

Greenhouse Gas Profile of a Plastic Material Derived from a Genetically Modified Plant

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Summary

This article reports an assessment of the global warming potential associated with the life cycle of a biopolymer (poly(hydroxyalkanoate) or PHA) produced in genetically engineered corn developed by Monsanto. The grain corn is harvested in a conventional manner, and the polymer is extracted from the corn stover (i.e., residues such as stalks, leaves and cobs), which would be otherwise left on the field. While corn farming was assessed based on current practice, four different hypothetical PHA production scenarios were tested for the extraction process. Each scenario differed in the energy source used for polymer extraction and compounding, and the results were compared to polyethylene (PE). The first scenario involved burning of the residual biomass (primarily cellulose) remaining after the polymer was extracted from the stover. In the three other scenarios, the use of conventional energy sources of coal, oil, and natural gas were investigated. This study indicates that an integrated system, wherein biomass energy from corn stover provides energy for polymer processing, would result in a better greenhouse gas profile for PHA than for PE. However, plant-based PHA production using fossil fuel sources provides no greenhouse gas advantage over PE, in fact scoring worse than PE. These results are based on a cradle-to-pellet modeling as the PHA end-of-life was not quantitatively studied due to complex issues surrounding the actual fate of postconsumer PHA.

Introduction

Production of plastics worldwide consumes about 270 million metric tons¹ of fossil fuel each year (Gerngross and Slater 2000), 120 million tons as feedstock and another 150 million tons as process energy. Although conventional plastics such as polystyrene and PE have very good material properties, their reliance on fossil resources as a raw material, their lack of biodegradability, and their contribution to a growing solid waste stream (in particular, in the United States) have been historically cited as potential long-term shortcomings. Finding alternatives that are made from renewable resources and are biodegradable has thus become the focus of intense research efforts (Gerngross and Slater 2000).

Background on Biopolymers Production

Among the biopolymers having commercial potential, poly(hydroxyalkanoates) (PHAs) have been viewed as particularly promising, and diverse PHA production pathways have been studied and compared (Gerngross and Slater 2000). PHAs are natural products produced by many bacterial species for carbon and energy storage, and many types of PHA with diverse physical properties can be produced by growing the bacteria on an appropriate feedstock. Indeed, PHA production via bacterial fermentation has been performed commercially, most notably for production of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), commercialized under the trade name Biopol™. Biopol™ has been used to make plastic bottles and to coat paper. Greenpeace, an environmental advocacy organization, produced a credit card made of this polymer. However, PHBV production was recently discontinued because manufacture based on fermentation cannot compete economically with petrochemical processes used to produce conventional plastics such as PE (Gerngross and Slater 2000).

Despite the economic difficulties associated with PHA production, one might think that the environmental benefits would justify higher cost and provide chances for success in the market place. After all, the polymer is derived from a renewable resource (sugar from corn starch) and

products made from PHBV are completely biodegradable. However, earlier work has shown that PHA production based on fermentation is not a sustainable process (Gerngross 1999). In fact, when considering the energy and material requirements for corn farming and wet milling, fermentation, and polymer recovery, a rather discouraging picture emerges. All major environmental indicators such as carbon emissions, air acidification, eutrophication, and depletion of natural resources show that fermentative PHA production has considerably more negative environmental impact than conventional plastic production. These counterintuitive findings demonstrate the need for a comprehensive life-cycle assessment prior to dedicating significant resources to the development of a new technology.

Efforts to produce PHAs have since focused on synthesizing the polymer in agricultural crops modified by using genetic engineering techniques, followed by recovery of the polymer by extraction with organic solvents. Producing PHAs in plants was expected to allow more economical performance compared to petrochemical polymers because it eliminated the requirement for a fermentation process. Getting a plant to synthesize PHAs involves the stable introduction of several microbial genes into the plant. These genes encode for the biosynthetic conversion of acetyl-CoA, a naturally occurring metabolic precursor, and likely additional plant metabolites, into a polyester of high molecular weight.

Several types of plants, including the laboratory organism *Arabidopsis thaliana* (Nawrath et al. 1994; Poirier 1992), and the crops *Brassica napus* (Houmiel et al. 1999; Slater et al. 1999), *Glycine max* and *Zea mays* (Gruys et al. n.d.) have been successfully engineered to produce the simple polymer poly(3-hydroxybutyrate). In addition, both *Arabidopsis* and *Brassica* have also been engineered to produce the commercial product PHBV (Slater et al. 1999), albeit at a low polymer content. Analysis of potential production systems led to three plants in which commercial production appeared economically attractive. These were, in order of decreasing economic and increasing technical viability, switchgrass, sugar cane, and corn. Switchgrass grows to very high biomass density on marginal land, and has been extensively investigated as a potential source of

biomass fuel (Department of Energy 1998). However, the genetics of switchgrass are complex and poorly characterized, and an efficient system for making transgenic plants is not currently available. Sugar cane can be genetically modified, but is also an extremely poorly understood genetic system. Thus, corn was chosen as a model because it can be both genetically modified and well characterized. The polymer is produced in genetically engineered corn in which grain is harvested in a traditional manner, and polymer is extracted from the corn stover (stalks, leaves, and cobs). Although the technical and economic aspects of PHAs obtained through transgenic crops are increasingly understood, the impact of their life cycle on the environment is less known.

This paper presents the greenhouse gas profile associated with the production of such a polymer, derived from research at the Monsanto company. This profile has been assessed from a life-cycle perspective, that is, accounting for the life-cycle

stages including corn farming, extraction of polymer, and compounding. The end-of-life step has been excluded from the quantitative modeling, due to the wide variety of uses applicable to PHA and their corresponding end-of-life possibilities. End-of-life considerations and their potential influence on the results are nevertheless presented, from a qualitative viewpoint only.

Modeling

This section describes the life-cycle steps of PHA production taken into account in the calculation of the greenhouse gas profile of PHA. A special focus is placed on farming. Two different options for allocating greenhouse gas emissions to stover and grain are analyzed. Then, various scenarios are described according to the nature of the energy required for extraction and compounding. A comparative scenario describing PE production is finally detailed.

