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ENVIRONMENTAL IMPACTS OF THE BIOBASED ECONOMY

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ENVIRONMENTAL IMPACTS OF THE BIOBASED ECONOMY

Overview and Background

Why the biobased economy appears likely to occur: a concise statement

1. The biobased economy will grow rapidly during the 21st century. A combination of low cost plant raw materials and gradually improving biorefinery process technologies for converting these raw materials into a variety of fuels, chemicals, materials, foods and feeds will drive the adoption of the biobased economy. The biological sciences, including techniques for genetic manipulation, will have a particularly powerful impact on both the raw materials and the processing technologies underlying the biobased economy.

2. The biobased economy, and its associated biorefineries, will be shaped by many of the same forces that shaped the development of the hydrocarbon economy and its refineries over the past century. These similarities include the importance of yield (using the whole “barrel of biomass”), continuing diversification of products, and gradual process improvement in functioning biorefineries. However, significant differences between the biobased economy and the hydrocarbon economy are also apparent. Among these are the great compositional variety of plant raw material, requiring a greater range of processing technologies to add value to the basic components, and the much wider geographic distribution of both raw materials and the associated refineries.

3. This wide geographic distribution of both raw materials and biorefineries will promote greater economic/national security and more equitable distribution of wealth. We believe that supposed limits on agricultural productivity to support the biobased economy are mostly illusory. There is no “food vs. fuel” conflict. Economic profitability and process efficiency will force the adoption of “food and fuel” scenarios.

4. Biorefineries and their associated crop production systems will be highly integrated. Furthermore, integrated biorefining systems will be designed to achieve not only economic profitability but also environmental benefits. Truly transformational environmental benefits can be achieved by creative design of these integrated biorefining systems. For perhaps the first time we have the opportunity to design a new industry so that it meets both economic and environmental performance criteria. This report is intended to outline how we might use life cycle analysis and other tools to ensure the environmental performance of the emerging biobased economy. Special attention is given to the role of biotechnology in improving the environmental performance of current and projected industrial, agricultural and energy systems.

The size of the resource base & the demand for services

5. Materials that contain carbon play an integral role in the world economy including the primary commercial fuels, virtually all food and fiber products and the major share of commodity chemicals, pharmaceuticals and nondurable manufactured goods (Arntzen and Dale, 2000). Carbon rich raw materials originate through the process of photosynthesis in which plants and some bacteria use solar energy to convert atmospheric carbon dioxide into organic substances including simple sugars, polysaccharides, amino acids, proteins, lipids and aromatic compounds such as lignin. Some carbon rich raw materials come
from fossil sources such as petroleum, coal and natural gas. Fossil sources result from photosynthesis in ancient times and comprise a large, but non-renewable, reserve.

6. In contrast, present day photosynthesis provides a potentially renewable source of carbon. Renewable agricultural and forestry resources have been used since ancient times as fuels and the raw materials for numerous products. Starting in the late 1700s, at the beginning of the Industrial Revolution, coal began to displace wood as a fuel. In the mid 1800s, the large scale processing of petroleum to fuel and chemical products began, taking away some markets from coal and many more from renewable carbon sources. In the last half of the 20th century, uses for natural gas began to expand greatly, both as a fuel and as a feedstock for chemical production (Arntzen and Dale, 2000). Currently petroleum provides 40% of the United States’ and 35% of the world’s direct primary energy supply, while plant material in all forms provides approximately 10% of world energy supply.

7. While remaining supplies of petroleum, coal and natural gas are very large, it is nonetheless obvious that the world is using these essentially non-renewable resources at a huge and growing rate. Natural processes are simply not replacing fossil carbon at even a minute fraction of the rate at which we are using it. For example, some experts believe that the peak rate of production of conventional oil will occur within this decade, while others predict this will occur before mid century (Campbell & Laherrere, 1998; Ivanhoe, 1996). After that point, conventional, inexpensive oil production will irreversibly decline. Natural gas production will peak later than conventional oil, but will still begin permanent decline within the next few decades. Although other sources of petroleum exist (e.g. tar sands, deepwater oil), they will be more difficult and much more expensive to produce. Whatever the exact date of peak oil production, we are approaching a major change in the way we must provide energy and other services to the world’s population.

8. Renewable carbon based raw materials are produced in agriculture, silviculture and microbial systems, including managed and unmanaged systems. While estimates are necessarily imprecise, the total amount of new carbon based plant material fixed yearly by terrestrial plants is on the order of $100 \times 10^{12}$ kg (assuming biomass is on average 50% by weight carbon) (Houghton, 1995; Graboski & Bain, 1981). This amount of plant material has an energy content (via heat of combustion) roughly 5 times the energy value of all forms of energy used worldwide and over 10 times the energy content of all petroleum used worldwide (Energy Information Agency, 2002). Although this plant resource is dispersed, has competing uses and, as a solid, is not in an ideal form for easy transporting and processing, the size of the renewable carbon resource and its associated energy content clearly suggest significant potential to provide raw material and energy services.

9. The amount of new plant biomass dwarfs the use of fossil carbon to produce organic chemicals. For example, the United States produces about $100 \times 10^9$ kg of fine, specialty, intermediate and commodity organic chemicals each year, or approximately 0.1% of total world biomass production (Chemical Engineering News, 2002). Less than 10% of this total is produced from renewable carbon (Arntzen & Dale, 2000). The total mass of these organic chemicals is roughly equal to 40% of U.S. production of corn grain, about twice the grain that the United States exports each year. In fact, there is pressure on the U.S. and the E.U. from developing countries to reduce export and other subsidies their agricultural products. As this occurs, more U.S. and European grain may rather quickly find its way into fuel and chemical production. Already about 9 billion kg (3 billion gallons) annually of fuel ethanol are produced primarily from corn in the U.S., consuming about 12% of domestic corn production. However, there is no reasonable expectation that grains will be able to provide the approximately 750 billion kilograms per year of refined petroleum products used in the United States (Statistical Abstract of the United States, 2000). That quantity of renewable carbon must come from crop and forestry residues and energy crops (crops grown specifically to produce energy products)—not from food/feed grains.
10. In addition to existing uses of renewable carbon to produce organic chemicals and fuels, renewable carbon sources provide about 90% of organic materials such as lumber and paper, natural fibers and composites, cellulosics and certain proteins (Arntzen & Dale, 2000). Finally, renewable carbon provides nearly all of our food and animal feed. There is no reasonable alternative to using renewable carbon to meet food/feed demand, although the efficiency with which this demand is met is certainly subject to change and innovation.

11. In total, the organic chemical, fuels (solid, liquid and gaseous), carbon based materials, food and animal feed portions of the U.S. domestic economy exceed USD 2 trillion per year. Similar or greater figures probably apply to the E.C. Much of this economic activity is already based on renewable carbon. The question naturally arises: could the fraction of fuels, chemicals and other industrial products derived from renewable carbon be significantly increased without interfering with other essential uses of plant material?

12. We address this issue in more detail below but here we simply wish to point out two important facts. First, there are several largely unexplored alternatives for coproducing animal feeds and human foods with fuels. Doing so would make the whole enterprise more efficient, and very likely more economically competitive and environmentally sound. Second, both U.S. agriculture and European agriculture are currently constrained by demand, not by ability to produce. Respective national governments have been paying farmers not to produce to capacity for many years. If large new demands for renewable carbon were to arise, there is every reason to believe that much more plant material could be produced on the same or similar acreages.

13. Given the amount of grain available in the U.S. and the E.U. and the ability to supply very pure dextrose in large quantities for around USD 0.20 per kg at corn wet mills, we suggest that material supply, convenience and purity considerations favor dextrose derived from corn (and perhaps other grains) as a feedstock for organic chemical manufacture. The supply of grain dextrose is more than adequate to produce all organic chemicals that conceivably can be made from dextrose.

14. Over the past fifty years, U.S. corn yields have increased from about 40 bushels per acre per year to over 130 bushels per acre, an average increase of about 2% per year. The current U.S. corn crop of about 10 billion bushels per year contains about 180 billion kg of starch. Nature Works LLC (Minnetonka, Minnesota) has recently completed building a plant to produce 140 million kilograms per year of polylactic acid (a plastic) from fermentation of corn starch and has announced plans to build up to four more such plants. If all these plants are built, with the sole exception of fermentation ethanol, lactic acid will be the largest volume fermentation product in the world.

15. However, even this very large plastic product, when produced by all five plants, will only consume the equivalent of about forty percent of one year’s increase in the U.S. corn crop, even assuming that corn yields increase at 1% per year, rather than 2% per year. It should be noted that, in general, as grain yields increase, the yield of the straws and residues associated with grain production also increase and become additional potential raw materials for biobased products. Also, increasing yields tend to increase soil organic matter, all other things being equal. It is obvious that the plant biomass resource base is huge, particularly in comparison with the use of petroleum to produce organic chemicals and materials. The biobased products industry will need to grow very rapidly even to consume the additional dextrose made available from new corn production. A switch from fossil carbon to renewable carbon for organic chemicals will occur as conversion technologies improve, conversion costs decline and various barriers to entry are overcome.

16. Since the U.S. consumes a disproportionate amount of fuels and chemicals compared to the rest of the world, there is reason to hope that other countries can also provide much more of their fuel and
chemical needs from renewable carbon sources. We offer further evidence below that this is the case. The only situation for which biobased feedstock supply adequacy for materials and chemicals does not seem to be the obvious conclusion is the case of massively increased liquid fuel production from renewable carbon. Much of the remainder of this report deals with the paradigm of liquid fuel production from renewable carbon (specifically agricultural crops and crop residues) in mature, integrated processing facilities called “biorefineries”. We emphasise ethanol (since the available information is much greater for ethanol) with some attention paid to biodiesel.

**Economic drivers**

17. Of course, the widely dispersed and renewable nature of biomass feedstocks is of little practical importance unless we can reasonably expect to convert these feedstocks to products that will compete economically with petroleum derived products. Fortunately, this is an entirely reasonable and feasible goal. To support this statement, we note that competitive pressures and continually improving conversion technologies gradually force many high margin new products to eventually become mature, commodity products with narrow margins. This process has occurred with products as diverse as penicillin, nylon and, of course, gasoline (Dale, 1987).

18. Experience shows that approximately 60-70% of the cost to manufacture commodity products depends on the cost of the raw materials from which these commodities are made (Tong, 1978; Wyman, 1999). This is true for petroleum derived commodities in particular, and explains the large swings in gasoline prices as crude oil prices change. We envision a mature biorefining industry producing liquid biofuels to replace gasoline and diesel fuel. In such a mature biorefining industry the cost to manufacture biofuels will also depend very strongly on the raw material cost. The question therefore arises: how does the cost of renewable plant biomass compare with the cost of petroleum?

19. Figure 1 shows the cost of plant biomass relative to cost of petroleum on two different bases: 1) cost per kg of material and 2) cost per unit of energy. Three different horizontal lines are drawn representing different classes of plant biomass available at three different prices. Crop residues are valued at USD 20 per ton (U.S.) in Figure 1, hays and forage crops such as low quality alfalfa are valued at USD 50 per ton and corn grain at USD 120 per 1000 kg is roughly equivalent to current U.S. Corn Belt prices of corn at about USD 2.75 per bushel. Historically, corn grain has been priced at closer to USD 2.00 per bushel in constant dollars, see Figure 2 below.

