Assessing the socio-economic and environmental impact of GMO corn varieties and consequential changes in farm management practices

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ABSTRACT

Both herbicide-tolerant and insect-resistant GMO varieties as well as combinations thereof are now widely used in corn production in the US. The introduction of these traits has led to changes in farm management practices most notably adapted pesticide usage and adoption of no-till cultivation practice. This study assesses the social, economic and environmental impact of GMO corn cultivation in Nebraska using an LCA-based approach. The Nebraska Crop Budgets published by the University of Nebraska, Lincoln, are used as main input data. Whereas the social impact remains similar in the sum of all aspects considered, the economic and environmental impact assessment showed clear advantages of the use of GMO traits in all economic and most ecological aspects considered. Overall, the study shows that production and use of fertilizer as well as the yield achieved are the main drivers for sustainable corn production. The environmental impact of pesticide production and its adapted use through the introduction of GMO varieties is comparably limited although the economic benefits of reduced pesticide use associated with GMO corn varieties are significant.

Keywords: GMO, corn, farm management, no-till, pesticide use

1. Introduction

Corn is the dominant crop in the US grown on 95,6 mio acres in 2013 (USDA National Agricultural Statistics Service; http://www.nass.usda.gov). Corn is used mainly as a source of starch and protein rich feed, for the production of bio-ethanol and processed as high-fructose corn syrup in food production. Corn productivity has increased substantially from 72 to 153 bushels per acre in the time between 1970 and 2010 (USDA National Agricultural Statistics Service; http://www.nass.usda.gov). Since their introduction in 1996, GMO traits have been rapidly adopted by farmers in the US with roughly 90% of all corn being GMO corn in 2013.

GMO traits that are being used by farmers on a regular basis now include herbicide-tolerance for efficient weed management and insect-resistance to control major Lepidopteran pests such as the corn borer (e.g. Ostrinia nubilalis) or corn rootworm (e.g. Diabrotica sp.). In particular, herbicide-tolerant crops expressing a mutant version of the 5-enolphyruvylshikimate-3-phosphate synthase gene conferring tolerance to the application of the broadband herbicide glyphosate also known under its brand name RoundUp (RR) is widely used. Alternative herbicide-tolerance traits to be used in combination with glufosinate, dicamba or 2,4-D are available to farmers. For insect-resistance, corn expressing different versions of *Bacillus thuringiensis* toxins (Bt) in different parts of the plant or constitutively are generally used by farmers to control pests. Furthermore, a variety of stacks of different Bt traits as well as in combination with herbicide-tolerance traits such as Agrisure or SmartStax in which 8 different transgenes in one corn variety is combined are the latest in development of GMO corn varieties.

For farmers the economic benefits of GMOs in terms of better weed and pest management and resulting higher yields and profits are evident (Brookes and Barfoot 2009). An important factor for the rapid and vast adoption of GMOs in corn production also seems to be a better management of yield risks associated with for example pest infestation (Shi et al., 2013). In terms of environmental benefits, herbicide-tolerant GMO corn in the US alone is associated with a 10,9% reduction in use of pesticides or 180,2 million kg of active ingredient and insect-resistant GMO corn in the US with a 41,9% reduction or 40,7 million kg of active ingredient cumulatively in the period between 1996 and 2011 (Brookes and Barfoot 2013). The same analysis furthermore calculates that herbicide-tolerant crops in the US have saved 77 million liters of fuel due to the adoption of no-till practices and consequential changes in field operations in the year 2011 alone.

The benefits of GMO corn reported above are impressive though they represent singular benefits at farm level. For a comprehensive analysis if GMO varieties contribute to sustainable development in corn production, the social, economic and ecological impacts need to be assessed and impacts both at farm as well as within the value chain need to be considered

In this study we have applied an LCA-based methodology to assess the social, economic and environmental impacts associated with the cultivation of 4 different corn varieties in Nebraska. Whereas one corn varieties was a conventional variety produced by "classical" breeding methods, the three other varieties had either only a GMO herbicide-tolerance trait, a combination of herbicide-tolerance and insect-resistance or incorporated the current maximum of traits as in SmartStax.

Lifecycle assessment (LCA) has been used before to assess environmental and economic impact of corn production, but mostly in relation to its use as feedstock for bio-ethanol production from corn grain or stover (see for example Pieragostini et al. 2014; Whitman et al. 2011). LCA has not been applied so far to specifically assess the impact of GMO traits in corn production.

Incorporation of herbicide-tolerance and insect-resistance GMO traits into corn varieties directly translate into changes in farm management practices such as new crop protection regimes. These GMO traits also greatly favour adoption of new soil management practices such as no-till cultivation. These changes in farm management are specifically accounted for. In scenario analysis, the robustness of the model and options for further improving the sustainability of corn production are evaluated.