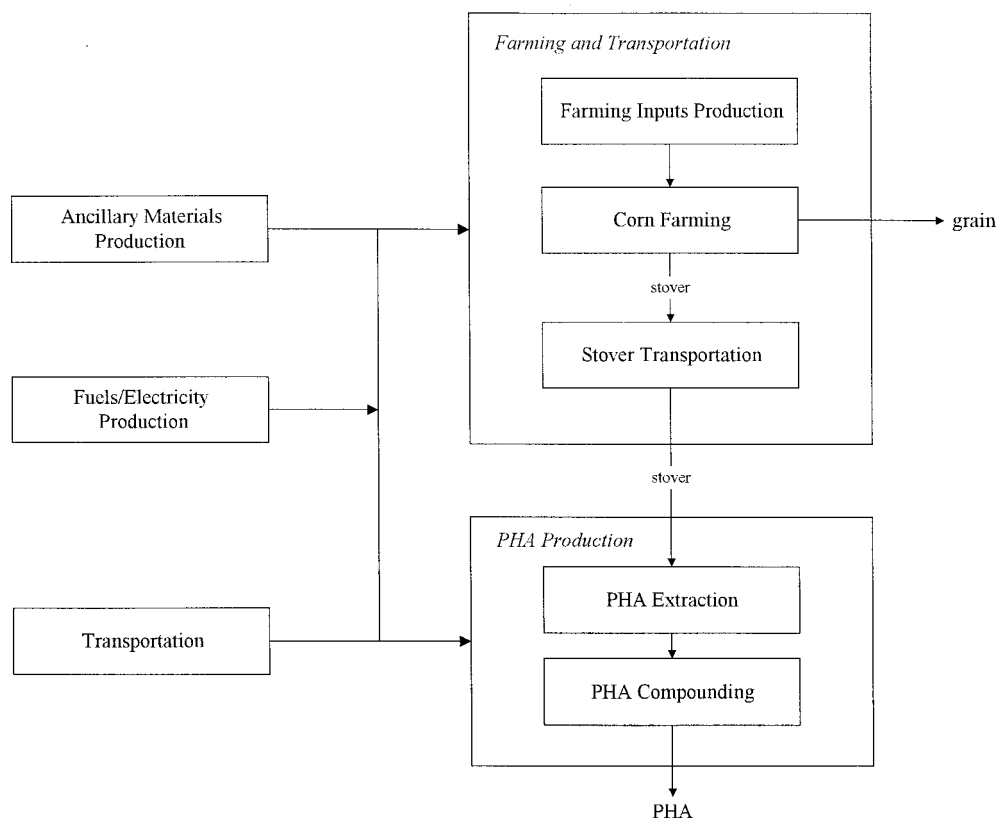


Figure 1 Overview of the system boundaries defined for the PHA production system

System Boundaries

The greenhouse gas profile has been calculated for the production inputs used during farming, as well as PHA extraction and polymer compounding as detailed in figure 1. The different end-of-life options—landfilling, composting, and incineration—are discussed from a qualitative viewpoint only, as explained in the background section.

Allocation of Burdens to Harvested Stover

Both grain and stover are intentionally co-produced through the farming of engineered corn. The impacts associated with farming (use of fertilizers, direct emissions from the field, etc.) have to be distributed to both corn grain and stover. The allocation procedure in the study follows the ISO 14041 standard, which deals with the inventory phase of the life cycle. According to this procedure, it is recommended to extend the stover production system to include the production of all co-products, that is, stover and grain. When using this allocation approach, also called system extension, the full farming impacts of growing the genetically engineered corn (including grain/stover separation) is attributed to harvested stover only (around 60% of total stover) but the impact due to producing the same quantity of conventional corn grain is subtracted (see figure 2). Conventional-corn farming requires less input (fertilizer, energy, land, etc.) than engineered-corn farming to produce the same amount of grain. We assume a 5% grain yield loss for corn producing PHA. In essence, the system extension approach is designed to burden the PHA-containing stover with only the incremental impact due to the slightly lower yield per acre associated with the production of genetically engineered corn.

The system extension is used as the baseline approach in the study, accordingly to ISO recommendations (ISO 14041 1998). Nevertheless, additional calculations using a different approach are performed in order to test the sensitivity of the overall results to the allocation method. Allocation issues have sometimes proved contentious and critical to the outcome of life-cycle studies, and a careful analysis of al-

ternate allocation methods was an important component of this study.

In the second allocation approach, the farming impacts are partitioned between grain and stover based on an “underlying relationship” (ISO 14041 1998)—a physical relationship when possible—that exists between these co-products. Applied to corn, an immediate relationship to consider between grain and stover is the one between their relative mass. The allocation procedure in that case partitions each total input and output according to the relative dry mass of each co-product harvested from the field. The use of mass partitioning reflects the assumption that any considered input such as a single fertilizer (or output such as a single air emission) is really consumed (or generated) by each co-produced part of the plant in the ratio dictated by its relative mass. As these physiological relationships are not known for sure, another type of relationship between grain and stover is actually discussed below.

Economic value of both co-products, when available, is another potential factor on which the allocation can be based, partitioning each total input and output according to the relative monetary value of each co-product. Nevertheless, this partitioning factor cannot be used in the study, as stover is usually considered to have no commercial value, and is almost never harvested. Even in the rare case of actual harvest and further use, an appropriate commercial value of the stover is difficult to determine as market pricing strongly depends on local, and highly variable, conditions. In an attempt to avoid these obstacles, one might consider deducing the stover economical value from the assessment of the potential saving that farmers achieve when they leave the stover on the field, “using” it as a potential chemical and physical soil improvement agent for the next season. Due to remaining difficulties associated with this economic assessment,² the mass-based partitioning is kept as the only possible alternative option to system extension, and is shown in figure 3.

PHA Extraction Energy Scenarios

The extraction process requires steam and electricity that can be generated by various primary energy sources, either biomass or fossil fuels. In the biomass scenario, retained as the