20. Figures 1 and 2 teach several important lessons. First, corn grain at USD 3 per bushel is roughly equivalent to petroleum at USD 35 per barrel on an energy basis (see arrow #1 on Figure 1). However, on a mass basis corn is less than half the cost of petroleum (see arrow #2)—giving corn starch and other corn components real potential as a feedstock for chemicals production to replace petroleum derived chemicals. Corn wet millers often use net corn cost to reflect the cost of starch available for chemical and fuel production after coproduct credits (e.g. for protein and oil) are subtracted. Typical net corn costs are roughly 70% of the purchased cost of corn, further reducing the actual cost of corn starch for chemical or fuel production. Anecdotal evidence supports this statement. The author recently spoke with the director of bioproducts development for a major U.S. company. He confirmed that all 6 of the bioproducts (not fuels) that this company has under development are economically profitable at petroleum prices of USD 30 per barrel and greater.

21. Ethanol production from corn grain currently requires various financial incentives to be competitive with gasoline from oil. No such incentives are required for chemicals from corn starch. Very large efforts are currently underway to produce chemicals (e.g. lactic acid, 1,3 propanediol, etc) from corn starch in either a wet milling or dry milling context. This is precisely how the petroleum refining industry developed. Additional valuable products such as plastics were added to the refinery over a period of
decades as these products and processes were invented or improved and economics became attractive for those new products.

22. Second, lignocellulosic biomass such as crop residues and herbaceous species (grasses, hays, forage crops) is available at prices that are a fraction (one fifth to one half) of petroleum costs (at USD 35 per barrel) on an energy basis, and even less on a mass basis. (See arrows #3 and #4 on Figure 1). Therefore, given processing technology that economically and efficiently converts the energy content of lignocellulosic biomass to liquid fuels, we can reasonably expect to derive fuel products that are available at prices similar to current gasoline and diesel prices. Sugar fermentation to ethanol is one such process. Over 90% of the energy content of glucose is captured in the ethanol product for high yield fermentations.

23. Feedstock costs are absolutely critical to commodity chemicals and fuels, and biomass feedstocks are already much less expensive than petroleum on both a mass and energy basis. It is impossible to overstate the importance of low cost renewable carbon feedstocks to the eventual commercial success of large scale, integrated biorefineries. Dr. Paul Roessler of Dow Chemical (U.S.) makes this point in a humorous and effective way in his list of ten required biomass feedstock properties, given as Table 1.

24. In line with the historical development of other processing industries, as the biomass processing industry develops and the related technology matures, raw material costs will become dominant in the cost of manufacture. This is very good news for the biobased economy. Biomass raw materials are already less expensive than petroleum and will become increasingly so as the years go by.

Supply of Biomass Raw Materials: Some Perspectives

25. As noted above, renewable carbon feedstock prices are absolutely critical to the economic success of biorefineries. We believe the data on likely biomass prices are encouraging. However, the ultimate possible scale of the industry, and hence its ability to displace petroleum, will also be determined by the amount of biomass available at these prices. We now briefly examine this subject using Table 2 to frame our discussion.

26. Table 2 summarises the world production of crop residues. In all, approximately $1.55 \times 10^{12}$ kg of residue are produced annually, the equivalent of around 600 billion litres of bioethanol at expected ethanol yields for mature technology of about 400 litres per 1000 kg of residue (Wyman, 1999). The figure of 600 billion litres is close to the volume of gasoline and diesel consumed each year in the U.S., a very significant figure indeed.

27. Rice straw must be removed from fields prior to planting the next crop and is likely available at close to collection costs given a demand for the straw. Currently most rice straw is field burned to remove it; a practice that is becoming less and less tolerated everywhere. World wide, over $700 \times 10^6$ kg of rice straw are produced annually, mostly in Asia. Almost $200 \times 10^6$ kg annually of sugar cane bagasse is collected in many locations worldwide. Bagasse is probably available at its fuel cost or below, since it has only limited value to provide energy for the sugar mill. Thus nearly one thousand billion kgs of rice straw and sugar cane bagasse are probably available at nominal costs.

28. Considering other residues, approximately 100 billion kg per year of corn stover and wheat straw in the Corn Belt and Great Plains regions of the United States are likely available at delivered prices of USD 20 per 1000 kg and less (Gallagher, 2003). Similar amounts of residue, mostly wheat straw and barley straw, are available in Europe, probably at comparable costs to those in the United States. At USD 50 per 1000 kg, crop residue availability increases significantly. Approximately 150 billion kg of U.S. crop residues are available at this price compared to 100 billion kg at USD 20 per 1000 kg (Gallagher,
2003). Other countries should also experience increased incentive to collect and utilise crop residues at higher prices.

29. At about USD 50 per 1000 kg, farmers will also begin to produce hays and grasses specifically for biorefineries (United States Dept. of Agriculture Hay Reporter, 2004); and lignocellulosic biomass supplies will expand greatly. The degree to which supplies expand at a price of USD 50 per 1000 kg depends largely on the productivity of crop and pasture lands. The U.S. has nearly 16 million ha in its Conservation Reserve Program (CRP), lands which are removed from grain crop production but which would be very suitable for grass and hay production. In the U.S., pasture lands (including crop land used as pasture) average about 5,600 kg of biomass per ha per year (United States Department of Agriculture Agricultural Statistics, 2003). There is little incentive to increase production on these lands since markets for increased hay production do not exist.

30. However, biomass production for energy would provide increased demand for using these lands efficiently and an increase of several fold in average yield over time seems entirely likely. For example, some lands supporting dairy cattle in Michigan are managed intensively for maximum biomass production, including the use of winter cover crops and corn harvested as silage. Such lands are currently yielding 20,000 kg of dry biomass per ha per year. Double these yields (40,000 kg/ha per year) of other species such as sugarcane and elephantgrass have also been achieved on degraded lands (Stricker, et al, 1993). If all the CRP lands and one half of crop land used as pasture (15 million ha) achieved 20,000 kg per ha, an additional 600 x 10^9 kg of biomass would be produced annually in the U.S.

31. We believe the large scale conversion of cellulosic biomass to fuel will be based first on crop residues, given their low cost and availability. There is more than enough low cost crop residue in the U.S. and elsewhere to begin such an industry. As the industry expands, and processing economics improve with research and experience, the “demand pull” for additional biomass will cause the agricultural research and production sector to learn how to produce much larger amounts of herbaceous biomass profitably at costs approximating USD 50 per 1000 kg on lands that compete only modestly or not at all with food crop production. In addition, biorefineries producing fuels will also produce both protein and energy feeds for animals, just as corn wet and dry mills producing ethanol fuel do today. Coproduction of animal feeds with fuel and chemical products in biorefineries will increase feed supplies and reduce pressure on cropland.

Environmental drivers and some links with economics

32. In addition to these economic drivers, substantial environmental drivers exist for the developing biobased economy. In most cases, environmental forces will probably not be enough by themselves to force adoption the biobased economy. However, when environmental goals align with economic pressures, a more rapid adoption of the biobased economy will result. This coupling of environmental and economic pressures is evident in the many of the specific instances in which biotechnology has already been adopted in energy production, agriculture and industry.

Other driving forces

33. Before concluding this treatment of biomass feedstock costs, we note that the wide geographic availability, abundance and variety of biomass will tend to reduce the risks of raw material supply availability and diminish price swings. Uncertain availability and price volatility are major features of the current petroleum economy. As an essentially fixed world endowment of easily recoverable petroleum is gradually consumed, these risks will only grow and an increasing price paid in terms of national security and stability (Campbell & Laherrere, 1998; Lugar & Woolsey, 1999). Therefore, this economic and energy security issue will only grow in importance. Furthermore, many developed and developing nations which lack petroleum can grow large quantities of plant biomass, and thereby begin to escape the “development
trap” that petroleum dependence brings in an era of decreasing petroleum supplies and high and volatile prices (Lugar & Woolsey, 1999)

**A note on the “food vs. fuel” argument**

34. While grain might be used to produce chemicals and plastics with little or no effect on food supplies, there is not sufficient grain at low enough prices to replace all but a relatively small percentage of liquid transportation fuels. However, there is ample lignocellulosic biomass material (grasses, hays, crop residues, trees, etc) to supply large quantities of liquid transportation fuels if effective, economical conversion technologies can be developed. One of these enabling technologies that has yet to be developed is a low cost, high yield pretreatment to efficiently and economically increase the yield of fermentable sugars from treated lignocellulosic biomass. If such pretreatments are developed, the vast reservoir of sugars in lignocellulose will also become available for animal feeding, thereby relieving considerable pressure on feed/food supplies.

35. In other words, the same factors that limit the digestibility of cellulosic materials for ruminant animals also limit its digestibility toward hydrolytic enzymes. Developing the technology to overcome the recalcitrance of cellulosic biomass toward bioconversion to fuels and chemicals will also open up a much larger reservoir of much less expensive carbohydrates for animal feeding.

36. A second technical requirement of a large scale liquid fuel industry from lignocellulose will be to recover and use all of the components of biomass. One such component is protein. Very large quantities of protein will probably become available for animal and human use if lignocellulosic biomass is converted to liquid transportation fuels (de la Rosa, et al., 1994; Greene, et al., 2004). Since protein and calories (sugar) are the major dietary requirements of humans and animals, it seems unlikely that even liquid fuel production from plant materials will significantly impact food or feed resources. In fact, it appears that food and feed resources might actually increase due to large-scale production of liquid transportation fuels. This could happen because of the “new” calories made available by an effective, economical pretreatment and the “new” protein made available by recovery and utilisation of all of the components of plant biomass, in essence coproducing these feed and fuel products in a biorefinery.

**Time frame considerations-how fast can this happen?**

37. Although this is a difficult area to predict, the author believes that the transition to a biobased economy will actually occur much more rapidly than the many decades long transition that most analysts suggest. The world is growing wealthier and wealthier and the demand for the products that can be produced from biomass continues to increase. The “demand pull” is certainly there. How about the “technology push”?

38. If I am correct, and the renewable carbon feedstock prices are already less than fossil carbon prices in many instances, then improvements in crop processing technology will continue to undercut the fossil conversion routes at an increasing rate as cheap petroleum is exhausted. A “tipping point” will be reached where the advantages of renewable carbon conversion approaches are increasingly obvious. At that point, it will be a matter of capital available to finance the new plants and make the transition. The capital required to finance the transition already exists in the current fuels and chemicals industry in the developed world. And it is precisely the developed world that will have the greatest economic and political incentive to move away from a petroleum-dominated economy.
Environmental design as a new system design objective

Fundamental principles of engineering design

39. At this point in the report, I begin a transition from overview to the use of actual case studies, including many for biobased products, to explain the principles of life cycle analysis and the potential for the biobased economy to achieve both economic and environmental success.

40. Engineering design has traditionally had one major objective: maximising the profit potential of new or existing products and processes. As society has grown wealthier, it has been able to devote increasing attention and resources to environmental quality. The first manifestations of environmental pressures were in the clean up of existing contamination and contaminating processes. More recently emphasis has begun to be placed on designing processes that are cleaner by their nature. So-called “green engineering” and “green chemistry” are manifestations of this new emphasis on environmentally-sound design.

41. Over the past decade or so, life cycle analysis (LCA) has emerged as a method to evaluate the environmental impact of existing or projected products and processes. I believe that LCA will increasingly play a coequal role with traditional economic analysis to predict and then improve the economic and environmental performance of the engineered systems that support humankind. An illustration of this approach will follow a brief description of life cycle analysis.

Life cycle analysis as a new design tool

42. I believe that the environmental performance of the biobased economy is best addressed using the concept of sustainability as an organising framework and life cycle analysis as a powerful analytical methodology (Barthouse, 1997) to quantify sustainability to the extent possible. By such quantification, intelligent and rational design becomes possible. As illustrated below, thoughtful, intelligent design and implementation of integrated agricultural production and biorefining systems can do much more than simply maintain the environmental status quo. Rather, I believe it is possible to effect significant improvements in local, regional and global environmental metrics by using life cycle analysis of integrated crop production and refining systems as a design tool.