2. Methods

2.1. Goal and scope

The aim of this study is to assess the impact of the introduction of GMO traits on corn production in the state of Nebraska, USA. Since 1996, GMO traits conferring tolerance to the application of broad-band herbicides, mainly glyphosate or RoundUp (RR), or traits to control major Lepidopteran pests such as the corn borer (e.g. Ostrinia nubilalis) or corn rootworm (e.g. Diabrotica sp.) by expressing insecticidal proteins from Bacillus thuringiensis (Bt) in corn. In the study the production of non-GM corn is compared to GM corn with only herbicide-tolerance based on glyphosate (RR), a commonly used combination of herbicide-tolerance and insect-resistance (RR&Bt) as well as a SmartStax corn in which multiple modes of both herbicide-tolerance and insect-resistance are stacked (SmartStax). The functional unit was defined as "the production of 1 ton of corn at field gate in the state of Nebraska using either of the 4 described corn alternatives".

2.2. Input data and assumptions

Main input data are taken from the 2011 Nebraska Crop Budgets (Wright et al 2011). The Nebraska Crop Budgets are annually updated projections for crop cultivation produced by the Extension Division of the Institute of Agriculture and Natural Resources at the University of Nebraska - Lincoln in cooperation with the Counties and the United States Department of Agriculture. Budget 8 describes the cultivation projections for non-GM corn, budget 9 for the RR&Bt alternative and budget 10 describes the main input data for SmartStax. The input data for the RR alternative were interpolated from the non-GM alternative in relation to the use of insecticides and from the RR&Bt alternative in relation to herbicide treatments and the field operations of no-till cultivation practice (see Table 1).

Table 1. Amount of herbicide and insecticide active ingredient (a.i) applied for non-GM and 3 GMO corn varieties (kg a.i/ha).

	Active ingredient	**non-GM**	**RR**	**RR&Bt**	**SmartStax**
Herbicides	Atrazine	1,82	1,85	1,85	1,85
	S-Metolachlor	1,43	1,5	1,5	1,5
	Prosulfuron	0,0075	0	0	0
	Primisulfuron-methyl	0,0025	0	0	0
	Glyphosate	0	2,37	2,37	2,37
Insecticides	Fibronil	0,29	0,29	0,058	0,015
	Chlorpyrifos	0,084	0,084	0,017	0,0042
	Bifenthrin	0,018	0,018	0,009	0,009
	zeta-Cypermethrin	0,0028	0,0028	0,0028	0,0028

Yield for the RR alternative was modelled from the RR&Bt alternative based on a yield comparison of two transgenic herbicide-tolerant and insect-resistant varieties with their isogenic non-Bt counterparts (Haegele and Below 2013) showing that the Bt trait conferred an on average 11,8% yield benefit. As stated in the Crop Budgets, the alternatives are assumed to be in a continuous corn system (i.e. no crop rotation) and rainfed (i.e. no irrigation). In consultation with an expert panel from the University of Nebraska – Lincoln and in line with the recommendation in the Crop Budgets, the study assumed equal nitrogen use efficiency for all 4 corn production alternatives. Soil erosion is at 2,24 to/ha/year for the alternative using conventional tillage and 0,62 to/ha/year for the alternatives applying no-till practices (W. Vanek, USDA-NRCS Nebraska, pers. comm.).

2.3. Impact assessment

The environmental assessment is based on established life-cycle impact assessment (LCIA) categories as used also in Eco-Efficiency Analysis (Saling et al. 2002) and a wide range of other LCA approaches. Primary energy consumption, resource depletion, emission to air, emission to water and solid waste are assessed. The ecotoxicity potential of all chemicals intentionally released into the environment, e.g., fertilizers and pesticides is accounted for (Saling et al. 2005). Land use is assessed using to the scheme of the ecosystem damage potential (EDP; Köllner and Scholz 2007, Köllner and Scholz 2008). Consumptive water use is assessed as described by Pfister et al (Pfister et al. 2009).

Additionally, environmental indicators addressing the specific impacts of agricultural activity on biodiversity in agricultural areas, and on soil health and conservation, have been incorporated into the methodology (see Schoeneboom et al, 2011 and references therein). More specifically, biodiversity is assessed using the “driving force – state – response” model which is proposed by OECD to structure the complex relationships between agriculture and biodiversity (OECD 2003). The indicator set for biodiversity compiles factors which negatively affect biodiversity resulting in a decline of the state of biodiversity such as low crop rotation or high farming intensity. It also takes into account the effect of the applied pesticides by integrating ecotoxicological characterization factors from USEtox (Rosenbaum et al. 2008). The “state” indicator quantifies the status quo of biodiversity using a proxy such as the widely accepted bird indicator (Bird indicator 2013). “Response” indicators reflect activities which are able to promote or conserve biodiversity such as high crop rotation or the adoption of field margins or flower strips (for details see Saling et al. 2014).