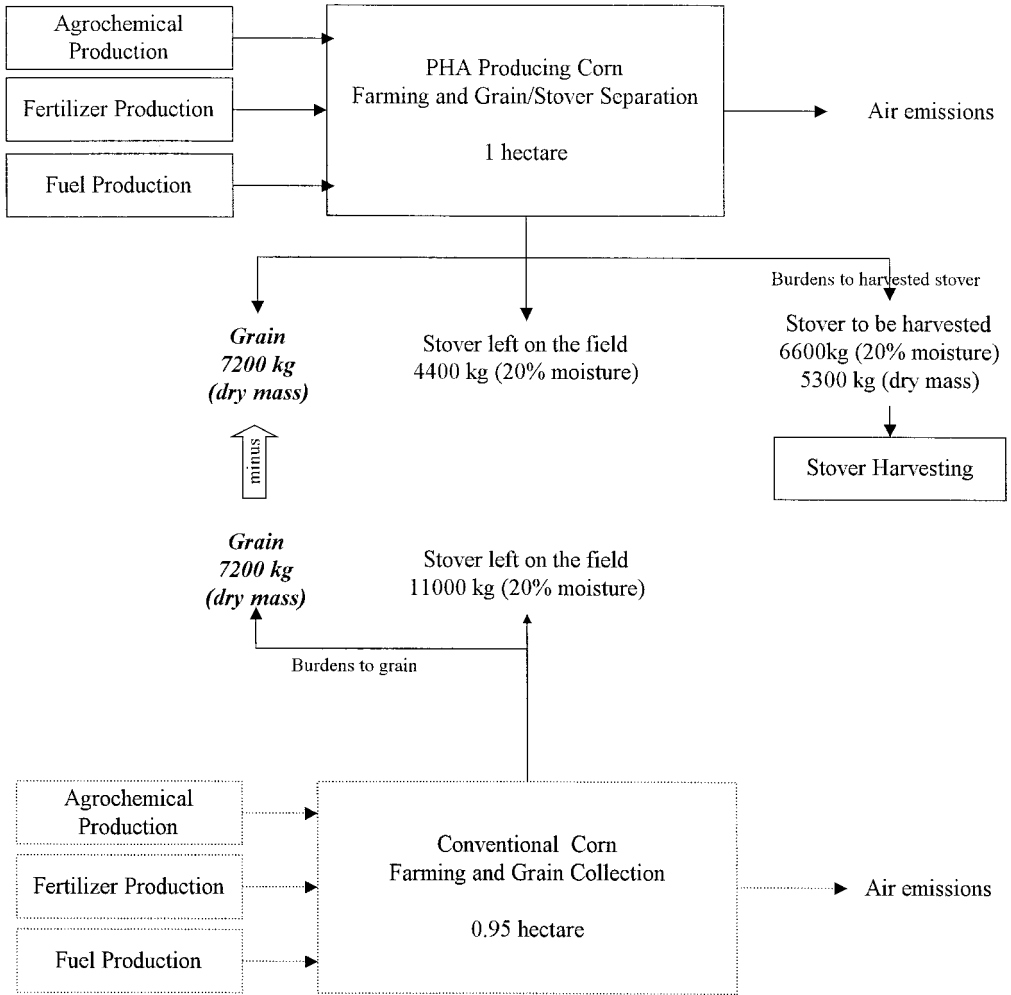


Figure 2 Extending the system boundaries

baseline case, a boiler burns the residual biomass that stover yields after PHA has been extracted. The PHA production process uses steam and electricity generated by biomass burning and the surplus unused steam is converted to electricity and sold. In order to account for this net production of electricity, the impacts due to electricity production from an alternate source (e.g., electricity from grid) have been subtracted from the system. This “biomass burning” modeling is shown in figure 4.

In the alternative scenarios, the energy sources are fossil fuels. Therefore, the dried stover obtained after the PHA extraction is not burned nor used beneficially in any other way.

Instead, all environmental burdens of the extraction are placed on the PHA and none are placed on the extraction residue that is considered as waste. The “fossil fuel burning” modeling is shown in figure 5.

All data for natural gas, coal, and oil, as well as electricity production come from Ecobalance’s DEAM™ database, reflecting average production conditions in the United States (Ecobalance 1999).

Comparison with PE

Because PHA presents similar material properties as PE and can replace it in various appli-

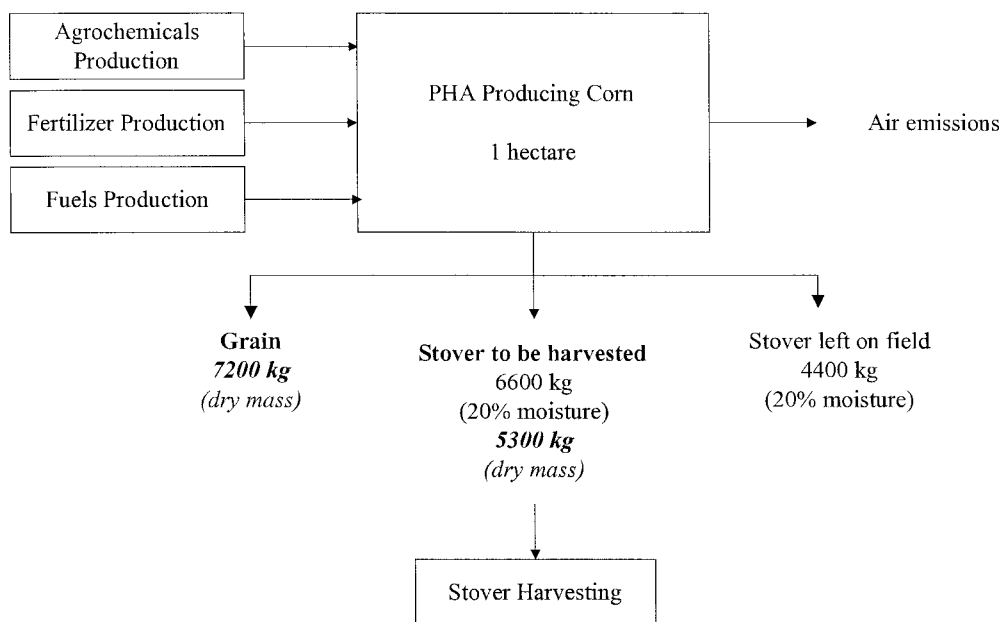


Figure 3 Allocation of burden based on dry mass produced

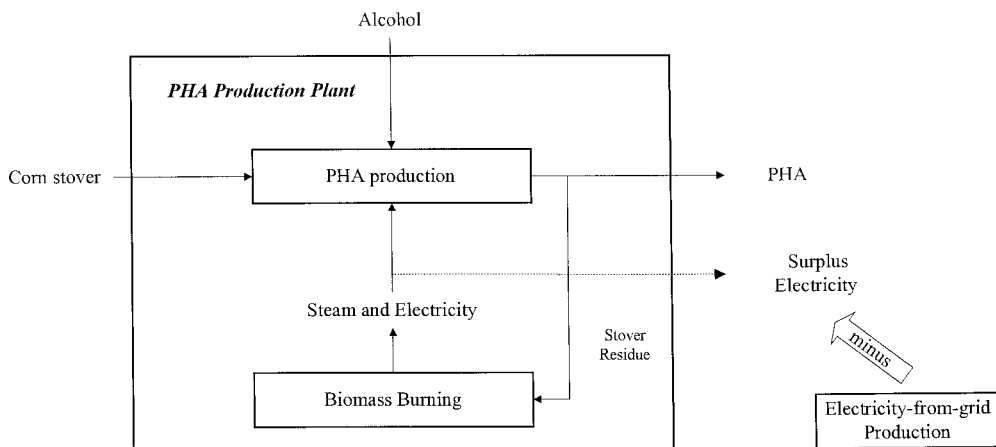


Figure 4 Biomass Scenario

cations (Holmes 1988), a comparison of the two polymers is included in the study. Therefore, in addition to each of four PHA production scenarios, a greenhouse gas profile is calculated for PE production, both for low-density PE (LDPE) and high-density PE (HDPE). The PE production systems include extraction of raw material, processing of crude oil and natural gas, petroleum refining, ethylene polymerization, and PE separation (EPA 2000).