43. Life cycle assessments are not really new—early attempts to quantify environmental burdens date back to the 1960s (Sheehan et al, 2003). The field of life cycle analysis now has clearly recognised standards and practices as summarised by the International Standards Organisation (ISO 1997, 1998, 2000) standards (14040-14043) outlined below. For example, setting the goal and scope of a study has become a separate and distinct step in LCA. The scope of the study will define what is studied and how it is studied, including level of accuracy, limitations, etc. Two key definitions are needed to clarify what is to be studied.

44. First, the function to be studied and its related functional unit must be established. Different technologies can be compared only if they perform the same service to society. All resource consumption and environmental flows are then expressed on a normalised basis, for example, per mile of travel delivered. Second, the system boundaries must be set. Although on “Space Ship Earth” the system boundaries are the world, in practice we must draw boundaries around the system we are studying to make our task manageable.

45. The inventory analysis phase is straightforward but time-consuming. In this phase, all of the data needed to describe the environmental flows are gathered and expressed in coherent terms. The impact assessment phase is more difficult. Many of the impacts (e.g. biodiversity, public health, etc.) are controversial and poorly quantified. Since LCA is inherently a quantitative tool, such impacts may not be easily expressed by LCA (or any other method). Finally, the results of the inventory and impact assessment
must be interpreted so that they can provide the guidance needed. The entire LCA process must be transparent and the procedures and data readily verified.

**Allocation procedures and sensitivity analysis in LCA**

46. The allocation procedure in a multi-input/output process is one of the most critical issues in life cycle assessment. The coproduct allocation procedure allows one to partition the environmental burdens associated with a multi-output process to its product and coproducts. Biorefineries will be almost certainly be multi-output systems, so the issue of allocation is a critical one for determining the environmental performance of biobased products. Furthermore, it is critical to understand the sensitivity of LCA results to the data and/or methods employed in the study.

47. I illustrate the importance of allocation procedures in LCA (Kim and Dale, 2002) and sensitivity analyses (Kim and Dale, 2005) by quoting extensively from the papers cited. It is likely that these illustrations will apply to most biobased products and to the biobased economy as a whole, so they are inserted here to explain general principles and provide appropriate context for the whole report. Here is the quotes (in italics below).

**Allocation Procedures**  “According to ISO 14041, “the allocation should be avoided by dividing the unit process to be allocated into two or more subprocesses or expanding the product system to include the additional functions related to coproducts”. Furthermore, ISO 14041 also states “where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships or other relationships between them.” The subdivision approach and the system expansion approach are preferable to other procedures. We describe here a system expansion approach, not fully attempted previously, to estimate environmental burdens in producing fuel ethanol from corn grain (corn ethanol)....

The net energy value allocated to ethanol by output mass is lowest, and the net energy value associated with ethanol done by the system expansion is highest. The choice of allocation approach influences the final results more significantly than any other parameter investigated. Therefore, the allocation procedure is a critical part of determining the environmental burdens associated with producing ethanol from corn grain.” End of quote on allocation.

**Sensitivity Analysis**  “Two factors are considered in this sensitivity analysis: 1) the avoided electricity systems for electricity exported from the corn stover conversion process, and 2) the tailpipe emissions from vehicle operations. The avoided electricity system is assumed to be electricity generated from a coal-fired power plant in the CC50 and the CwC70 cropping systems. It is also possible that electricity generated from a natural gas-fired power plant or from a petroleum oil-fired power plant can be replaced by electricity exported from the corn stover conversion process. The differences between the impacts caused by the choice of the avoided electricity systems are less than 7 %, except for natural resources used, global warming and acidification, even though the environmental impacts of fossil-fuel-fired power plants (e.g. global warming impact, acidification, eutrophication and photochemical smog) are quite different from each other.

No significant differences in non-renewable energy, photochemical smog and eutrophication occur because the fractions of the impacts associated with the avoided electricity system compared to the total impacts are small. Greenhouse gas production from the cropping systems is increased by 10 % (7 %) in both CC50 and CwC70 when a natural gas-fired power plant (a
petroleum oil-fired power plant) is the avoided electricity generation plant. A coal-fired power plant has the highest greenhouse gas emissions among fossil fuel-fired power plants.

Acidification varies significantly with the choice of the avoided electricity systems. The cradle-to-grave acidification rate is increased by 29 % (12 %) in CC50 and 52 % (21 %) in CwC70 when a natural gas-fired power plant (a petroleum oil-fired power plant) is the avoided electricity generation plant.

Thus the environmental outcomes of the avoided electricity systems are very sensitive to the natural resources used (or avoided). Regardless of the avoided electricity system, using ethanol as an E10 fuel can save crude oil and non-renewable energy, and reduce greenhouse gas emissions. The primary contributing processes are the vehicle operations by E10 fuel and gasoline. The upper/lower bound tailpipe emissions are applied to identify the sensitivity of the tailpipe emissions on photochemical smog, acidification and eutrophication. The largest changes occur in the CwC70 cropping system due to the large amount of ethanol produced.

The upper/lower bound tailpipe emissions are changed for photochemical smog by 22 – 42 %, for acidification by 15 – 36 %, and for eutrophication by 9 – 31 %, compared to the results obtained from applying average tailpipe emissions. When the upper bound tailpipe emissions are applied, the CC cropping system offers the best environmental performance in photochemical smog, while the application of the lower bound tailpipe emissions indicates that the best performance in photochemical smog occurs in CwC70. The conclusions on other environmental impacts (i.e. acidification and eutrophication) remain unchanged regardless of the tailpipe emissions.” End of quote on sensitivity analysis.

Some limitations of life cycle analysis

48. Although LCA is a powerful and important tool, it has definite limitations. As illustrated above, choice of allocation method can influence results more than any other parameter, and conclusions may also change when a sensitivity analysis is performed. Obviously, an LCA study cannot rise above the quality of the data on which it is based. Old, irrelevant or poor data will produce an LCA report that is also poor or irrelevant. Also, LCA is a quantitative method and is poorly suited to resolving disputes that are essentially philosophical or ethical in their content, including arguments about social equity. Finally, even when various environmental impacts are expressed quantitatively, LCA offers no guidance in weighting the different impacts or comparing their relative importance. As we will see below, integrated crop production and processing systems may achieve great reductions in non-renewable energy use and carbon dioxide production, but may in fact increase eutrophication and acidification compared to petroleum-derived products. LCA cannot resolve by itself whether reductions in petroleum use are more or less important than the potential for increased eutrophication.

Systems design for environmental & economic performance: an illustration

49. I conclude this section by illustrating what I believe will become an important paradigm: the simultaneous economic and environmental design of biobased product systems. Kim and Dale (2004) considered the case of coproduction of ethanol and PHA (a bioplastic) from corn and corn stover. Essentially all biobased products and biofuels will be produced as coproducts in biorefineries so this illustration can potentially apply to all biobased products. Here is the relevant section of this reference in italics below.

“The question arises therefore: if ethanol and PHA are produced together from the same unit of arable land, what fraction of biomass would be utilised to produce ethanol in the more
sustainable practice. To quantify the term “sustainable practice”, an eco-efficiency is used as defined below.

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In this equation, the environmental impact ratio is defined as the ratio of the environmental impacts from the operating processes (e.g. corn production, wet milling, PHA fermentation and recovery process, etc.) to the environmental credits from the avoided product systems (the products replaced in the economy by the biobased products). This term reflects how much environmental impact per environmental credit occurs in the product system. If the ratio is one, the impact and credits are equal. If less than one, the credits exceed the impacts. The economic value added is defined as a ratio of the market value of biobased products (i.e. ethanol and PHA) and coproducts (e.g. CGM, electricity, etc.) to the cost of raw materials and fuel (e.g. corn grain, corn stover, coal, crude oil, natural gas, etc.) used in process operations. Thus a practice with a greater eco-efficiency would be more sustainable as defined here.

Since the eco-efficiency is dimensionless, it is possible to add the eco-efficiency of each impact category if all the impact categories are appropriately weighted. However, the weighting factors applied to each impact category vary significantly between decision-makers. Therefore, the eco-efficiency of each category is presented here instead of weighted results. ... In estimating the eco-efficiency, it is assumed that PHA replaces five types of petroleum based polymers (HDPE, LDPE, PC, PP, PS) by equal mass fractions.

As seen in Table 3 in this paper (not included here), the fraction of biomass utilised for ethanol production varies with the impact categories. For example, the maximum eco-efficiency with respect to global warming in the CwC70 cropping system occurs when 100% of corn grain and no corn stover are utilised for producing ethanol. For crude oil use and non-renewable energy, the maximum eco-efficiency occurs when both corn grain and corn stover are utilised for PHA production.”

Thus it seems entirely feasible to consider using LCA as a tool along with classic economic analysis to simultaneously improve the economic and environmental performance of the biobased economy, including coupled farming systems and crop processing systems. We now consider integrated crop production and processing systems in more detail, including the tools available for modeling these systems.

Integrated Crop Production and Processing Systems

A model of integrated biorefining systems

50. Because biomass feedstocks are solids and tend to be bulky, there is considerable economic incentive to refine them close to where they are grown. Likewise the waste streams from biorefineries will tend to be high in organic material and therefore biological oxygen demand. But these biorefinery wastes will not be particularly toxic. Many of these waste streams are therefore suitable candidates for returning to agricultural land. Given the capital and operating costs associated with waste handling in the biorefinery, there is a strong economic incentive to land apply these wastes. I believe there are also sound environmental reasons for doing so.
51. Furthermore, agriculture is by nature a regional or local activity because of differences in soil and climate. Therefore crops grown for biorefineries can be or will be adapted to local conditions. The relatively smaller scale of biorefineries (compared to petroleum refineries) also enhances the likelihood that the farmers who produce the crops will have some sort of formal or informal “ownership” of the biorefinery. This pattern of local ownership of the biorefinery, or at least participation in ownership, is observed in many corn dry mills in the U.S. However, corn wet mills are much larger than dry mills (the largest wet mills approach the mass throughput rate of petroleum refineries) and are not farmer owned. Local ownership of the biorefinery will give farmers an additional incentive to utilise animal feeds, mineral fertilisers and organic waste streams from the biorefinery. We call this framework the “All Biomass is Local” paradigm. The paradigm is illustrated in Figure 4.

A Brief Explanation of the Model: Industrial Ecology

52. We envision farmers using locally appropriate agricultural systems growing biomass specifically for the biorefinery or providing their crop residues for processing. In the biorefinery, biomass is separated into its major components. Some of these components (e.g. protein and minerals or “ash”) may be salable or usable without further upgrading. The ash is returned as fertiliser to the land. Protein is fed to animals, preferably in a nearby location to avoid costs of drying and transportation. Animal wastes and organic waste streams from the biorefinery are used in the agricultural system. The nature of these waste streams makes them particularly appropriate for land application to perennial grass systems, where the potential for runoff and leaching to groundwater is minimised. This overall approach utilises the principles of industrial ecology in which outputs from one part of the system serve as inputs to other parts and the overall system is highly integrated.

Why this Choice of Model?

53. Therefore, the convergence of these factors: a) local ownership/participation in biorefineries, b) the widespread geographical distribution of these refineries, c) the fact that biorefineries will be intimately involved with land use practices and, d) society’s continuing concern with the environment, virtually guarantee that biorefineries will be conceived, designed, built and operated with an unprecedented emphasis on their local and global environmental impacts. Petroleum refineries largely avoided environmental/social issues when that industry was in its infancy, but now are being forced to do so at great cost. Biorefineries that do not adequately address appropriate environmental and social issues will be at considerable risk of failure.

54. The model forces system level thinking about the biorefinery and cropping systems that supply it, including appropriate feedback loops between the major systems, thereby facilitating integrated modeling and sound decision making. The “carrying capacity” concept can be directly integrated into the model, given application rates for wastes and fertilisers as well as the productive capacity of the land to supply the biorefinery. Furthermore, appropriate siting of a biorefinery is facilitated by this type of integrated thinking.