The impact category of soil health is comprised of indicators assessing soil organic matter balance, soil erosion, soil compaction and the nutrient balances of the main nutrients N, P, K. More specifically, the depletion and build-up of soil organic matter is assessed as a balance derived from estimations by the IPCC LULUCF for cropland (IPCC LULUCF), or alternatively on the standard German cross-compliance ‘humus balance’ model (VDLUFA 2004). An assessment function, developed by Hülsbergen in 2003 (quoted in Ehrmann & Kleinhanss, 2008 and Christen 2009) is then used to evaluate the balance results. Nutrient balance is assassed as a function of the amount of fertilizer applied and the amount of nutrients retrieved through harvest. This balance is furthermore corrected for the ability of the soil to mineralize and thereby provide nutrients as indicated by soil nutrient supply classes. The nitrogen balance also considers different sources e.g. nitrogen fixation by leguminoses. The result of the nutrient balances is subsequently evaluated, using nutrients specific models with optimal scores around an equal nutrient balance of zero and decreasing scores for either nutrient deprivation or over-fertilisation. (Christen 2009). The potential for soil erosion is calculated default using the Universal Soil Loss Equation (USLE). This equation predicts the long term average annual rate of erosion on a field, based on slope, rainfall pattern, soil type, topography, crop system, and management practices (Hudson 1993).

In terms of economic assessment, both production costs as well as economic performance are taken into account. Production costs are grouped into variable and fixed costs and quantified using an overall total cost of ownership for the defined functional unit (Kicherer et al. 2007). Economic performance is assessed using indicators for farm profitability as the central criterion for economic sustainability, subsidies which may excert distorting economic effects and productivity as measured as the production value of agricultural goods per hectare weighted by the contribution of the agricultural sector to the national GDP.

The social assessment in AgBalance is derived from the SEEBALANCE method for social LCA, which was developed in 2005 by Universities of Karlsruhe and Jena, the Öko-Institut (Institute for Applied Ecology) Freiburg e.V., and BASF (Schmidt et al. 2005, Kölsch et al. 2008). Based on the UNEP-SETAC guidelines for social LCA of products 5 stakeholder categories were defined: Farmer, consumer, local community, internal community and future generations. The SEEBALANCE indicators and data sources are employed to assess the social impacts of industrial up- and downstream processes. For the agricultural activities in the life cycle, a set of adapted social impact indicators was integrated into the AgBalance method which were designed to match closely the same social sustainability topics addressed in the assessment of the upstream and downstream processes.

3. Results

3.1. Environmental impact assessment

The number of field operations as described in the Nebraska Crop Budgets are 14 in case of non-GM corn and 8 for the GM alternatives. The adoption of no-till practices makes the field operations of chiseling and chopping stalks obsolete and changed type of fertilizer used and its mode of application. These changes in field management reduced labor and machinery costs, but also significantly reduced fuel use for field operations from 62,78 l/ha for the non-GM alternative to 33,62 l/ha for SmartStax. Expressed in relation to the customer benefit of 1 ton of corn, fuel use for field operations is reduced by 60,4%.

The significantly reduced fuel consumption per functional unit is also reflected in better scores in the impact categories energy consumption and resource consumption. Both categories however are dominated by the energy and resource requirement for fertilizer production (see Figure 1 for energy consumption). In fact the production and use of fertilizer constitutes roughly 3 quarters or more of the impact in these categories.

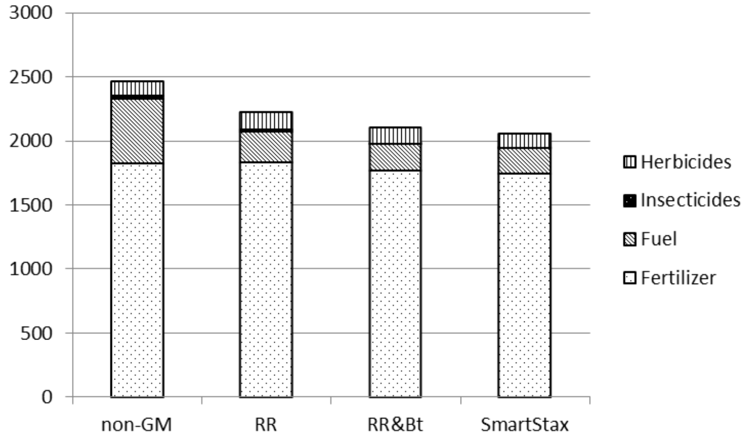

Figure 1: Total energy consumption derived from the production and use of the major inputs (in MJ/customer benefit of 1 ton of corn)

The footprint of all 8 environmental impact categories considered (Figure 2) shows furthermore the positive effect of higher productivity on land use - which is for over 95 % determined by land used for agriculture - and reduced by 26 % from non-GM to SmartStax due to higher yields.