Global Warming Potential Calculation

The flows contributing to global warming potential and their respective coefficients—for a time horizon of 100 years—from the Intergovernmental Panel on Climate Change (IPCC 1998) are displayed in table 1.

The calculation is performed for six different scenarios based on the allocation approach, system extension or partitioning, and the source of

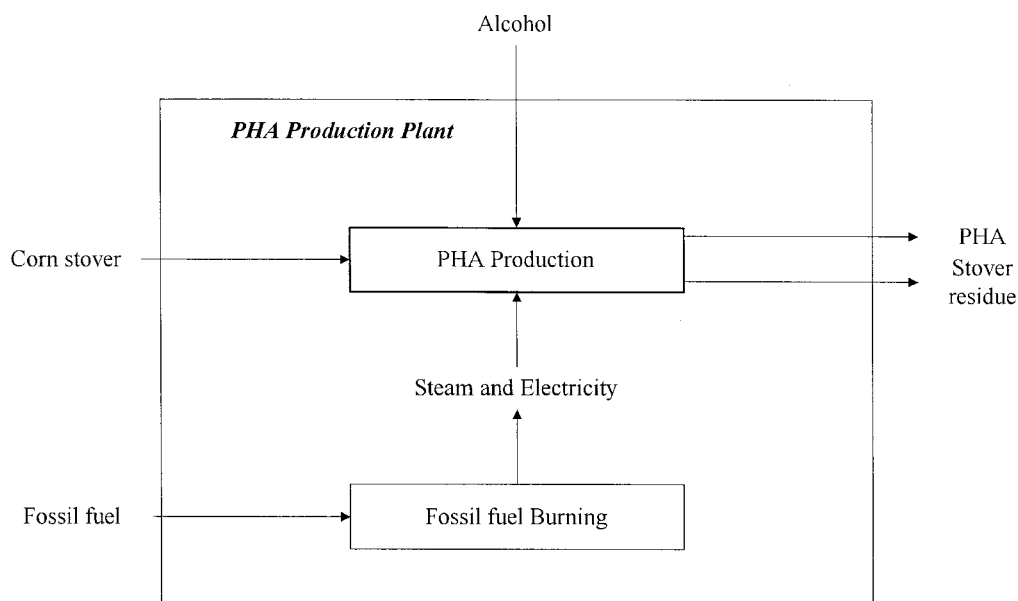


Figure 5 Fossil fuel Scenarios

energy for extraction, as listed in table 2.³ Both allocation approaches are applied to the biomass and the natural gas scenarios, and only the system extension to the coal and oil scenarios.⁴

Data Sources

Farming Inputs and Outputs

The farming model takes into account corn yield parameters of genetically engineered corn as derived from Monsanto's own assumptions. In particular, grain corn value is chosen based on current farming situations and is assumed to reach 8,950 kg/ha (143 bushels/acre). Although on the high side of the U.S. national average, this grain yield is realistic for the most productive part of the United States and is congruent with Monsanto's expectations for PHA yield. Taking into account the ratio of stover har-

vested, and that of dry content grain/stover, stover yield reaches 5,300 kg/ha (dry weight) based on 8,950 kg of grain/ha. Good farming practice requires that at least 40% of the stover be left on the field to prevent erosion and provide organic matter for the following season, so only 60% of the output stover is assumed harvested (Nielsen 1995). Based on an approximate 20% water content at harvesting time, harvested stover wet weight is 6,600 kg/ha, corresponding to 5,300 kg/ha dry weight. Regarding corn producing PHA, we assume a 5% grain yield loss. Table 3 summarizes the farming yield assumptions used to build the model.

Much of the data regarding farm production inputs are provided in a study from the Economic Research Service (ERS) of the United States Department of Agriculture (USDA) (Shapouri et al. 1995). Such farm production data include energy (diesel, gasoline, electricity, and natural gas) as well as fertilizers and other chemicals consumption, and are based on USDA's 1991 Farm Costs and Returns Survey. More recent numbers regarding cost and returns are available but the corresponding ERS study had not been updated at the time of this assessment. The data encompass the nine major U.S. states producing corn for ethanol (Illinois, Indi-

Table 1 Elementary flows in global warming indicator and corresponding coefficient

Elementary flows	Coefficients
CO ₂ (fossil and biomass)	1
CH ₄	24
N ₂ O	360

Table 2 Scenario listing

	Energy source	Allocation approach	
		System extension	Mass-based partitioning
1	Biomass	Biomass, System extension	not applicable
2	Biomass	not applicable	Biomass, Partitioning
3	Natural gas	Natural gas, System extension	not applicable
4	Natural gas	not applicable	Natural gas, Partitioning
5	Coal	Coal, System extension	not applicable
6	Oil	Oil, System extension	not applicable

Table 3 Corn yield parameters

Parameters	Data source or formula	Units	Values
Figures for grain and stover (regular corn)			
Grain yield (15.5% water content)	Derived from current situation	bu/ac	142.6
Grain density	Nielsen 1995	lb/bu	56
Grain yield	$142.6 \cdot 56 \cdot 0.4536/0.1047$	kg/ha	8,950
Grain dry content	Nielsen 1995	(kg/kg)	0.845
Ratio of dry grain to dry stover	Monsanto's data	(kg/kg)	55/45
Stover yield (dry basis)	$55/45 \cdot 8,950 \cdot 0.845$	kg/ha	9,244
Figures for harvested stover (regular corn)			
Stover harvest rate	Nielsen 1995	(kg/kg)	0.6
Harvested stover (dry basis)	$9,244 \cdot 0.6$	kg/ha	5,546
Figures for modified corn			
Grain yield loss	Monsanto's data	(kg/kg)	0.05
Corn grain	$8,950 \cdot 0.95$	kg/ha	8,503
Harvested stover (dry basis)	$5,546 \cdot 0.95$	kg/ha	5,269
Figures for stover (modified corn, 20% water content)			
Stover water content when harvested	Monsanto's assumption	(kg/kg)	0.2
Harvested stover	$5,269/(1-0.2)$	kg/ha	6,586

ana, Iowa, Minnesota, Nebraska, Ohio, Michigan, South Dakota, and Wisconsin). The average grain yield in this ERS study is 7,700 kg/ha (122 bu/ac) for 1991, which is below the objective of 8,950 kg of corn grain per hectare. In order to take into account this projected higher grain yield, the farming inputs as found in the ERS study are scaled up to 8,950 kg/ha. Even though there is not always a direct relationship between high inputs and high yield, the same increasing factor—8,950/7,700, for example, 16% increase—is conservatively applied to all inputs. Furthermore, as will be shown in the results, farming is often a minor contributor to global warming potential of the PHA life cycle. There-

fore, the bias due to scaling up does not change the final results of the study.