Modeling biorefining system performance: inputs and outputs

The crop production system

55. Agricultural processes play a crucial role in the environmental performance of fuels, chemicals, and materials (“biobased products”) produced from agricultural raw materials, i.e. in the biobased economy. Thus more sustainable farm management will result in better environmental performance of these biobased products. However, farm management practices must be considered in conjunction with the overall system performance, not as an isolated event.
56. Farm management practices are probably best delineated using four crops as models. Corn, soybeans and alfalfa are major agricultural products in the United States and other countries, with nearly 200 million total acres grown including all three crops in the United States. Switchgrass is a perennial grass that formed a major portion of the native North American tall grass prairie. While not a major commercial crop at this time, switchgrass is nonetheless grown as a forage crop and is a model crop for large scale biomass energy production.

57. Thus these four crops (corn, soybeans, alfalfa and switchgrass) well represent the range of production practices and inputs for crops produced in North America and much of Europe today that might serve as feedstocks for bio-based products. They represent 1) an annual grain row crop (corn) that produces large amounts of residue (corn stover), 2) an annual leguminous oilseed row crop (soybeans), 3) a widely grown perennial legume field crop (alfalfa) and 4) a potential new perennial non-leguminous field crop (switchgrass). In fact, corn and soybeans are already used to produce industrial products including fuels, materials and lubricants. Agricultural production inputs include both natural and human inputs. These are seeds, agrochemicals, fuels, machinery, labor, climate (soil and rainfall) and farm management practices including tillage, fertilisation rates, etc.

The crop processing system

58. The crop processing or “biorefining” technologies for corn and soybeans are relatively well established, although improvements continue to occur in biorefining procedures (Shapouri et al. 2002). Alfalfa and switchgrass (and corn stover) are lignocellulosic materials for which biorefining technologies are not well established (Wyman 1999). For corn and soybeans, the grain and seed, respectively, are the harvested, transported and biorefined portions of the plant. However, for alfalfa and switchgrass the entire above ground portion of the plant is assumed to be harvested (using similar equipment), transported and biorefined.

59. In the biorefinery, crops are processed into a wide variety of industrial products (Arntzen & Dale, 2000). Figure 5 outlines how various crops might be processed to a smaller number of intermediate compounds in the biorefinery (carbohydrates, proteins, oils, etc.) and then these intermediate compounds might be upgraded by further processing to a wide variety of industrial products. Inputs within the biorefinery include fuels, electricity, other chemicals, machinery, labor and new technologies or management practices.

60. The biorefining system inputs and the subsequent use of these bio-based products generate their own sets of environmental impacts. Therefore, evaluating the environmental aspects of bio-based products should consider all of the phases of bio-based products: agricultural production, biorefining and product use as an integrated whole employing life cycle assessment according to strict international standards to identify the likely environmental impacts of producing and using bio-based products. While a detailed discussion of modeling is outside the scope of this paper, we provide a brief introduction here to give the appropriate context.

Modeling Environmental Impacts of the Integrated System

The Crop Production System

61. Several agricultural ecosystem models are available. For example, dynamics of soil organic carbon and related nitrogen containing species are simulated by the DAYCENT model, which is the daily time step version of the CENTURY model (Parton et al., 1996; Del Grosso et al., 2000, 2001). In the CENTURY model, conversion of carbon from dead plant material to soil organic carbon depends on the lignin concentration and C:N ratio of the material, abiotic temperature/soil water decomposition factors,
and physical properties of soil. Dead plant material with low C:N ratio and low lignin content goes to the
active soil organic carbon pool with turnover rates of 0.5 to 1 year. Dead plant residues with high C:N ratio
and high lignin contents flow into the slow soil organic carbon pool, which has intermediate turnover rates
(10 to 50 years). Products of soil organic carbon decomposition that are resistant to further breakdown
make up the passive soil organic carbon pool (turnover rates of 1000 to 5000 years). The decomposition of
both plant residues and soil organic carbon results from microbial activities with an associated loss of CO2
as a result of microbial respiration. The potential decomposition rate depends on soil moisture, soil
temperature, cultivation practices, and lignin contents. To illustrate the detail available through
CENTURY, an outline of the carbon cycle in a plant/microbe/soil system is given below.

62. The CENTURY model also quantitatively describes the soil nitrogen cycle. N₂O is released from
soil through two microbial activities - nitrification and denitrification. Nitrification is an aerobic pathway.
The net result of complete nitrification is oxidation of NH₄⁺ to NO₃⁻, but NO₃ and N₂O are both produced
as intermediates and/or byproducts. Denitrification is an anaerobic pathway in which NO₃⁻ is reduced to
N₂. NO₃ and N₂O are also produced via the denitrification pathway. Nitrous oxide emissions from
agricultural soils depend on the concentrations of the various forms of mineral nitrogen (NH₄⁺ to NO₃⁻),
soil water content, soil temperature, soil texture and labile carbon availability. Thus, the emission rate of
nitrous oxide and other nitrogen species varies with location and climate.

63. In contrast to the potential detail and location specific information provided by CENTURY,
Wang assumed that 1.5 % of the nitrogen in the nitrogen fertiliser for corn is converted into N₂O gas
(Wang et al., 1999). The US Environmental Protection Agency (USEPA, 2001) also published a method for
estimating N₂O emissions from soil that includes emissions from: 1) the nitrogen fertiliser used, 2) the
decomposition of crop residues and 3) nitrogen fixed by nitrogen-fixing crops. However, estimates
generated by both the Wang and EPA methods do not account for local differences such as soil properties
and climate.

64. The CENTURY model can simulate ecological disturbances and management practices such as
fire, grazing, cultivation, and organic matter or fertiliser addition. Required input parameters in both
models include climate information (temperature and precipitation), and site-specific soil properties (soil
texture, soil organic content, soil moisture content, and soil mineral content). In the United States, climate
information is obtained from the National Oceanic & Atmospheric Administration and site-specific soil
textures are available from the US Department of Agriculture. These soil and climate data are available on
a county-by-county basis, hence our choice of specific counties in each state.

65. Thus powerful, proven, quantitative tools for modeling at least some of the environmental
impacts of agriculture already exist. These tools take into account local climate and soil differences, as
well as differences in agricultural management approaches. Therefore I believe these tools should be used
in preference to approaches that do not provide such power or specificity regarding local conditions.

The Crop Processing System

66. In the biorefining system, the best information for LCA will of course be that generated by the
actual manufacturer in real operating plants. Some such actual process data may be available for LCA, but
competitive pressures will often preclude the use of process specific information. Fortunately, in the past
few decades, the chemical process industries have been greatly benefited by the development of process
simulation software such as ASPEN™ and CHEMCAD™. These software tools calculate energy and mass
flows within chemical processing systems, and already have emissions information built into them. In the
absence of process specific information, models based on these simulation tools may prove useful.
67. In addition, commercial databases such as DEAM™ (and the associated software called TEAM™) have been developed to account for the inputs and outputs of both products and processes, including agricultural and industrial systems. Such databases and software continue to develop given the demand for LCA and related analyses.

The Product Use System: Displacing Petroproducts

68. Both the crop production and the biorefinery systems will generate emissions or use raw materials that produce environmental impacts. Modeling tools such as the U.S. EPA’s TRACI model will help translate these emissions and raw material consumption information into actual environmental impacts. TRACI is an exceedingly important tool, developed for the U.S. system, and merits an extended description here.

69. TRACI, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts, characterises potential environmental effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human particulate effects, human carcinogenic effects, human non-carcinogenic effects, fossil fuel depletion, and land use effects. The human health cancer and non-cancer categories were heavily based on the assumptions made for the U.S. EPA Risk Assessment Guidance for Superfund and the U.S. EPA's Exposure Factors Handbook. For categories such as acidification and smog formation detailed US empirical models, such as those developed by the US National Acid Precipitation Assessment Program and the California Air Resources Board, allowed the inclusion of the more sophisticated location specific approaches and location specific characterisation factors. Methodologies were developed specifically for the US using input parameters consistent with US locations for the following impact categories - acidification, smog formation, eutrophication, land use, human cancer, human non-cancer, and human criteria effects. TRACI is currently downloadable at the following web site: http://www.epa.gov/ORD/NRMRL/std/sab/iam_traci.htm.

70. In all such cases, the environmental impacts of the integrated biobased economy must be compared with the environmental impacts of the petroleum economy to provide meaningful results. In other words, it is not enough to know that biobased products have environmental impacts. What matters is how the environmental impacts of the biobased products relate to the petroproducts that these biobased products are displacing.

71. Given this brief description of the integrated system, at least four crucial LCA-related issues arise here. First, how much (mass) of biobased product will be required to displace an equivalent mass of the petroproduct? The environmental impacts of both classes of products will be calculated per unit mass of the product. Thus it will be essential to know how much of one product is equivalent to the other product when used in its intended function. Such information is critical to meaningful comparisons but may in fact be very difficult to obtain.

72. Second, biorefinery processes are generally not mature, while the petroleum based processes have been under development for over a century and are generally mature. Thus biorefinery processes will generally be improving their technical and thus environmental performance over time, while future improvements will be much more difficult for petroproducts. It may be possible to account for expected improvements in biobased products using sensitivity analysis of the biorefinery (and indeed of the whole system), but this will necessarily be a somewhat speculative effort and inherently controversial.

73. Third, how will biobased products perform in the expected application and its associated end of life considerations? Such information may be available for petroproducts but is probably not available for biobased products. For example, biobased products may be burned, landfilled or composted at end of life. The environmental effects of each disposal pathway are different and probably unknown.
Finally, we return to the allocation issue. Biobased products, like petroproducts, will be produced in multiproduct systems. Allocating the environmental burdens fairly and rationally among all the products, while focusing LCA on the performance just one product, will be a very challenging exercise. (For the specific case of biorefineries versus petroleum refineries, it might be considered appropriate to allocate to a whole class of compounds, e.g. the biobased products, rather than to specific products.) In any event, allocation is likely to have a greater effect on the imputed environmental performance of biobased products than almost anything else. The system expansion approach is preferred but requires more data than is usually available.

I conclude this section by an illustrative example. This example, taken from our own work on environmental performance of biobased plastics, illustrates many of the issues mentioned above such as allocation, mass equivalency of petroproducts and biobased products, relative maturity of petroproducts and biobased products, local differences in agricultural performance, end of life considerations, etc. Quotations of the relevant portions of one of our papers (Kim and Dale, 2004) follow in italics below.

“We chose 1 kg of PHA resin as the functional unit. The system boundary includes corn production, dextrose production (corn wet milling), PHA fermentation and upstream processes (e.g. fertilisers, agrochemicals, fuels, electricity, etc.). Thus, the analysis has been done from cradle to gate. Management of PHA wastes is not included in the system boundary because the fate of waste PHA is not clear at this point. Most processes are assumed to occur in the United States. The corn production sites are specified and occur in 14 counties in the Corn Belt states of the United States – Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin. The primary factors governing selection of corn production sites are as follows: 1) the local region could supply a local crop producing facility, 2) regions are quite different agronomically and 3) even within a state, agronomic characteristics can be different. Corn wet milling and PHA fermentation are assumed to occur at the same location.

Data for corn production, including agronomic inputs and fuel used, are available from the United States Department of Agriculture. The distance for transportation of corn grain to a wet milling operation is assumed to be the same as the distance corn grain travels in the ethanol from corn grain production system. Process information on the corn wet milling process was obtained from Cargill Dow LLC. Metabolix Inc. (Cambridge, Massachusetts, USA) provided the energy consumption and yield of PHA in the PHA fermentation process (including fermentation and recovery) and specified various technologies as current and near future technologies. The near future technology is an improved process that is achievable over a 2-3 year time horizon, extrapolating from current laboratory results. Along with Metabolix’s operating data on the PHA fermentation process, literature data for the PHA fermentation were also used to identify technology trends in the PHA fermentation process.