The impact on the local biodiversity potential is determined among others by the ecotoxicology of the crop protection products used: whereas the herbicide tolerance trait requires higher use of herbicides, although with a more favorable eco-toxicological profile, the insect-tolerance in the alternative RR&Bt as well as SmartStax leads to a reduced intensity of use of insecticides with a potential positive impact on beneficial insects and thus a more favourable score for the local biodiversity potential. The other indicators in this impact category are equal (e.g. crop rotation, protected areas, agri-environmental schemes) or more or less similar (nitrogen surplus).

In the impact category soil the benefits of no-till on soil erosion are taken into account whereas the figures for soil compaction, soil organic matter balance as well as the nutrient balances are more or less equal for the alternatives considered. Soil erosion is decreased by 1,61 ton/ha/year or 72 % by the adoption of no-till cultivation practice. The impact of consumptive water use seems greatest of all environmental categories, but since the study assessed rainfed corn, differences in water use are related to the application of fertilizer and pesticides only. As a consequence the result of this impact category looks very favorable for the alternatives with insect-resistance, but in absolute terms the savings in water are of limited impact.

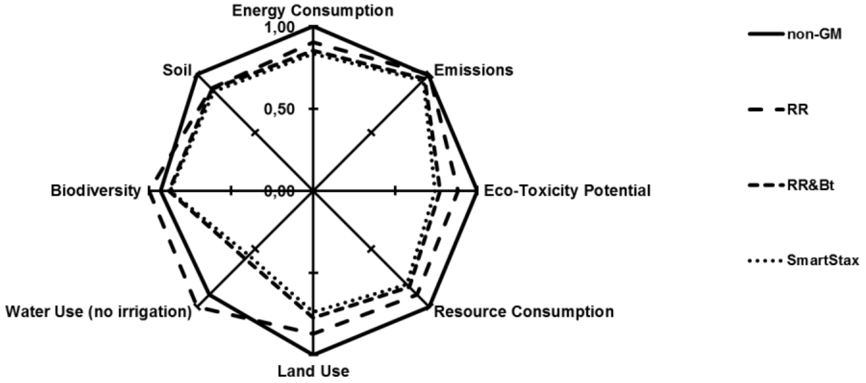

Figure 2. Representation of relative environmental impact category results for the different alternatives in fingerprint diagram. Relative improvement in each impact category is represented by smaller values on the respective axes; hence the smaller the fingerprint, the better the relative performance of the corresponding alternative.

For the impact assessment of emissions, both emissions to air and water as well as solid waste are considered. The final score is more or less unchanged in the sum of all aspects considered since this impact category is highly determined by emissions related to the production and use of nitrogen fertilizer. For example, greenhouse gas emissions are dominated by 89% in the case of the alternative non-GM to up to 95% in case of SmartStax by production of fertilizer and field emissions from nitrification processes in soils (data not shown). Since equal nitrogen use efficiency is assumed for the 4 alternatives the impact in this category are similar.

3.2. Socio-economic impact assessment

The economic assessment shows clear results both in terms of reduced fixed and variable associated with GMO corn alternatives as well as higher margins and farm profits (Table 2). Fixed costs related to machinery, buildings and equipment is reduced by up to 37% and variable costs by 22% between non-GM and SmartStax when expressed per functional unit. Profits per hectare have more than tripled.

Table 2. Overview of costs, revenue and profit.

	Unit	non-GM	RR	RR&Bt	SmartStax
Fixed cost	USD/1 t corn production	93,81	69,15	60,99	58,65
Variable cost	USD/1 t corn production	100,53	94,04	75,39	78,49
Total cost	USD/1 t corn production	194,34	163,19	136,38	137,14
Total cost	USD/ha	1036,80	993,82	941,69	989,98
Revenue	USD/ha	1280,40	1461,60	1657,20	1732,45
Profit	USD/ha	243,60	467,78	715,51	742,47

A main point of criticism for GMO corn is often the high price for seed. The results in Table 3 show that first of all, cost of seed are not the main variable cost, but rather fertilizer (see Table 3). And secondly, the higher cost for seed is more than compensated for by reduced cost for pesticides especially insecticides. For example, for SmartStax almost $ 9,97 extra seed costs per functional unit have to be paid, but this investment in return leads to reduced pesticide cost of $ 30,49 per functional unit. In other words, for every dollar spend on seeds, the farmer receives 3 dollars in return.

Table 3. Costs for main inputs ($/functional unit).

	non-GM	**RR**	**RR&Bt**	**SmartStax**
Seed	13,91	15,74	16,90	23,88
Fertilizer	25,83	28,23	27,59	27,31
Herbicides	13,68	11,58	10,21	9,77
Insecticides	25,22	22,10	4,24	1,36
Total	78,64	77,66	58,94	62,31

The assessment of the social impacts shows a more or less equal result for all alternatives in the sum of all impacts considered. For example, positive effects of higher productivity on the statistical occurrence of working accidents or occupational diseases are balanced by reduced employment opportunities and reduced contributions to social security funds as expressed per functional unit (data not shown). All other social impact indicators remain unchanged since the study investigates different alternatives for same crop in same region and same year.