Table 4 describes the inputs that are used in this study. The energy requirement figures include the following farming steps: growing seed, land preparation and plowing, planting, weeding, chemicals distribution, irrigation, and grain/stover separation (grain harvest step). The pre-production steps related to the input production (raw material extraction, refining, etc.) are derived from Ecobalance's DEAM™ database. The greenhouse gas emissions related to the production of fertilizer, agrochemicals, and fuel are included in the calculations, along with those corresponding to the combustion of fossil fuel in farm equipment.

Table 4 Farming inputs

<i>Fertilizers and agrochemicals</i>	<i>Units</i>	<i>Data</i>
Nitrogen as N	kg/ha	163
Phosphate as P ₂ O ₅	kg/ha	76
Potash as K ₂ O	kg/ha	69
Lime	kg/ha	315
Agrochemicals (unspecified)	kg/ha	5.1
<i>Energy requirements</i>		
Diesel oil + Gasoline	l/ha	111
Electricity	kWh/ha	96

Although tilling practices and residue management are well-established factors affecting the soil organic content (Duiker and Lal 1999; Lal 1997), and as such are important to greenhouse gas considerations, no specific data have been identified as to which tilling practice is likely to accompany 60% stover removal. Therefore, the carbon sequestration in soils attributable to tilling practices because of the export of 60% of the stover is not included in the modeling. Additionally, the effect of tilling practices depends on soil and climate conditions, which are beyond the scope of this study. Finally, and most important, the farming contribution (fertilizer, agrochemicals, and fuel use) to global warming potential is minimal compared to that of PHA extraction (see Results section). All those reasons lead us to assume in the study that harvesting 60% of the stover does not change the fertilizer, agrochemicals, and fuel requirements nor the soil carbon content (beyond the net exportation of carbon corresponding to the mass of harvested stover) compared to leaving 100% of the stover in the field.

The CO₂ plant intake related to the corn growth is estimated from the stover carbon content. This latter is assumed to approximate 50%, based on the composition of sugar cane bagasse (sugar cane residues), as both plants have a similar cellulosic content (Broder and Barrier 1990; EPA 1997).

Nitrous oxide emissions related to farming are more difficult to evaluate. In addition to small emissions due to the operation of farm equipment when applying fertilizer, a major source of nitrous oxide emissions is the nitrogen fertilizer itself (part of the nitrogen applied to the soil is transformed into N₂O through microbial pro-

cesses). These emissions from the soil, however, are not necessarily specific to corn raising as they are generated even in absence of fertilization and/or any cultivation. In this study, the nitrous oxide emission from the soil directly related to the quantity of nitrogen fertilizer used is taken into account, whereas the unspecific emission from the field is excluded. No well-documented and internationally recognized method is available to model these N₂O emissions from field-derived fertilizer use. The method chosen for this work (Conrad 1983) is based on field measurements of nitrogen fertilizer losses rather than chemical reactions, as used in other models. It evaluates the N₂O emission to the air to 5.1 g per kg of nitrogen applied. It should be mentioned that N₂O contribution to the overall greenhouse gas impact does not reach 1%. No significant changes are expected in the overall results if another method is used.

PHA Production Inputs and Outputs

PHA preparation from the dried stover includes a two-step solvent extraction (Kurdikar et al. 1998). The materials and utilities requirement data (table 5) are derived from engineering estimates made by Monsanto, and are based on extraction of PHA using a C₄-C₁₁ alcohol (Kurdikar et al. 1998). The model built for C₄-C₁₁ alcohol is based on butanol production with the consumed amount of C₄-C₁₁ alcohol, and includes the energy requirements for compressed air.

The compounding step produces PHA pellets ready to be sold to processors. These PHA pellets are comparable to the PE resin modeled in the study. The final compounding step that processors might perform on resin, either PHA or PE, is not included in the study.

In the baseline scenario, the dried stover (after PHA extraction) is burned for steam and electricity generation, and the surplus steam is converted to electricity to be sold. The projected CO₂ emission from the stover combustion is displayed in table 6. Emissions data specific to burning dried corn stover were not readily found. Therefore, available emissions data related to bagasse-fired boilers were used instead (Air Chief, EPA 1997). Heating values (on a dry basis) of bagasse and corn are quite similar, approximately

Table 5 Expected inputs of PHA production from modified corn stover

Raw PHA extraction	Unit per kg PHA	Value
Stover (dry basis)	in kg	6.8
Alcohol (losses)	in kg	0.08
Steam	in kg	12.5
Electricity	in MJ elec	8.8
Stover residue (dried, after PHA extraction)	in kg	5.8
<i>PHA compounding</i>		
Electricity	in MJ elec	2.4
Titanium oxide (TiO ₂)	in kg	0.003

17 MJ/kg for dry corn stover (Ontario Ministry of Agriculture, Food and Rural Affairs, OMAFRA) as is their composition (Janick 1990).

PE Production

Data on PHA production were compared to data on the production of PE, both LDPE and HDPE. Data assumptions related to PE production are found in the EPA data set for Plastic Materials (2000). These EPA data include polymerization data from the Association of European Plastics Manufacturers (Boustead 1993, 1997), based on 36 European plants producing 4.5 million tons of PE of all grades. A weighted average is used for LDPE and HDPE, respectively. These European process data are combined with U.S. data regarding the energy supply (electricity grid and the actual average for steam). Results in this work are given per kilogram of PE resin; in other words they do not include final compounding, which is consistent with what was done for PHA. This exclusion from the model is reasonable as the differences in final compounding recipes between PE and PHA are very slight and are expected to generate only minimal changes in the greenhouse gas profile of both polymers. The influence of polymer density, however, is taken into account as it could affect the comparison between PE and PHA. Densities are on average 0.93, 0.95, and 1.2 for LDPE, HDPE, and PHA, respectively. Replacement of PE by PHA could be volume-based in some applications, or mass-based in oth-

Table 6 Characteristics for corn stover-boiler

Heating value of stover	in MJ/kg of dry stover	17.6
CO ₂ emission factor	in g/kg of dry stover	1,560

ers (mixed situations being also possible). Therefore, the graphical results for both LDPE and HDPE show the range obtained from volume-based (favorable to PE) to mass-based (favorable to PHA) calculations, both to be compared to PHA results given per 1 kg of biopolymer.