The electrical power grid for the foreground systems (e.g. corn production, wet milling and PHA fermentation) is estimated from ECAR (East Central Area Reliability Coordination Agreement), MAIN (Mid-America Interconnected Network), and MAPP (Mid-Continent Area Power Pool), which cover these seven states. The US national power grid in 1998 is used in estimating the environmental burdens associated with the background systems (e.g. fertilisers, agrochemicals, fuels, etc.).

The corn wet milling process is a multi-output process, in which dextrose, corn oil, corn gluten meal (CGM) and corn gluten feed (CGF) are produced together. The allocation is done by introducing avoided environmental burdens of alternative products for the wet mill coproducts – this is called the ‘system expansion approach’. The alternative product for corn oil is soybean oil produced in soybean milling, in which soybean meal is also produced. The environmental
burdens of soybean oil are also estimated from the system expansion approach. The alternative products for CGM and CGF, which are used as animal feeds, are corn grain and nitrogen in urea, with their appropriate replacement factors. For example, the function of one kg of CGF is equivalent to the functions of one kg of corn and of 15 g of nitrogen in urea.

The greenhouse gases (GHG) evaluated include carbon dioxide, methane and nitrous oxide (N2O). The GHG evaluation also includes carbon sequestration due to increasing (or decreasing) soil organic carbon and N2O releases from soil during cultivation. Carbon content in PHA is not credited (i.e. sequestered) in the GHG emissions analysis because the carbon content in PHA is assumed to be released at the end of the product life.

Soil organic carbon dynamics and N2O emissions from soil during the cultivation are estimated by the DAYCENT model. This model can also simulate disturbances and management practices such as fire, grazing, cultivation, and organic matter or fertilizer addition. Required input parameters for the model include climate information (temperature and precipitation), and site-specific soil properties (soil texture, soil organic content, soil moisture content, and soil mineral content). Climate information is obtained from the National Oceanic & Atmospheric Administration. Site-specific soil textures are available from the US Department of Agriculture. Since other site-specific soil properties (organic carbon, soil nitrogen level, moisture, and mineral contents) are not available, the model is run for 1860 years with default values given by the model to generate the initial site-specific soil properties and to equilibrate the modeling run.

In the initialisation used here, native grass is assumed to be cultured up to 1860 years to reach a steady state (the ‘spin up’ process), and then the modified crop history of western Iowa given by Kristen is followed from 1860 to 1994. The modified crop history of western Iowa is applied here because no information is available on the crop history of each county under consideration. Effects of the crop history on the final results, particularly on greenhouse gas emissions, are scrutinised in a sensitivity analysis. After completing the model spin-up process (initialisation) and the previous cropping system, continuous corn culture under no-tillage practice is simulated.

Two counties in each state were selected to estimate soil organic carbon changes and N2O emissions from soil. Counties were chosen because they produced significant amounts of corn and because of the availability of other data such as soil textures and weather information. The corn production of the two selected counties in each states ranges from 4 – 12 % of the total corn production of that state. Corn is assumed to be continuously cultured under no-tillage condition for 40 years to estimate carbon taken up by soil and N2O emissions from soil. The climate conditions (e.g. daily temperature and precipitation) are based on weather data from 1997 to 2000. Results from the DAYCENT model show that carbon sequestration rates range from 377 to 681 kg C/ha/year under no-tillage practice, as presented in Figure 7, consistent with the rates given by other studies: 300 – 600 kg C/ha/year in the US Great Plains.

Fluxes of N2O from soil during corn culture range from 0.5 to 2.8 kg N/ha/year under no-tillage practice. ratio of the flux of N2O to the application rate of nitrogen fertiliser is from 0.4 up to 1.7 %, showing that the flux of N2O depends on local situations – e.g. application rates of nitrogen fertiliser, soil textures, soil nitrogen content, climate conditions, etc. The environmental burdens of PHA are presented as average values over 14 counties weighted by their corn production.

To summarise this section, proper understanding of the sustainability of the biobased economy requires careful and detailed LCA studies over the entire integrated system of crop production, processing
and use. Unfortunately, the system is exceedingly complex on many levels, as illustrated by this in depth examination of only one portion—the agricultural part of the system. Thus performing quality LCA studies has been and will be extremely difficult. As this report now transitions into analysis of existing LCA studies on the biobased economy, and how the biobased economy might be affected by biotechnology, these limitations of LCA analysis, including our own analyses, must be kept firmly in mind.

**Biotechnology and Integrated Crop Production and Processing Systems**

*Introduction to biotechnology: the old and the new*

77. We define biotechnology here as the use of biological materials (plants, microbes, enzymes, etc), and non-biological technologies (thermal, chemical and physical processes, etc) to transform carbon dioxide and other renewable carbon sources and into products that meet human needs for food, feed, fuels, chemicals, materials and a clean, healthful environment. Classical plant breeding and microbial strain selection are thus included in this definition as are more modern approaches using molecular tools to manipulate life at the most basic level, the gene. In principle, with molecular biology, specific genetic capabilities can be transferred from one organism to another, thereby vastly increasing the potential of biotechnology to meet human needs.

*Some practical limitations of biotechnology*

78. Although biotechnology, including molecular biology, has great potential to meet human needs, it has both practical and theoretical limitations. In practice, biotechnology may be limited in specific applications because of economic considerations (alternative low cost raw materials, competing process technologies, barriers to entry, etc.), social constraints including societal limitations on genetic manipulation, intended and unintended policy barriers and simply by lack of adequate information to apply the technology.

79. “Theoretical” constraints include, among others, the laws of thermodynamics. No technology, including biotechnology can violate the laws of conservation of matter and energy. It will never be possible for biotechnology to transform sand into gasoline or to change the total amount of carbon on earth. It will never be possible for biotechnology to transform one energy carrier into another energy carrier without the loss of some useable energy to waste heat (the second law of thermodynamics). This point is illustrated in the net energy discussion below.

*Potential impacts of biotechnology on the integrated system: an overview*

*Choice of products*

80. Potentially biotechnology can produce any compound containing carbon in any living system (plant, animal or microbial) or non living processing system, including such systems using enzymes and cells as catalysts. Since all foods and feeds, all organic chemicals, many materials, and most fuels contain carbon, this potential gives biotechnology enormous reach in its ability to satisfy human needs. Biotechnology has other potential advantages, including great potential for less polluting, more sustainable processes and processing, that will be discussed below.

*Engineering the crop: yield, composition and processing*

81. Although petroleum feedstocks vary somewhat in composition, their compositional variety is much less than for biomass feedstocks. Biomass compositional variety is both an advantage and disadvantage. Biomass feedstocks consist of grains, crop residues, oilseeds, sugar crops, forage crops and a wide variety of woody crops. Figure 9 provides typical compositions of some of these biomass feedstocks.
The major components of biomass include carbohydrates (cellulose and hemicellulose for crop residues, forage crops and woody crops—called lignocellulosic materials, starch for grains and primarily sucrose for sugar crops), lipids (fats, waxes and oils), proteins of many types, aromatics (primarily lignin) and ash (non-carbon minerals such as calcium, phosphorus, potassium, etc.).

82. Biotechnology can increase the content of desired components in the plant raw material (e.g. of valuable enzymes or other proteins), or decrease the content of other components. For example, biotechnology can be used to decrease the lignin content of plants, thus allowing easier conversion of lignocellulosic materials to fermentable sugars and hence to fuels and chemicals. The petroleum industry has no such ability to manipulate its raw material to make it easier to process or to contain more valuable components. This is a huge potential advantage of the biobased economy over the petroleum economy. Given all the entrenched advantages of the petroleum economy, I believe that the advantages of the biobased economy should be exploited whenever possible.

Agricultural system performance: inputs and outputs

83. Likewise, biotechnology offers real potential to improve the economic and environmental performance of the agricultural systems for biobased products. Plants can be bred or engineered for: a) drought or pest resistance, b) increased yield of total biomass (rather than just seeds or sucrose content, for example), c) efficiency of nitrogen uptake, d) heat or cold stress and e) many additional desirable traits with significant economic and environmental advantages. For large scale fuels and chemicals from lignocellulosic biomass two particular desired traits of the plant/agricultural system stand out. These are high yields and reduced lignin content. High yields will help reduce the final biobased product costs and also the amount of land needed to satisfy our requirements. Reduced lignin content will probably do more than anything else to increase the efficiency and reduce the costs of cellulosic biorefineries.

Some Perspectives on Biorefineries

84. As noted above, biomass is inherently more different in composition and raw materials than petroleum. An advantage of biomass compositional variety is that biorefineries can make more classes of products than can petroleum refineries, thus providing additional economic stability and opportunities for new product development. Biorefineries can also use a wider range of raw materials than can petroleum refineries. Among the products that might be produced from biomass are liquid transportation fuels (including both gasoline and diesel substitutes), electricity and steam, a tremendous variety of chemicals containing carbon, oxygen, hydrogen and nitrogen and combinations of these elements, monomers and polymers, lubricants, adhesives, fertilisers and, significantly, animal feeds and human foods. Some of these products are summarised in Figure 5 (presented above) in their life cycle context as possible replacements for petroleum based or petroleum dependent products.

85. A disadvantage of biorefineries compared to petroleum refineries is that a relatively larger range of processing technologies is needed, not all of which are currently cost competitive with petroleum refineries. Traditionally, feedstock variation has been a difficult issue for the processing industries to overcome. Biorefineries, particularly cellulosic biorefineries, will have to deal with this problem as they will probably be required to handle different feedstocks harvested at different times with somewhat variable properties.

86. It is important to note in Figure 5 that biorefineries will probably operate by first preprocessing (separating and reacting) the inlet raw materials to a relatively small range of intermediate products including carbohydrates, protein, syngas (mixtures of carbon monoxide, hydrogen and carbon dioxide) and a few other products. At this stage, the processing can become much more uniform and less susceptible to feedstock variation. These intermediate products will then be upgraded by further reaction and separation
steps to a very wide variety of final products. Some of these reaction and separation steps are well
developed, others remain to be developed. However, once these and other processing technologies are
developed and deployed, they will find use for a much wider variety and much more geographically
dispersed set of renewable raw materials than is the case for petroleum.

87. In particular, the processing technologies to convert lignocellulosic materials economically and in
high yield to carbohydrates and other products are not yet fully available. Effective and economical
lignocellulose conversion may be the single most important technological development enabling the
ultimate size of the biobased economy.

88. Prototype biorefineries already exist, including corn wet and dry mills, pulp and paper mills and
other renewable carbon based processing facilities. Corn wet mills perhaps best exemplify many of
the features that are likely to be found in mature biorefineries for large scale fuel production. Wet mills are
large, highly integrated facilities producing a wide range of chemical, biochemical, feed, food, and fuel
products. Over 90% of the inlet corn leaves as value added products (selling price per kg greater than corn
feedstock). Corn wet mills have continued to add products with time, particularly higher value
chemical/biochemical products. Like petroleum refineries, wet mills alter their product mix to meet
changing market conditions, including seasonal variations in demand.

**Impacts in the biorefinery: effects on capital & operating costs**

89. The following discussion is critical to enable the reader to understand the associated
interpretation of how biotechnology can improve the environmental and economic performance of
biobased products. The key technical parameters within the biorefinery which will tend to dominate its
environmental and economic performance include yield, product concentration and reaction rate. Please
recall that most refining systems for upgrading raw materials (whether based on renewable feedstocks or
fossil feedstocks) operate in linked reaction/separation systems. Raw materials are chemically converted to
increase their value, but the reactions are seldom complete, and separation of the reaction products must be
performed to increase the purity of the product(s) to required levels and to recover and recycle unreacted
raw materials.