3.3. Scenario analysis

In total 4 different scenarios are calculated to investigate the robustness of the model in relation to major assumptions made in the study as well as major trends in corn cultivation. First of all, the study calculates with a lower yield potential for non-GM corn as based on the input data from the Nebraska Crop Budgets. Whereas the yield advantage of insect-resistant corn varieties seems well established, a clear effect on yield by the herbicide-tolerance trait is more difficult to establish and seems to depend more on the context of cultivation (Shi et al. 2013). Scenario 1 therefor calculates with a yield level for non-GM similar to RR corn. As a result, the environmental impact of non-GM corn is now similar in the environmental impact categories emissions, eco-toxicity potential and land-use. Benefits for RR remain in relation to resource and energy consumption (related to reduced diesel use) and soil erosion whereas biodiversity and water consumption is unaltered (Figure 3). In the sum of all environmental and socio-economic impacts considered, there is no significant difference between non-GM and RR in this scenario whereas the performance of alternatives RR&Bt and SmartStax remains significantly better.

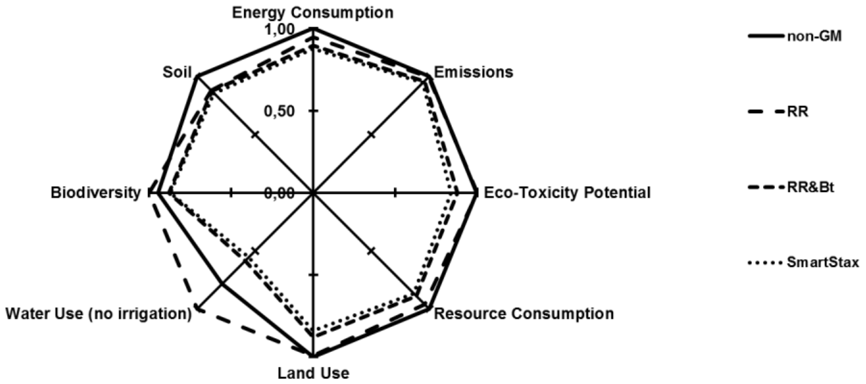

Figure 3. Representation of relative environmental impact category results for the different alternatives in scenario 1 in fingerprint diagram. Relative improvement in each impact category is represented by smaller values on the respective axes; hence the smaller the fingerprint, the better the relative performance of the corresponding alternative.

Evolution of resistance in weeds and pests to the herbicide and insecticides applied can reduce the efficacy of crop protection strategy. This is by no means restricted to the use of GMOs but is known in all areas where crop protection products are used intensively (Powles et al, 1997). Glyphosate-tolerant weeds have increasingly been reported in the US since the 2004/2005 growing seasons (Heap 2014). In recent years Bt–resistant pests (Tabashnik et al. 2013) have been reported that threaten the efficacy of Bt crops. In scenario 2 and 3, a 50% increase in the use of herbicides or insecticides, respectively, are assumed to model the potential impact of the consequential higher rates of pesticide use. The results of these scenarios show that the environmental impact of higher rates of pesticides is very limited since most environmental impact factors are dominated by fertilizer production and use as well as productivity (data not shown).

Finally, scenario 4 assessed the impact of changing from continuous corn cultivation to a system where corn follows soybean cultivation. High demand for corn as feed and for biofuel production has shifted crop rotation patterns from corn-soy rotations to continuous corn over the last decade (Plourde et al. 2013). A yield penalty has been associated with long-term continuous corn cultivation and nitrogen availability identified as a major factor (Gentry et al. 2013). The Nebraska Crop Budgets 2011 specifically include a budget for this scenario (budget 11) which assumes a 33% reduction in use of inorganic nitrogen fertilizer due to the availability of nitrogen fixed by the soybean nodule mycorhizza and an increased yield potential from 110 bu/acre to 115 bu/acre. The Crop Budgets assume no change in pesticides applied for this scenario. These assumptions were modelled on alternative RR&Bt in scenario 4. As a result, the impact of fertilizer production was greatly reduced in the categories greenhouse gas emissions, energy and resource consumption (Figure 4). Also local biodiversity potential improved through better crop rotation. The overall environmental score has improved significantly whereas the socio-economic score is highly dependent on the revenue prices for corn in relation to soybean (data not shown).