Results

The following section presents the overall global warming potential for several scenarios, biomass and natural gas being analyzed in further detail. Unless otherwise noted, all scenarios are analyzed using the system extension approach (see Modeling section). The results of a sensitivity analysis comparing this approach to mass-based partitioning are also presented. For all scenarios, the greenhouse gases derive from both the farming and processing steps, but are primarily the result of processing. Among the greenhouse gases relevant to this study, CO₂ (whether from biomass or fossil fuels) is the primary greenhouse gas in all scenarios, both in quantity of CO₂ and in global warming impacts, overshadowing CH₄ and N₂O (as displayed for the biomass scenario). Furthermore, in all results, the harvested stover is assumed to release its embedded carbon through burning (biomass scenario) or natural degradation (stover residue in fossil fuel scenarios). The nonharvested stover is not included in the accounting, as its CO₂ uptake is assumed, according to standard carbon accounting practices, to equal its CO₂ releases during long-term degradation.

Biomass Scenario

The overall generation of greenhouse gas through the production of PHA in a biomass scenario equals -4,000 g CO₂ eq/kg PHA (first column of figure 6) with CO₂ being the major contributor, as shown in table 7.

Figure 6 displays a breakdown by farming steps (corn growth and fertilization) and by process

Table 7 Relative contribution of greenhouse gases to global warming impact in biomass scenario. Negative values indicate CO₂ absorption or credit

Per kg PHA	CO ₂	CH ₄	N ₂ O
Emission in g	-4,000	2	0.06
Coefficient	1	24	360
Contribution in g CO ₂ eq	-4,000	48	21

steps (extraction and compounding). The corn plant absorbs around 12,500 g CO₂ eq/kg PHA produced, which is mostly released when the stover is burned for energy generation (9,000 g CO₂ eq/kg PHA). The difference (3,500 g CO₂ eq/kg PHA) corresponds to the carbon embedded in the PHA (2,000 g CO₂ eq/kg PHA based on carbon content) and in the ash from the boiler (1,500 g CO₂ eq/kg PHA due to incomplete combustion). In addition, the surplus electricity generated in the biomass scenario yields a small greenhouse gas credit (e.g., offset of grid electricity). The end-of-life of the ash has not been modeled in the study, but its most probable fate is disposal in a landfill, unless its composition is appropriate for application on farming land (depending on the mineral composition of the ash). Even though it is not clear what the degradability of this boiler-generated ash might be, either for landfill or land application, global warming potential corresponding to this waste is not expected to exceed 1,500 g CO₂

eq/kg PHA. Based on this conservative consideration, the overall global warming impact becomes -2,500 g CO₂ eq/kg PHA.

Natural Gas Scenario

When natural gas is used as the energy source for the extraction/compounding process, the stover residue is still assumed to release over time 100% of its carbon to the atmosphere (around 10,500 g CO₂ eq/kg PHA). In addition, the extraction and compounding steps combined release around 5,500 g CO₂ eq/kg PHA through steam and electricity production. The overall process generates a net greenhouse effect of approximately 3,800 g CO₂ eq/kg PHA as shown in figure 7.

All Scenarios

In figure 8 all scenarios are compared. All fossil fuel scenarios appear to have a higher global warming potential. The biomass scenario on the contrary shows a much better profile, with a greenhouse gas credit from surplus electricity production and CO₂ sequestration in the biopolymer.

Sensitivity Analysis of Allocation Approaches of Farming to Stover

Figure 9 presents the results of a sensitivity analysis comparing the system extension to the

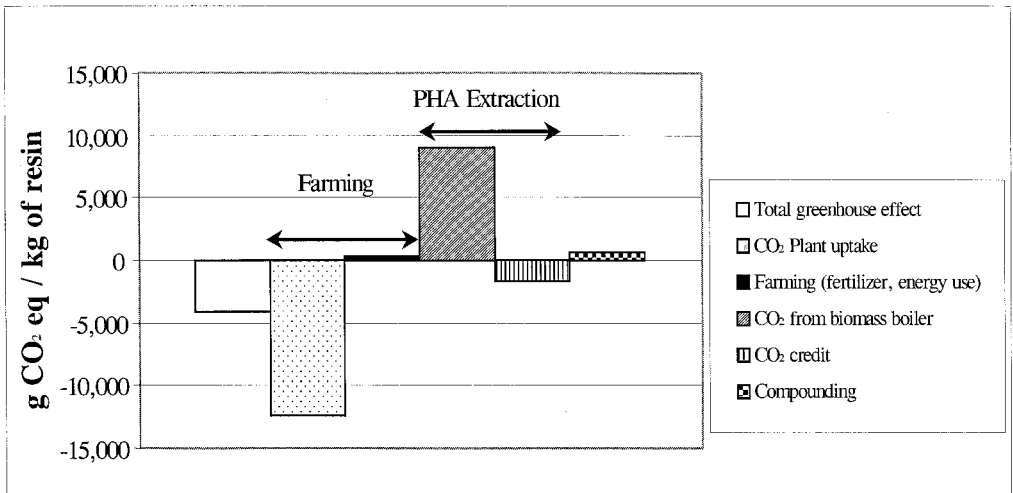


Figure 6 Global warming potential for PHA biomass scenario

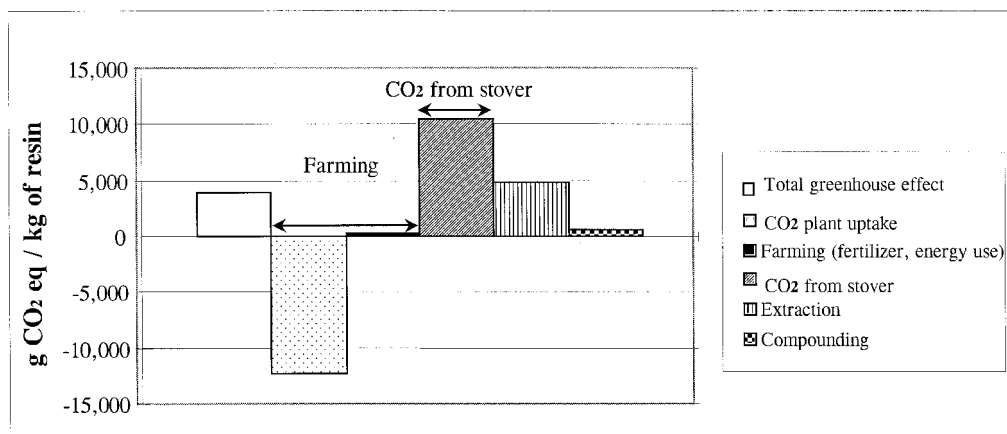


Figure 7 Global warming potential for fossil fuel scenarios

mass-based partitioning approach (see Modeling section) for the biomass and natural gas scenarios only. In the system extension approach, the greenhouse gas generation from stover alone is obtained by subtracting that of conventional-corn farming (including grain collection) from that of engineered-corn farming (including grain/stover separation). In the partitioning approach, the environmental burdens are distributed between grain and stover based on the respective dry mass harvested. The partitioning scenarios lead to an overall PHA global warming potential 20% higher than those obtained through system extension. For emissions related to the farming step, partitioning puts a burden to the harvested stover approximately eight times higher than that determined by the first approach. But, when considering the overall system, which in addition to farming encompasses PHA extraction and production, this ratio is highly reduced.