90. Of these three factors (yield, concentration and reaction rate), yield (kg of salable products per kg
of purchased raw materials) is usually by far the dominant factor governing the economics of a given
reaction/separation system to produce commercial products. Since essentially all chemical and biological
reactions produce multiple products, the yield of salable products influences the economics (and
environmental performance) of the system in the following ways.

91. **Raw material cost increases per unit of product as yield declines.** For example, at USD 0.10 per
pound of glucose and 90% yield of lactic acid produced by fermentation of this glucose, the glucose raw
material cost is USD 0.11 per pound of lactic acid. At 50% yield, the raw material cost is USD 0.20 per
pound of lactic acid. Since the cost to manufacture commodity fuels and chemicals depends strongly on
raw material costs, a lower yield significantly increases the cost of manufacture. Lower yield also means
that the environmental impacts of biobased products in the agricultural and biorefinery systems must be
allocated to a smaller mass of products, thereby significantly diminishing the environmental performance
per unit mass of products.

92. **Cost of the reaction system increases.** If a fixed total annual production rate is required, then at
50% yield almost twice the total reactor volume is needed compared to 90% yield to provide that amount
of product. As the reaction system size is increased per kg of product, the associated operating expenses
(heating and cooling of vessels, pumping and mixing costs) will likewise increase as will their associated
environmental impacts.
93. **Cost of the separation system increases even more rapidly than the reaction system.** The cost of separation is proportional to volume of fluid handled. Under similar reaction conditions, a lower yield means lower concentration of product and therefore a greater volume of reaction fluid must be handled for a given production rate. The cost of separation also increases with the number of components needing separation. Decreasing yield usually means there are more components that must be separated. All of these factors also tend to increase the use of energy and other chemicals in the separation system, thereby negatively impacting the environmental performance.

94. **Cost of waste treatment increases.** Either markets for byproducts must be found, which is not always possible, or the resulting waste streams must be treated prior to disposal, adding both capital and operating expense of the overall system as well as increasing the environmental burdens.

95. **Given the dominance of yield in process economics for commodities,** a number of conclusions regarding biorefinery development for fuels and commodity chemicals arise. First, fuel production in biorefineries will tend to be performed first in existing facilities where the yield of products can be improved by adding fuel production and where substantial capital investment has already been made, reducing the risk to innovators. Second, given the mild conditions (moderate pH and temperature) of biological catalysts, bioprocessing and biotechnology will tend to be used in biorefineries instead of harsh chemical or thermal processing to avoid degradation (and thereby the loss of value) of sugars, proteins and other labile biomolecules. Third, there will be continuing pressure to utilise all of the components of the biomass feedstock at their highest possible value. Thus the number of products will increase over time as will the yield of salable products per unit of raw material(s) consumed. This is precisely the trend that has occurred historically in the petroleum refining industry.

**Product diversification: Using the whole barrel of biomass**

96. **The importance of finding valuable uses for all biomass components is illustrated by the following example based on the composition outlined in Figure 9.** Assume a corn stover based biorefinery producing 378 million litres per year of fuel ethanol at a yield of 420 litres of ethanol per 1000 kg of stover. At a 50% removal rate for stover, about 200,000 ha of corn will be required to provide the stover. Such a biorefinery will also produce nearly 21 x 106 kg of minerals (Ca, K, Mg and P), 20 x 106 kg of lipids, fats and waxes, 52 x 106 kg of protein (the equivalent of the protein produced from nearly 70,000 ha of soybeans), electricity from burning the lignin residue and probably residual sugars for animal feeding. These conclusions arise directly from the chemical nature of the components of biomass and the realities of chemical and biological processing outlined above. A biorefinery will be in many businesses (fuels, chemicals, power, feeds, etc) simultaneously. This fact cannot be evaded, but must be faced and dealt with, hopefully to the benefit of the overall biorefining system.

97. **One significant potential benefit that arises from this analysis is that the net requirement for agricultural land to provide feed protein decreases by 70,000 ha, or about 1/3 of the land from which stover is harvested.** Put another way, 3 ha of corn production are now able to replace 1 ha of soybean production, while still providing all the grain these corn acres produced before as well as 900 x 106 kg of stover for liquid fuel production. If herbaceous biomass species such as switchgrass are grown for energy production, they will likely be higher yielding and will also contain significantly more protein than corn stover. Thus such crops should provide even greater net savings of crop land required to meet protein needs. For example, if switchgrass or another herbaceous species such as coastal bermudagrass is produced at dry matter yields of 20,000 kg/ha per year (about 9 tons/acre-yr) and contains 10% protein of which 80% is recovered (Greene, *et al.* 2004), the system will produce 1,600 kg/ha of protein, over twice the amount of protein produced per ha of soybeans. Since the United States currently devotes about 30 million ha to soybean production, this emphasis on using the whole barrel of biomass could lead to substantial coproduction of energy and protein, but without devoting any new acreage to energy crop production. This
is one of the reasons I do not believe that the choice is between food and fuel—the biobased economy will integrate food and fuel production to the benefit of both.

98. As described in above, if the various components of biomass are not used in salable products, they must be disposed of at a cost. If they are not used in products, they must also be carried along with all of the other streams in the process, adding to the capital and operating costs of all the related processing equipment. Likewise, if these components are not used in products, then the remaining products must bear a larger portion of the overall costs, particularly the crucial feedstock costs. All of these factors diminish the economic and environmental performance of biobased products.

99. Thus many forces converge on a single objective: utilising the entire “barrel of biomass”. The overall result of this convergence is quite simple: there is strong and unrelenting pressure to increase the yield and value of the multiple products of biomass and not to waste even a fraction of the raw materials. Because of this driving force, continuous process improvement, both revolutionary and incremental, is a key feature of both oil refineries and biorefineries. Each improvement in the refining processes will tend to enhance both economic and environmental performance, as outlined above.

A Few Case Studies to Illustrate and Explain Principles

The “net energy” of ethanol from corn grain- a cautionary example of perverted LCA analysis

100. Dr. David Pimentel of Cornell University (and his coworkers) has published information for the last 25 years to the effect that ethanol from corn grain (and more recently ethanol from cellulose and biodiesel from rapeseed) has a negative energy balance (Pimentel, 1991; Pimentel, 2005). By “negative net energy” Professor Pimentel apparently means (although a clear definition of net energy is seldom offered) that ethanol takes more fossil energy (coal, natural gas and petroleum) to produce than the lower heating value (LHV) of the ethanol itself. In other words, producing ethanol is an energy losing proposition, since ethanol has a -29% net energy according to Dr. Pimentel. Dr. Pimentel’s analyses have received a good deal of media attention in the U.S. and even in Europe his work is often cited as an argument against biofuels.

101. Even though Pimentel occasionally claims to be doing life cycle analysis, his papers never meet the tests imposed by ISO 14040-14043. His system boundaries are never drawn clearly, functional units are not defined, sources of data are often obscure or anecdotal and allocations are either done improperly or not at all. For example, Professor Pimentel allocates only the heating value of distillers grains (a high protein animal feed byproduct of ethanol manufacture) to this byproduct. The ISO standard is system expansion allocation. Even a simple mass allocation would be preferable to presuming, as Professor Pimentel does, that the proper function of a protein rich animal feed is to be burned instead of eaten. The effect of different allocation approaches on the ethanol net energy is illustrated in Figure 10. Obviously, allocation profoundly affects the net energy value assigned to ethanol.

102. However, even worse is the fact that Pimentel’s analysis rests on a faulty premise. The net energy argument proceeds by assuming that a BTU of coal is equal to a BTU of electricity is equal to a BTU of crude oil and so on. Nothing could be more mistaken. We pay up to 30 times as much for a BTU of electricity as we do for a BTU of coal from which that electricity was generated. Clearly, all BTU are not created equal. Further, Professor Pimentel never compares ethanol with existing fuels such as gasoline or electricity, so that the uninformed reader is led to infer than “negative net energy” is a bad thing and that good fuels have positive net energy. Comparisons are central to LCA, but he never performs any comparisons at all. In fact, using Pimentel’s own definitions of net energy, gasoline has a net energy of about -39%, worse than ethanol’s -29% net energy, and electricity has a terrible net energy of -235%.
Following Professor Pimentel’s logic, we should immediately shut down all refineries and power plants because they have negative net energy.

103. The “net energy” argument offers a powerful example of the ability of LCA, done poorly, to mislead society. I offer it here as a cautionary tale. We rely heavily on LCA to tell us whether biobased products are preferable to those derived from fossil carbon. However, if our premises are mistaken or our methods or data are inadequate, our LCA studies will not be reliable nor will the conclusions based on such studies. Those of us involved in LCA and who wish to see the biobased economy emerge have a great responsibility to be certain our premises are sound and our methods and data adequate to the task. All consumers of LCA and related literature should critically question premises, methods and data used to arrive at the conclusions presented—and should not hesitate to loudly state when these conclusions are not justified. The ISO standards for LCA provide a firm basis for such critical questions.

104. Given all this background and illustrations, I believe we are now in a position to evaluate the existing LCA studies on biobased products and to offer some preliminary conclusions about the potential of biotechnology to improve the environmental performance of biobased products.

Review of the LCA and related literature on biobased products

Comprehensive studies

105. Most LCA studies on biobased products to date have estimated one or at most two environmental or related impacts. The few exceptions will be summarised first; then single impact studies will be treated.

106. Kadam (2000) “Environmental Life Cycle Implications of Using Bagasse-Derived Ethanol as a Gasoline Additive in Mumbai” This excellent study was prepared according to strict LCA standards and compared the life cycle impacts of converting sugar cane bagasse (a crop residue) to ethanol compared with burning it (the current practice). Lower net values for the ethanol scenario were observed for carbon monoxide, hydrocarbons (except methane), SOx and NOx, particulates, carbon dioxide and fossil energy consumption. Six impact assessment categories were lower for the ethanol scenario compared to the burning scenario including greenhouse potential, depletion of natural resources, air acidification potential, eutrophication potential, human toxicity potential, and air odor potential.

107. Kadam et al (1999) “Environmental Life Cycle Implications of Fuel Oxygenate Production from California Biomass” This likewise excellent report compared biomass (rice straw, forest residue and chapparal) burning in California versus conversion of the biomass to ethanol. Ethanol use as ETBE was also compared with the petroleum derived fuel oxygenate MTBE. Eutrophication potential, depletion of natural resources, greenhouse gas potential, and air acidification potential were all reduced for the ETBE scenario compared to the MTBE scenario, in spite of the fact that nitrates in water run off were higher for the ETBE scenario. The acid-based process for ethanol production generated lower amounts of criteria pollutants compared to the enzyme-based process, but both ethanol production approaches were superior to MTBE.

108. Fu, et al (2005) “Preliminary Conclusions from Environmental Life Cycle Assessment Studies of Bioproducts-Literature Review” This rigorous meta-study was intended to reach preliminary conclusions about the environmental performance of Canadian bioproducts (biofuels, biobased materials and industrial chemicals from biomass) based on existing literature. As the authors note, no studies were found that met all their criteria perfectly. Among the preliminary conclusions were that non-renewable energy demand and greenhouse gases are reduced for biofuels and bio-based materials. Less certain trends included generally reduced potential for photochemical smog but increased potential for eutrophication and acidification. Nothing definitive could be stated about other impact categories including toxic emissions,
land-use/biodiversity, water consumption, etc. No positive or negative trends were identified for industrial chemicals, perhaps due to the small number of studies available. Two significant conclusions of the report were that waste biomass has better performance compared to dedicated crops and that existence of co-products increases the apparent benefits of individual bioproducts. This report highlighted the importance (and general lack of) “ideal” studies, *i.e.* studies designed to answer specific questions for a specific set of conditions. This observation parallels our “all biomass is local” model.