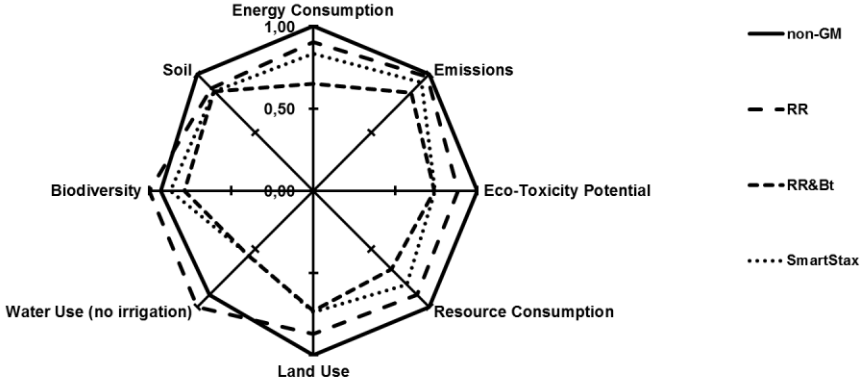

Figure 4. Representation of relative environmental impact category results for the different alternatives in scenario 4 in fingerprint diagram. Relative improvement in each impact category is represented by smaller values on the respective axes; hence the smaller the fingerprint, the better the relative performance of the corresponding alternative.

4. Discussion

Since their introduction in 1996, GMO traits have become standard technology incorporated into the major row crops in the Americas as well as cotton production globally. This rapid adoption makes clear that there are agronomic and economic benefits for the farmer from use of GMOs. This stands in contrast to the public perception that exists around GMOs. The GMO traits that are available today do not offer a direct customer benefit and this may have hampered acceptance of the technology. It is therefore even more important to assesses the potential impacts of GMO traits in a holistic and comprehensive way and use the results to inform the public and as guidance for further development. We used an LCA-based methodology assessing environmental, economic as well as social impacts of GMO traits in this study.

We could show that there are significant advantages associated with the use of GMO insect-resistance traits. It is accepted that Bt traits are responsible for higher and more stable yield levels (Shi et al., 2013). This yield advantage alone is responsible for a largely more positive ecological footprint. Reduction in use of insecticides furthermore has positive effects on biodiversity since less non-selective products are sprayed that harm both pest and beneficial insects. Insecticides are also a major variable cost and the investment in insect-resistant traits certainly pays-off for the farmer and it is easy to understand these GMO have become popular where Lepidopteran pests are common. The rising occurrence of insects resistant to Bt is now threatening the benefits of this trait. We could show in a scenario analysis that a 50% increased use of insecticides does not translate into a higher overall environmental burden. However, when Bt resistant insects can no longer be controlled effectively by increasing amounts of pesticides and negative effects on yield levels are occurring, this would directly negatively affect the environmental footprint as well as the economic performance of these traits. Appropriate resistance management programs need to be adopted by farmers to avoid any further development of resistant pest.

The impact of the herbicide-tolerance GMO trait is more ambivalent. A positive yield effect of herbicide-tolerant crops is more difficult to establish and seems to depend on type of herbicide-tolerance as well as geographical context (Shi et al., 2013). The scenario analysis assuming similar yield between non-GM and RR shows that without a yield benefit, the sustainability impacts of both systems are very much comparable. In contrast to earlier reports (see for example Brookes and Barfoot 2013), this study suggests herbicide-tolerant GMO corn is associated with higher levels of herbicide application. It is important to note however that the (eco-)toxicological profile of glyphosate, the herbicide that is most commonly used in combination with a herbicide-tolerant GMO corn, is more favorable than most other herbicides. As a result, even in a scenario where 50% higher application of glyphosate is assumed, the overall impact of herbicides on the environmental footprint of corn cultivation is low. Again, and analogous to Bt resistant pests discussed above, when herbicide-tolerant weeds can no longer been controlled effectively and negative impacts on yields are occurring, this most certainly will negatively impact the sustainability of this GMO trait.

Although no-till systems are adopted in regions and crops where GMO traits are not prevailing, it is generally acknowledged that herbicide-tolerant crop varieties have favored the adoption of no-till in soybean and corn in South and North America (Brookes and Barfoot, 2013). The advantages in soil conservation – i.e. preventing soil erosion and to a lesser extend enabling build-up of organic matter – are well described and are an important factor for long-term farming sustainability. Also in this study, soil erosion is reduced by 1,61 ton/ha/year or 72 % by the adoption of no-till cultivation practices. No-till is also the main driver for the reduction by over 60% in fuel use for field operations. This study has not accounted for a beneficial effect on greenhouse gas emissions through carbon sequestration in soil and this remains an upside potential for no-tillage cultivation systems that remains to be explored.