End-of-Life Considerations

After the polymers have been produced, processed, and used, they are discarded as municipal solid waste, then routed according to different waste management options, each of these presenting their own greenhouse gas implications (EPA 1998). A quantitative study of the greenhouse gas implications of various end-of-life practices was excluded from the scope of the project. This section attempts to qualitatively address greenhouse gas implications for different end-of-life options, for PHA and PE, respectively.

Implications for PHA:

- When PHA is composted, most of its CO₂ is released, which alters its greenhouse gas profile. The production of a valuable compost material could offset the production of another compost material. The subtracted alternative compost production could possibly provide PHA with some CO₂ credit but this effect is not clear, as the materials usually used for compost production (such as yard clippings) are considered to sequester their CO₂ for a longer period of time compared to what is known for PHA. The net impact from both PHA degradation and alternative compost production is unknown but would most probably be around 2,000 g CO₂ eq per kg of composted PHA (according to PHA carbon content).
- Incineration would increase PHA's CO₂ emission by 2,000 g CO₂ eq per kg of incinerated PHA based on its 50% carbon content. However, corresponding heat recovery and production of electricity (offsetting grid electricity) would generate a CO₂ credit. Based on PHA heating value (18 MJ/kg), and with an energy yield assumed to be 20% for electricity recovery, around 1,000 g of net CO₂ eq per kg of incinerated PHA would be released through PHA incineration.
- Landfilling would present a mixed picture for PHA products. Part of the biomass carbon contained in PHA would decompose

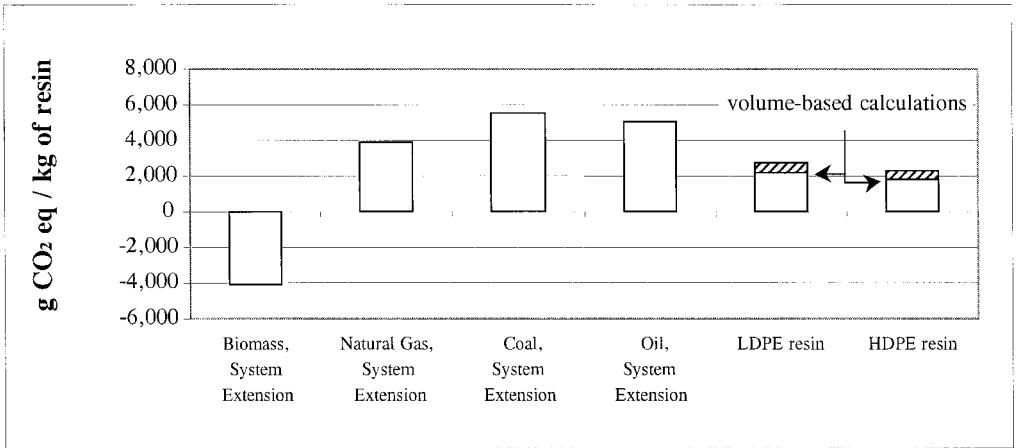


Figure 8 Global warming potential for PHA biomass and fossil fuel, and PE scenarios. The volume-based line in PE columns shows the influence of PE smaller densities compared to that of PHA, in volume-based applications. To manufacture PE products with the same volume as the PHA product, smaller quantities of PE resin are required compared to PHA, which generates smaller overall PE global warming potential than in case of mass-based applications (line topping the column).

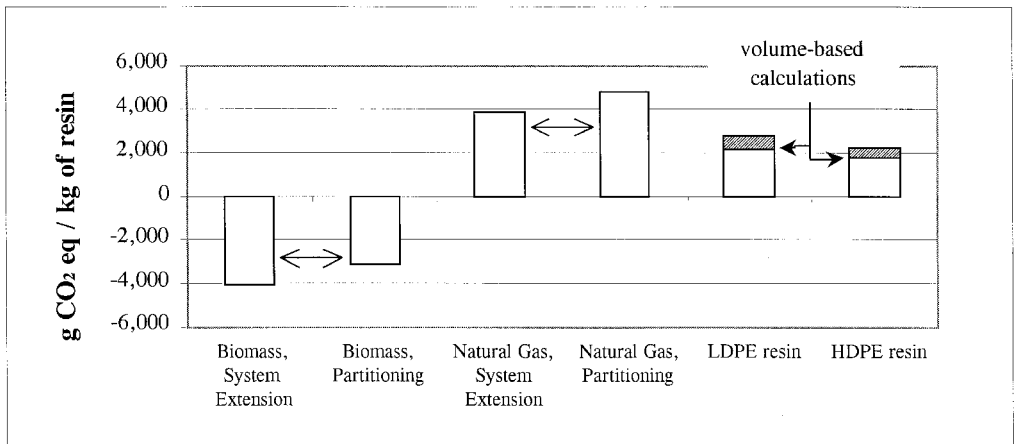


Figure 9 Global warming potential for PHA biomass and natural gas scenarios, with system extension and partitioning approaches, and PE. The volume-based line in PE columns shows the influence of PE smaller densities compared to that of PHA, in volume-based applications. To manufacture PE products with the same volume as the PHA product, smaller quantities of PE resin are required compared to PHA, which generates smaller overall PE global warming potential than in case of mass-based applications (line topping the column).

and be emitted both as CO_2 and CH_4 . While the CO_2 emission will simply add to PHA's greenhouse gas profile, the influence of CH_4 emissions will vary depending on the landfill technology. In a landfill where captured gas is beneficially used (i.e., in a turbine, engine, or boiler), the generated CH_4 will eventually result in a

CO_2 credit from the offset of the production of fossil energy. The absence of CH_4 recovery on the landfill will have an adverse effect on the PHA profile.