109. **Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline-Overview U.S. Dept. of Energy (1994)** This older document summarised then available studies and found that the biomass to ethanol fuel cycle generated many times more liquid fuels than did the production of reformulated gasoline (RFG). Five times more fuel energy were delivered to the transportation system per unit of fossil energy consumed for ethanol from cellulosic biomass than for reformulated gasoline. Net carbon dioxide emissions were 90% less for ethanol than for RFG and net sulfur dioxide emissions were 70% less.

110. **Total Fuel Cycle Emissions Analysis of Biomass-Ethanol Transportation Fuel (1994)** It appears that this paper contains the underlying data on which the Department of Energy overview (above) was based. The paper concludes that increased use of E95 is a promising option for reducing total carbon dioxide emissions from the transportation sector because E95 fuel cycles generate less than 10% of the carbon dioxide emissions produced by reformulated gasoline fuel cycles. When emissions from electricity generation are included in the fuel cycle analysis, E95 fuels also produce significantly less NOx, sulfur dioxide, and particulate emissions. Ethanol fuels extend our fossil fuel resources in the transportation sector.

111. **Life Cycle Assessment of Various Cropping Systems Utilised for Producing Biofuels: Bioethanol and Biodiesel (2005)** This recent paper considers a variety of cropping systems for biofuel production and evaluates their per hectare effects on non-renewable energy consumption, global warming impact, acidification and eutrophication. Corn stover removal provided lower nitrogen related environmental burdens from the soil, higher ethanol production per hectare, and energy recovery from the lignin-rich fermentation residues. The disadvantages of corn stover removal are a lower accumulation rate of soil organic carbon and higher fuel consumption for stover harvesting. Planting cover crops also permits more stover to be harvested and increases soil organic matter while reducing erosion. All cropping systems investigated reduce non-renewable energy consumption overall and global warming impact. However, unless additional measures such as planting cover crops were taken, utilisation of biomass for biofuels would also tend to increase acidification and eutrophication.

112. **Environmental Performance of Agricultural Systems for Ethanol from Corn and Switchgrass (2005 in preparation)** This paper by Kim and Dale is being prepared for publication in the International Journal of Life Cycle Assessment and is included here for completeness. The study estimates the environmental performance of land used to produce bioethanol. Ethanol is produced via corn wet milling and by cellulose conversion using the ammonia fiber explosion (AFEX) pretreatment process prior to enzymatic hydrolysis, including protein, electricity and steam as coproducts. Avoided systems were used for system expansion allocation of the coproduct environmental burdens. Three systems are compared: 1) corn with only grain harvested, 2) grain and corn stover harvested and 3) switchgrass. The impact categories of interest are fossil resource used, non-renewable energy, climate change, acidification, eutrophication and smog formation. A specific farming location (Fulton County, Illinois) was chosen to provide site specific agricultural data. Ethanol was used as E10 fuel. Switchgrass cultivation provides better environmental performance than corn cultivation for all impact categories considered. NOx emissions from the biorefinery (from burning lignin-rich residues) are identified as worthy of attention to improve system environmental performance as is eutrophication and acidification from nitrogen released during agricultural operations.
Single Impact Studies

113. **Global Warming** Essentially all credible studies conclude that biobased fuels (most studies were done on ethanol) will reduce net carbon dioxide generation (GCSI; Dillon Consulting; Lave, *et al*; Macedo, *et al*; and Sheehan, *et al*). However, some studies recognize that the agricultural production portion of the biobased fuels cycle may generate considerable amounts of nitrous oxide, a potent greenhouse gas, and that this compound, rather than carbon dioxide, may in fact dominate overall greenhouse gas production. According to the work of Kim and Dale, the generation of nitrous oxide is highly dependent on soil, climate and agricultural management techniques, i.e. on local conditions. Therefore broad generalisations about the role of nitrous oxide on global warming/greenhouse gas effects are probably inappropriate. However, there is ample evidence to conclude that greenhouse gases (via nitrous oxide) may increase overall while carbon dioxide levels decrease due to biobased products. Much more attention needs to be paid to the role of nitrogen containing species on the environmental impacts of biobased products and bioenergy.

114. **Energy efficiency/petroleum displacement** Ethanol from crop residues or energy crops will displace 3 to 7 times as much fossil energy as the fossil energy required to drive a mile on gasoline [BIO, “New Biotechnology Tools…”]. Focusing on petroleum use alone, every mile fueled by ethanol requires only 5% of the crude oil that would have been consumed for a mile fueled by conventional gasoline (Sheehan, *et al*, 2002), effectively extending petroleum supplies by a factor of 20. Petroleum displacement is a much more appropriate measure of energy efficiency for liquid biofuels such as ethanol and biodiesel than is the “net energy” measure applied by Pimentel and coworkers.

115. **Nitrogen containing compounds and their effects** Comparatively few studies concern themselves with the role of nitrogen-containing compounds in the environmental performance of biobased products; exceptions include (GCSI, 2001; Sheehan, *et al*, 2002; and Powers, 2005). As explained previously, nitrogen containing compounds are interconverted by chemical and biological agents and, during this process, may escape the root zone as nitrous oxide, NOx and nitrates. These compounds will negatively affect greenhouse gas profiles and the eutrophication and acidification potential of biobased products. Nitrous oxide is by far the largest contributor to greenhouse gases generated in the crop production portion of the biobased economy (Kim and Dale, in preparation 2005). Unfortunately, nitrogen cycle related environmental impacts of biobased products have received comparatively little attention.

116. **Land use constraints/concerns, including food vs. fuel** Biodiversity is affected negatively by nitrogen-containing runoff from agricultural land (GCSI, 2001). At current crop yields, supplying a large fraction of biofuels from biomass may be difficult simply because there will not be enough biomass available, at least at current and projected levels of fuel consumption (GCSI, 2001; Fulton, 2005). Potential crop yields from dedicated biomass energy crops (while using sustainable agricultural practices) is perhaps the key question underlying the ultimate possible scale of the biobased economy. It is also a question that has received comparatively little research attention.

117. A related crucial question is the net effect on soils of growing biofuels crops or harvesting crop residues for biofuels. The biobased economy cannot be sustainable if soil health is thereby undermined. Some biofuel crops, such as grasses, may improve soils, protect sensitive lands and provide improved animal habitats. However, few studies have addressed the effects of cropping practices, residue removal, fertilisation rates, etc. on the primary indicator of soil health—soil organic matter. The work of Kim and Dale, discussed more fully below, does begin to address this question with some interesting initial results.

118. An interesting study done to ISO standards (van den Broek, *et al*, 2002) compared one hectare of land used to grow willow to displace coal-based electricity with that same hectare used to produce organic food. This study therefore explicitly assumes land as a limited resource. The willow system scored best on
acidification, climate change and energy carrier depletion, while the organic food system was better on
terrestrial eco-toxicity. Thus when climate change, acidification and energy carrier depletion are the major
drivers, environmental policy should focus not on less intensive ("organic") agriculture but rather dedicate
more land to energy crops.

119. **Other potentially negative effects of a biobased economy** Other cautions expressed or potentially
negative effects of a biobased economy include emissions of hydrocarbons and toxic compounds such as
aldehydes from ethanol combustion (Fulton, 2005). The GCSI report (2001) provides perhaps the most
complete summary of these cautions which include, in the biomass production phase, potentially negative
effects on wildlife and biodiversity, use of genetically modified organisms, continuation of highly
intensified forms of agricultural production, nutrient removal and the potential for soil depletion and
increased application of pesticides and herbicides. Potentially negative impacts at the biorefinery stage
include (GCSI, 2001; Contemporary Information, 2005; Dillon Consulting, 2005) air emissions
(particulate matter, VOCs, NOx, SOx, methane, carbon dioxide, odors and hydrogen sulfide) and water
emissions including high water use, large concentrations of suspended and colloidal solids as well as solid
wastes (digester solids and spent organisms). Most of these issues are simply raised as concerns since little
hard data is available to support them. Also, it is likely that proper management can adequately deal with
these concerns.

**Drilling down for more understanding—the work of Kim and Dale**

120. In order to provide additional illustration about the power of a detailed, mechanistic approach to
the agricultural system (integrated with biorefinery operations) to provide valuable insights, we quote
extensively (in italics below) and provide tables and figures from two recent papers by Kim and Dale
[refs].

Bruce E. Dale “The Biobased Economy of the 21st Century” (2005) Chapter 1.2 in
“Biorefineries: Biobased Industrial Processes and Products” Ed. B. Kamm, P. Gruber and M.
agricultural ecosystems has been an active area of research for over thirty year. Researchers
have studied a variety of biological and nonbiological processes connected with plant growth.
These processes occur in the soil, on the surface and above the surface of the ground.
Researchers have estimated the rates of these processes based on local factors such as
temperature, soil type, rainfall, plant genetic potential and the existing pools of carbon such as
microbial carbon, standing dead plant carbon, etc. Tillage and harvesting practices have also
been taken into account as have other human inputs such as fertilisers and irrigation. As a result
of such work, flexible, powerful agricultural ecosystem models such as the CENTURY model
have been developed, as described previously in this report.

Similar agricultural ecosystem models have been developed for nitrogen-containing species and
are being developed for phosphorus-containing compounds. When these ecosystem models are
combined with models of the biorefinery processes, they can be used to evaluate and then
improve the sustainability of integrated biorefining systems. This approach is illustrated below.

The model system chosen for illustration is an integrated biorefining system based on corn grain,
soybeans and corn stover, the cellulosic residue remaining after corn grain is harvested. A
second harvesting trip through the field is required to cut, bale and remove the corn stover. Fuel
ethanol is assumed to be produced from the corn grain by wet milling and additional ethanol
from corn stover by acid hydrolysis and fermentation. Residual fermentation solids are burned to
produce electricity and steam. Steam is used in the plant and excess electricity is exported to the
grid. Soybean oil is converted to biodiesel. To satisfy soil erosion prevention guidelines, a
minimum of 1,070 kg of corn stover are left behind per ha. None of the soybean stover is removed. Several different agricultural scenarios are investigated to determine the effect of cropping system management on environmental performance. The cropping system assumptions for sustainability analysis are summarised below in Table 3. The acronyms given each scenario in Table 3 are used in subsequent figures to identify simulation results.

In all, six different cropping scenarios are modeled and analyzed. Since “all biomass is local”, a particular location (Washington County, Illinois) was selected for analysis. Climate and soil data as well as cropping practices are available for this location. The agricultural base case is the conventional midwestern U.S. corn-soybean rotation with only corn grain and soybean harvested, using plow till for corn and no till cultivation for soybeans. (CPSN in Table 3). For all other scenarios both corn and soybeans are grown under no till cultivation practices, in which soil is left undisturbed from harvest to planting. A second scenario is the continuous cultivation of corn (CC), again with only corn grain harvested. A third scenario includes the harvest and removal of 56% of the corn stover as well as all the grain under continuous corn cultivation (CC 56%). A fourth scenario is the rotation of corn with soybeans and the removal of 54% of the corn stover, plus all the corn grain and soybeans (CS 54%).

The use of cover crops is explored in the two final scenarios. In some areas it is common to plant another crop such as wheat or oats in the late fall after the corn is harvested. These young plants grow a few centimeters, survive over the winter and then resume growth in the spring once conditions permit. Cover crops can be harvested, killed with herbicide or plowed under to increase soil organic matter. In this analysis the cover crop is not harvested by rather is killed with herbicide and the corn or soybean planted among the dead cover crop.