Whereas the impact from the production and use of pesticides was shown to be limited, this study clearly demonstrated that the highest ecological impact in corn cultivation is associated with the production and use of inorganic fertilizer. The production of the fertilizer requires large quantities of natural gas and accounts for roughly 75 % of all energy and resources consumed. Concurrently, emissions from production facilities together with emissions from its use in the field due to nitrification processes in the soil accounts for up to 95% of greenhouse gas emissions related to corn production. From these figures it becomes clear that any strategy to reduce inorganic fertilizer input for example by genetically increasing the nitrogen use efficiency of the crop (Xu et al 2012) or reducing the nitrification processes in soil (Liu et al 2013) will benefit the sustainability of corn production substantially.

The high impact of fertilizer production is also illustrated in a scenario looking at potential impacts of a corn-soybean rotation instead of continuous corn cultivation. A 33% reduction in inorganic nitrogenous fertilizer directly translates into significant reductions in air emission as well as energy and resource consumption. In addition, this crop rotation has a favourable impact on biodiversity and could be integrated into resistant management practices needed to maintain efficacy insect-resistance traits. These environmental benefits of a soy-corn rotation should be investigated further in a comprehensive and consequential assessment of both elements in crop rotation together with a proper economic assessment.

Next to fertilizer, the yield level of the different alternatives is of course a major factor in any assessment which uses a productivity factor as functional unit such as “a ton of corn produced” in this study. The yield level is a product of the genetic potential of the crop, the environment it is grown in and the cultivation practice used and these factors are highly interdependent. As such the yield levels of the alternatives in this study are a product of continued breeding efforts, incorporation of traits through biotechnology and changes in management practices. From reports of side-by-side comparison of GMO varieties with their non-GM isogenic counterparts a positive effect on yield is demonstrated for the insect-resistant trait (Haegele and Below 2013). Likewise other genetic approaches to increase the intrinsic yield potential (Condon et al 2002) or enhance resilience of crops against pest, diseases or stresses have great potential to benefit the sustainability of corn production.

5. Conclusion

The study shows that GMO traits contribute to more sustainable corn production in Nebraska. The positive impact of the Bt insect-resistance trait is associated mainly with higher yield levels or less yield risk, reduced cost and to a lesser extent reduced environmental burden from insecticide use. Glyphosate herbicide-tolerance can have a positive impact too if the trait contributes to higher yields - or at least not less yield - and leads to a higher adoption of no-till cultivation practice which in turn is favorable for soil erosion and leads to reduction in field operations and associated fuel use.

Overall the study shows that the environmental impact of the production and use of pesticides is low and that highest burden is from the production and use of inorganic fertilizer. Yield is another main driver for the sustainability of corn production. Likewise, crop varieties, farming practices or technologies that reduce the need for inorganic fertilizer, increase the yield potential or its resilience against pest, diseases and stresses should be the main targets for sustainable development in corn production..

6. References

Bird indicators | BTO - British Trust for Ornithology www.bto.org › science › monitoring (2013).

Brookes G, Barfoot P (2009) Global Impact of Biotech Crops: Income and Production Effects 1996-2007. AgBioForum, 12(2):84-208

Brookes G, Barfoot P (2013) Key environmental impacts of global genetically modified (GM) crop use 1996–2011. GM Crops Food Biotech Agric Food Chain 4(2):109-119

Christen O, Hövelmann L, Hülsbergen KJ, Packeiser M, Rimpau J, Wagner B (2009) Nachhaltige landwirtschaftliche Produktion in der Wertschöpfungskette Lebensmittel, Schmidt Verlag, Berlin.

Condon AG, Richards RA, Rebetzke GJ, Farquhar GD (2002) Improving intrinsic water-use efficiency and crop yield. Crop Sci.42(1):122-131

Ehrmann M, Kleinhanss W (2008) Review of concepts for the evaluation of sustainable agriculture in Germany and comparison of measurement schemes for farm sustainability. Arbeitsberichte aus der vTI Arbeitsökonomie, von-Thünen Institut, Braunschweig (Germany).

Gentry LF, Ruffo ML, Below FE (2013) Identifying Factors Controlling the Continuous Corn Yield Penalty. Agron. J. 105: 295–303

Haegele JW, Below FE (2013) Transgenic corn rootworm protection increases grain yield and nitrogen use of maize. Crop Sci 53:585-594

Heap, I. The International Survey of Herbicide Resistant Weeds. Online. Internet. Wednesday, August 20, 2014 . Available www.weedscience.com

Hudson, N (1993). Field Measurement of Soil Erosion and Runoff, Issue 68. Food and Agriculture Organization of the United Nations. pp. 121–126. ISBN 9789251034064.

IPCC LULUCF (2003) Penman J, Gytarsky M, Hiraishi T, Krug T, Kruger D, Pipatti R, Buendia L, Miwa K, Ngara T, Tanabe K, Wagner F (Eds.) Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF), Institute for Global Environmental Strategies (IGES), ISBN 4-88788-003-0.