- Recycling could be a significant component of PHA's waste management, but the absence of data does not allow specific expectations.

Implications for PE:

- Composting is not applicable to PE.
- Incineration would increase the direct CO₂ emission from PE, probably to a higher extent than for PHA, because of PE's higher carbon content (around 85% for PE). The CO₂ credit from electricity production would likely be higher for PE than for PHA as its heating value is higher (42 MJ/kg vs. 18 MJ/kg for PHA). Based on PE heating value, and with an energy yield assumed to be 20% for electricity recovery, around 1,000 g of net CO₂ eq per kg of PE incinerated would be released through PE incineration.
- Landfilling will not alter PE's greenhouse gas profile, as it is essentially inert.

Based on these end-of-life implications, the relative performance of PHA compared to that of PE is not straightforward. Nevertheless, the overall global warming potential of each polymer, considering the worst end-of-life option for PHA (composting) and the best end-of-life option for PE (incineration), should be around -2,000 g CO₂ eq per kg of PHA in a biomass scenario, and between 2,500 and 3,000 g CO₂ eq per kg of PE (all PE densities and applications included). PHA with a biomass scenario shows a more favorable profile than PE. PHA remains more favorable than PE if 100% of the CO₂ sequestered in the boiler ash is released, which is highly hypothetical.

The outcome of the comparison of PHA to PE regarding the end-of-life step of their life cycles cannot be determined more precisely at this point of the analysis for the following reasons:

- Based on the previous qualitative considerations, it is apparent that opposite factors could affect the greenhouse gas profile of PHA leading to a variable position of PHA over PE inside each end-of-life option.
- Also, PE and PHA probably will not follow the same end-of-life pathways. For instance, PHA is likely to be targeted, at least initially, in niche markets where composting would be the preferred end-of-life option.

Conclusion

This study evaluates the greenhouse gas impact of producing plastic from (mostly) atmospheric CO₂ using metabolically engineered corn. The production system capitalizes on existing farming infrastructure and requires no petroleum for polymer feedstock. Therefore, the impacts were initially hypothesized to be minimal. However, polymer extraction and compounding are extremely energy-intensive, so processing energy dominates the environmental impact of the overall scheme. This means that a low-impact product is possible, but only if the processing energy is itself renewable. Use of traditional fossil fuels results in an overall greenhouse gas impact that is worse than the greenhouse gas impact from PE production. In the PHA process analyzed here, the copious residual biomass generated during plastic extraction provides a ready source of biomass energy. Thus, it is the use of biomass power, not renewable feedstock, that makes the product preferable to PE from a greenhouse gas perspective. The use of renewable resources to produce the PHA plastic itself compared with the use of non-renewable feedstock to produce PE has the added benefit of sustainability.

With only a few exceptions, biomass power has failed to gain a foothold in energy production. The existing infrastructure makes fossil fuels relatively inexpensive and easily available, so they are the most likely energy source for a manufacturing process. Sugar production from sugar cane is one instance in which biomass fuel is consistently exploited. In sugar production, as in the PHA process outlined above, the biomass fuel (sugar cane bagasse) is a readily available by-product of the sugar. Thus, the fuel is harvested and transported to the plant along with the final product. This provides fuel at a very low cost, and it is burned to power sugar extraction and purification. Most of the waste, which would otherwise require disposal, is burned and so eliminated. The biomass energy option is currently available to the corn processing industry, but it is not used (Department of Energy 1994). Convenience, additional infrastructure requirements, and cost are cited in justifying the use of fossil energy in corn processing over a renewable

energy source. It is noteworthy in this context that corn-farming states use coal disproportionately in electricity generation.

Harvesting fuel as a co-product in this PHA production scenario makes biomass energy fairly inexpensive and efficient, as it is in sugar production. However, there is no particular reason that the energy derived from corn stover must be used for PHA extraction. In fact, one could argue from a global warming perspective that it might be better to simply burn the stover, and use the energy to power production of PE. All CO₂ generated would be recaptured in the next growing season, and PE (if landfilled) would provide a carbon sink that would minimize greenhouse gas emissions. Nonrenewable oil depletion for PE feedstock is the primary disadvantage to this scenario from a sustainability perspective. This scenario would weigh the negative impact of oil depletion versus the positive impact of reduced greenhouse gas emissions. The balance of this equation would be expected to shift as oil becomes a scarcer resource.

A truly sustainable system for plastics production would require renewable feedstock, renewable fuels used in harvesting and transportation, and renewable energy for production of agricultural inputs and for polymer extraction and processing. It would also minimize the consumption of energy in general. Renewable energy on this scale will require redistribution of infrastructure to exploit renewable fuels, and it will be many years before this becomes both technically and economically feasible. However, much work is ongoing and it appears clear that such a switch will eventually be essential as environmental concerns increase and fossil fuels, particularly oil, become scarce.

Notes

1. 270 million metric tons = 296 million short tons or 270 million megagrams (Mg). Unless otherwise indicated, tons as used in this article refers to metric tons.
2. The cost of displaced fertilizer and fuel (for mechanical equipment) between "stover left on the field"-scenario and "stover harvested"-scenario could theoretically serve as a base of the calculation. The overall effect of stover removal on

farming practices in general, however, and on future yields in particular, is a complicated issue that is still being addressed by experts. Studies are underway but so far, no consensus has emerged. On the one hand, stover removal tends to reduce carbon buildup in the soil, and leads to long-term yield loss, presumably by acting on mineral retention in soil components. Similarly, tillage favors biodegradation and tends to reduce carbon sequestration (as no quantitative data on how stover removal affects tilling practices are identified at this point, it is not possible to include this aspect in the study). On the other hand, within a more short-term view, stover removal diminishes plant pests' infestation as less stover debris means less refuge for pests and therefore allows for a better crop yield the next year with subsequent increased carbon sequestration. Also, especially in northern parts of the United States, removal of stover is actually recommended as it accelerates the ground warm-up after winter. But, as no model that we have identified has integrated these contrary effects yet, the intricate calculation of stover economical value has not been performed in this study, according to its scope.

3. In the six scenarios listed in table 2, 60% of the stover is assumed to be removed and processed (see data on farming inputs and outputs for explanation of that percentage). Another scenario would be to harvest 100% of the grown stover and to return the residual organic matter to the field after the stover has been processed for PHA. Since farmers might be reluctant to use stover residues that potentially contain traces of solvent (from the PHA extraction process), such a scenario is not modeled in this study.
4. The natural gas scenario receives more attention in the study compared to that of coal and oil because it is considered "cleaner" based on the favorable air acidification potential corresponding to its extraction and combustion taken together compared to that of coal or oil.

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