used in the same rotation or area: soybean, maize and cotton. Therefore, there is a clear incentive for diversification of weed management, by alternating herbicides with different modes of action in the crop rotation or through alternative non-chemical weed control options, or both. Such alternatives must be still available then.

In some regions in India there was a risk of technical lock-in during the introduction of Bt-cotton. The choice for good quality locally adapted Bt seeds was sometimes hampered by a quick succession of seed brands with a poorly verifiable varietal identity. Thus, farmers were not able to test the efficacy of new seed varieties for themselves, while there was also no accompanying reliable information on the performance of the seeds that could compensate for this. Illegal seed markets in India and China sometimes were helpful in making available Bt varieties to local resource-poor farmers, but also contributed to problems in obtaining reliable good quality locally adapted seeds. More recently, this situation has improved by state intervention, among others by the wider availability of locally adapted varieties with Bt traits, including also locally developed events, partly derived from public breeding programs.

At a more fundamental level, it is difficult to assess whether the development of transgenes came with a cost of a decrease in classical breeding improvements or less input into the development of agro-ecological measures, such as intercropping or the use of natural enemies of pest organisms. Some authors have argued that technical lock-in may already occur at the very basis of innovative developments, because GM solutions fit in favourably both with the competitive structure of fundamental research (publication in high-ranking journals) and with industrialized commercial plant breeding. This would not apply to basic and applied science targeting alternative solutions, such as agro-ecological measures. The two approaches are presented as mutually exclusive by some authors. However, recent publications do explore the possibilities of combining approaches, *e.g.* GM varieties and agro-ecological measures, in integrated pest management (IPM) schemes.

Freedom of choice

Freedom of choice has become an important issue in the GM debate. The freedom for the farmer to choose between GM or non-GM production is often presented as a practically unprecedented phenomenon, but this needs a more balanced appraisal.

Firstly, the freedom of choice for the crop or variety to cultivate has never been absolute for a farmer, as it depends on the prospects of marketing the product. As an example, Brazilian farmers in northern Mato Grosso primarily deliver soybeans to the traders that operate from harbours in the Amazon River basin, as transport costs to deliver to traders in the south are very high. The traders at two specific harbours in the Amazon basin only accept non-GM soybean to satisfy the demand for non-GM soy in foreign markets such as the EU and Japan. Thus, the infrastructure limits the choice of the farmers for GM soybean in this region. Elsewhere in Brazil, separate chains are in operation. On the other hand, in Argentina nearly all soybean is in fact GM. For some smallholders in India, freedom of choice may be limited by the higher prize of Bt cotton seed, which may be difficult to finance at the start of the growing season, even when there would be a good return on investment at the harvest. This constraint also applies to seeds of non-GM hybrid varieties, which are more expensive than seeds of open-pollinated varieties that farmers can keep from the previous harvest.

Freedom of choice also depends on the continuation of development of both GM and non-GM varieties and this could for instance be hampered when improved varieties, including those with traits generated by conventional breeding, are only introduced on the market as a GM version. Whether companies will continue to bring improved varieties on the market in both GM and non-GM versions, will for the larger part be a commercial decision. Considerations for breeding companies will be that on the one hand, GM varieties generate higher prices and have better intellectual property protection, but on the other hand, investments in development and market approval, and possible costs of liability are higher. Niche markets may also develop specifically for non-GM varieties, and small breeding companies may focus on such niche markets. Whether well-adapted non-GM varieties remain available may also depend on the activity of local institutes and local breeding companies, as for instance with cotton in India. The public research organization Embrapa in Brazil has a mandate to breed non-GM varieties as well.

A farmer's choice can also be limited by constraints in legislation or regulations. A special example of this arose when Romania entered the EU. Farmers in Romania grew herbicide-tolerant GM soybean, which was exceptionally profitable because of problems with weed infestations in conventional cultivation worsened at the time of the downfall of the communist regime at the end of the 1980s and the beginning of the 1990s. With the membership of the EU, farmers became blocked in their choice of growing GM soybean, as this GM crop has not been allowed for cultivation in the EU.

Freedom of choice is also related to arrangements for enabling coexistence of GM and non-GM cultivations next to each other. Such arrangements entail measures to minimize outcrossing of non-

GM crops with GM crops during cultivation, and admixture further down in the processing chain. Cross-pollination is a universal biological phenomenon, which is most extensive in obligately outcrossing crops. Thus for instance in maize there will always be a certain degree of outcrossing between a non-GM and a GM crop grown in each other's vicinity, although it may be very small. For that reason, the EU has developed coexistence frameworks based on thresholds, which led to the isolation distances to keep admixture from outcrossing in the final product below 0.9% GM. This 0.9% is the threshold above which labelling as GM is obligatory at present in the EU. In turn, such measures could hamper the choice for GM crops because of the additional costs of ensuring coexistence.