Kicherer A, Schaltegger S, Tschochohei H, Ferreira Pozo B (2007) Combining Life Cycle Assessment and Life Cycle Costs via Normalization. Int J Life Cycle Assess 12:537-534

Koellner T, Scholz R (2007) Assessment of Land Use Impacts on the Natural Environment, Part 1: An Analytical Framework for Pure Land Occupation and Land Use Change. Int J Life Cycle Assess 12:16-23

Koellner T, Scholz R (2008) Assessment of Land Use Impacts on the Natural Environment, Part 2: Generic Characterization Factors for Local Species Diversity in Central Europe. Int J Life Cycle Assess 13:32-48

Kölsch D, Saling P, Kicherer A, Grosse-Sommer A, Schmidt I (2008) How to measure social impacts? A socio-eco-efficiency analysis by the SEEBALANCE® method. Int J Sustain Dev 11:1–23.

Liu C, Wang K, Zheng X (2013) Effects of nitrification inhibitors (DCD and DMPP) on nitrous oxide emission, crop yield and nitrogen uptake in a wheat–maize cropping system. Biogeosciences, 10: 2427–2437

OECD, Agriculture and Biodiversity: Developing indicators for policy analysis, OECD 2003.

Pfister, S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43: 4098–4104

Pieragostini C, Aguirre P, Mussati MC (2014) Lifecycle assessment of corn-based ethanol production in Argentina. Sci Total Env 472: 212-225

Plourde JD, Pijanowski BC Pekin BK (2013) Evidence for increased monoculture cropping in the Central United States. Agriculture, Ecosystems & Environment 165: 50–59

Powles SB, Preston, C, Bryan, IB, Jutsum, AR (1997). Herbicide resistance: impact and management. Adv Agron, 58: 57–93

Ralph K. Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni M, McKone TM, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. The International Journal of Life Cycle Assessment 13: 532-546

Saling P, Kicherer A, Dittrich-Kraemer B, Wittlinger R, Zombik W, Schmidt I, Schrott W, Schmidt S (2002) Eco-efficiency Analysis by BASF: The Method. Int J Life Cyle Assess 7: 203-218

Saling P, Maisch R, Silvani M, König N (2005) Assessing the Environmental-Hazard Potential for Life Cycle Assessment, Eco-Efficiency and SEEbalance® Int J Life Cycle Assess 10: 364-371

Saling P, Schöneboom J, Künast C, Ufer A, Gipmans M, Frank M (2014) Assessment of Biodiversity within the Holistic Sustainability Evaluation Method of AgBalance, In: Schenck R, Huizenga D (Eds.), Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014), 8-10 October 2014, San Francisco, USA. ACLCA, Vashon, WA, USA, p. 1144-1153.

Schmidt I, Meurer M, Saling P, Reuter W, Kicherer A, Gensch CO (2004) SEEBALANCE®: Managing sustainability of products and processes with the socio-eco-efficiency analysis by BASF. Greener Management International, 45:79-94

Schoeneboom J, Saling P, Gipmans M (2011) AgBalance^{TM} Technical Background Paper, BASF, Ludwigshafen (http://www.agro.basf.com/agr/AP-Internet/en/function/conversions:/publish/upload/ sustainability/AgBalance/307736_BASF_Tech-E_Paper-AgBalance.pdf)

Shi G, Chavas J-P, Lauer J (2013) Commercialized transgenic traits, maize productivity and yield risk. Nature Biotechnology, 31(2): 111-114

Tabashnik B, Brévault T, Carrière Y (2013) Insect resistance to Bt crops: lessons from the first billion acres. Nature Biotechnology, 31: 510–521

VDLUFA (2004) Standpunkt Humusbilanzierung, Methode zur Beurteilung und Bemessung der Humusversorgung von Ackerland, Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten (VDLUFA), Bonn (Germany).

Whitman T, Yanni SF, Whalen JK (2011) Lifecycle assessment of corn stover production for cellulosic ethanol in Quebec. Can J Soil Sci 91: 997-1012

Wright RJ, Jackson TA, Giesler LJ, Wegulo SN, Sandell LD, Wilson RG, Hergert GW, Schild GA (2011) 2011 Nebraska Crop Budgets In: Klein R, Wilson RK (eds) 2011 Nebraska Crop Budgets. The Board of Regents of the University of Nebraska, Lincoln, pp 3-19

Xu G, Fan X, Miller AJ (2012) Plant Nitrogen Assimilation and Use Efficiency. Annual Review of Plant Biology, 63: 153-182

Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector

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Rita Schenck and Douglas Huizenga, Editors
American Center for Life Cycle Assessment

The full proceedings document can be found here:
http://lcacenter.org/lcafood2014/proceedings/LCA_Food_2014_Proceedings.pdf

It should be cited as:

Schenck, R., Huizenga, D. (Eds.), 2014. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014), 8-10 October 2014, San Francisco, USA. ACLCA, Vashon, WA, USA.

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ISBN: 978-0-9882145-7-6