Cover crops help eliminate wind and water erosion and are also effective in removing excess nitrogen fertilizer left behind in the previous cropping cycle. This excess nitrogen is vulnerable to conversion by various processes to soluble nitrogen species that leach through soil and are transported to streams, lakes, rivers and the ocean. This excess nitrogen can also be converted by anaerobic soil bacteria to nitrous oxide. The fifth scenario therefore considers continuous corn with 70% removal of stover plus winter wheat or oats as a cover crop (CwCo 70%). The sixth and last scenario assumes a corn-soybean rotation from which 70% of the corn stover is harvested and winter cover crops are grown (CwSo 70%).

Soil organic carbon levels were predicted over time using the six scenarios modeled. Depending on conditions chosen, either static or increasing soil organic carbon levels are possible as shown in Figure 11, as long as cultivation is no till. The use of winter cover crops permits very substantial removal of corn stover for industrial uses while still enhancing soil quality over time.

The total amount of protein, lipids, lignin and carbohydrate (including starch, cellulose and hemicellulose) produced by each of the cropping systems above was estimated over a 40 year period. Based on data from biorefinery operations and crop production databases, greenhouse gases were also calculated in kg of carbon dioxide equivalents per kg of each of these species produced. Figure 12 shows the greenhouse gas production per kg of carbohydrate for each of the six scenarios.

Once again, a significant effect of the cropping system chosen on the results is observed. The results range from a net production of 560 grams of CO2 per kg of carbohydrate for conventional corn-soybean rotation to -9 grams (net carbon sequestration) per kg of carbohydrate for continuous corn cultivation under no till conditions with winter wheat and 70% stover removal.
A similar life cycle approach is taken to estimate the greenhouse gas reduction when ethanol produced using the biorefinery systems outlined above is consumed in a mid-sized passenger vehicle. Figure 13 summarises these results. All of the cropping systems give a net greenhouse gas reduction, but substantial differences are observed between cropping systems. Aggressive corn stover removal when coupled with winter cover crops can give over 70% reduction in greenhouse gas formation compared with a gasoline fueled vehicle. But as Figure 11 shows, soil health can continue to improve even when large amounts of stover are removed.

Finally, even more dramatic reductions in leached nitrogen (inorganic nitrogen species escaping the root zone of plants) are possible by judicious choice of cropping systems and agricultural system management. Using the nitrogen flow submodel of the CENTURY model to predict the effects of different agricultural practices, it seems possible to reduce inorganic nitrogen losses by more than ten fold using conventional corn production as the base case. These results are summarised in Figure 14 below. The results are for a 40 year time period in which these practices are used in a specific geographic location--Washington County, Illinois.

As anticipated, the use of winter cover crops greatly reduces nitrogen leaching. It is also interesting to note that stover removal appears to reduce nitrogen leaching—compare CC with CC (56%). One mechanistic explanation of these results is that the nitrogen content of the corn stover (approx. 1% by weight) is not available for conversion to soluble inorganic nitrogen species when the stover is removed, thereby reducing leaching. Also the carbohydrates in harvested stover are not then available to provide metabolic energy for microbial processes that convert organic nitrogen into inorganic nitrogen.

Therefore, while stover removal must be carefully managed to maintain soil fertility, stover removal has some powerful environmental benefits. These benefits include providing renewable carbon for biorefining to fuels and chemicals as well as reduced inorganic nitrogen leaching. Based on these and other results, I believe that a combination of creative system design, careful planning and use of powerful ecosystem and biorefinery modeling tools can help us achieve very significant environmental improvements as we develop the biobased economy of the 21st century. We need not be content with maintaining the environmental status quo or even with modest improvements. Instead, very significant improvements are possible if we are both wise and informed.” End of quote.

To conclude this section on what we have learned from in depth LCA studies of the biobased economy, I likewise quote extensively from another of our recent papers.

Life Cycle Assessment of Biopolymers Derived from No-Tilled Corn. S. Kim and B. Dale. International Journal of Life Cycle Assessment (2005) “Biopolymers are generally considered as environmentally friendly materials in terms of biodegradability and use of renewable resources. A primary market driving force for biopolymers is the perceived scarcity of fossil resources, especially petroleum. Most conventional polymers currently available are made from crude oil. Plant materials have been recognised as a renewable alternative resource to replace fossil resources. For example, ethanol derived from corn grain is a widely used transportation fuel with the potential to save large amounts of petroleum–derived fuels). Polylactide (NatureWorksTM PLA) polymers derived from corn grain produced by Cargill Dow LLC (Minnetonka, Minnesota, USA) are commercially available to make products ranging from packaging materials to apparel.

Previous studies have attempted to scrutinise the non-renewable energy consumption and greenhouse gas profile of biopolymers. Gerngross estimated the fossil fuel equivalent (FFE) for
producing PHA from corn and compared it with polystyrene (PS) from petroleum, concluding that the FFE of PHA was slightly larger than that of PS. He also concluded that using fermentation–derived PHA would not appear to be a sustainable approach. Kurdikar et al. (2001) pointed out that corn stover–based PHA resin produced using fossil fuel sources had no greenhouse gas advantage over polyethylene (PE) resin. Kurdikar et al. also found that using biomass energy from corn stover in the PHA system, instead of non-renewable energy, would result in a better greenhouse gas profile for PHA resin than for PE resin.

Recently Akiyama et al. performed a life cycle inventory analysis of PHAs derived from soybean and from corn grain, concluding that PHAs are more favorable than petroleum based polymers in terms of energy use and greenhouse gas emissions. These authors credited the carbon content in PHA in the greenhouse gas emission analysis. Cargill Dow LLC also carried out an LCA study on their product (NatureWorksTM PLA), indicating that the PLA production system consumes 22 – 55 % less non-renewable energy than petroleum based polymers. The greenhouse gas emissions associated with the PLA production system are less than or comparable to those of petroleum based polymers. If wind power replaces grid electricity used in a biorefinery, or bioenergy from corn stover is used in generating steam for a biorefinery, PLA has much better environmental performance than petroleum derived polymers in terms of fossil fuel energy and greenhouse gas emissions.

Thus, the studies of Gerngross and Akiyama et al. arrive at completely different conclusions. The main reasons for these differences are the allocation approach in corn wet milling process, PHA yield during fermentation, and the operational data in the PHA fermentation and recovery process. Gerngross and Akiyama allocated the environmental burdens of wet milling to dextrose and its coproducts on a mass basis. Gerngross failed to allocate the environmental burdens associated with the input (corn grain) to dextrose and its coproducts. These burdens should be allocated in a consistent way. Failing to assign the burdens associated with corn production to dextrose may lead to inconsistent results. Akiyama did not include soil carbon and nitrogen dynamics in the agricultural ecosystem. Agricultural ecosystem effects could play an important role in analyzing greenhouse gas emissions from corn production.

PHA is more favorable than petroleum based polymers in terms of non-renewable energy consumption and crude oil use, indicating that crude oil would be saved when PHA replaces petroleum based polymers. GHG emissions associated with PHA production are higher than those of some petroleum based polymers (e.g. HDPE, LDPE, PP, etc.) under the current PHA production technologies considered. However, PHA production technologies are improving and GHG emissions are being reduced. This is the same pattern found in the development of other products, including petroleum-derived products when these were immature.

The PHA fermentation process, which is energy intensive, is the primary contributing sub-process to non-renewable energy consumption. Most crude oil used in the PHA production system is consumed in corn production (64 – 69 %) because of fuels used in field operations. The primary contributing sub-process to the GHG emissions of PHA is the PHA fermentation process, contributing 84 – 91 % of the total. The electricity consumption in the PHA fermentation process is the major GHG emission source. The fraction of electricity generated from a coal–fired power plant in the seven subject states in the United States is over 63 % of total electricity production.

The effects of tillage practices on the GHG profile of PHA are significant. Results show that converting from plowing tillage practice to no–tillage practice in corn production could increase the rate of carbon sequestration, resulting in reducing GHG emissions associated with PHA by
23 – 38% when corn grain under no–tillage practice is used as a raw material for PHA. Thus, no–tillage practice would improve some environmental aspects of PHA as well as soil quality even though more herbicides are used in no–tillage practice. More sustainable cropping systems (e.g. establishing winter cover crops, including perennial legumes in crop rotations, etc.) could also significantly improve the environmental aspects of biobased.

Although removing corn stover is somewhat less favorable in terms of soil organic matter improvement, utilising corn stover as a raw material for PHA production in an integrated system could significantly decrease GHG emissions and non-renewable energy consumption in the PHA production system. An integrated system, in which corn stover is harvested and used as raw material for PHA along with corn grain, could produce PHA that releases much less GHG emissions than petroleum based polymers. The integrated system could increase the PHA production efficiency per unit of arable land by 32 – 42%, including 0.7 ton of PHA derived from corn stover, compared to the utilisation of corn grain only. Figure 16 summarises this information by comparing global warming effects of different PHA production assumptions with that of petrochemical polystyrene as the PHA technology has matured over time. Figure 16 also compares greenhouse gases if PHA is produced from corn grain (the reference system) only or if it is produced in the integrated system described above.

The reduction of GHG emissions by burning lignin–rich fermentation residues is much higher than the increase of GHG emissions resulting from decreasing the accumulation rate of SOC due to removal of corn stover. However, the utilisation of corn stover gives rise to a trade–off between local concerns and regional (or global) concerns. Soil quality is probably a more important local issue, while crude oil use and GHG emissions associated with the PHA production system are probably more important regional/global issues.

Comparing current Metabolix PHA fermentation technologies to their projected near future technology, GHG emissions and non-renewable energy consumption of PHA are reduced by 29% and by 28%, respectively. These improvements are achieved by increasing PHA yield by 23% and reducing energy requirements (electricity and steam) by about 30%. This trend indicates that PHA fermentation technology, an energy intensive process, is still immature and has considerable room for further improvements, leading toward better PHA environmental performance. Studies such as the present one may help PHA manufacturers improve the overall environmental performance of their products by focusing on the most sensitive parts of the system, for example; increasing energy efficiency (or PHA yield) in the PHA fermentation process, asking farmers to use more sustainable practices, and working toward an integrated (corn stover utilising) system.”

How biotechnology can alter/improve the performance of a Biobased economy: A summary and vision for the future

Reprising the integrated model

121. As described above, it will be critical to examine the performance of the entire system, rather than selected portions of it, so that our conclusions, and the policies based on these conclusions, are correct. Most studies of the biobased products to date have not taken an integrated, whole system approach. Admittedly, this is a difficult task, but it is also a necessary one. Most studies also do not have sufficient information to determine whether the biobased process they are comparing with a petroprocess is mature, or whether significant process improvements are likely (see the PHA case above). Technological immaturity is a fact of life for most biobased products and LCA studies need to take this into account.
Using LCA to identify the critical issues/areas

122. As illustrated above, whole system studies using the best tools and done according to strict ISO standards can illuminate those portions of the overall system which have the greatest impact on environmental performance. Some of these results may be surprising. The great importance of nitrous oxide in greenhouse gas formation and the high degree of regional variation in agricultural system behavior were unexpected results. These high impact portions of the system then become the focus of attention for both technological and management approaches to improve their performance.

Comparing/contrasting technological versus management approaches to improving system performance

123. Both technology (development of new tools) and management (application of existing tools), will be important in improving bioeconomy performance. And these approaches can support each other. In the examples developed above, management of the agricultural production phase, including such options as no-tillage, can substantially reduce greenhouse gas generation, as can the use of cover crops. Technological advances, for example in efficiency of nitrogen uptake or water use in these cover crops, can further enhance their potential to provide economic and environmental benefits in the overall system.

How can biotechnology (and other technologies) help the biobased economy?

What biotechnology has already accomplished: a brief summary

124. In many, if not all, applications for which it has been tested, biotechnology has already proven itself environmentally as well as economically superior to existing processes. These applications include industries as diverse as pharmaceuticals, fine chemicals, bulk chemicals, food and feed, textiles, pulp and paper, minerals and energy production in eight different developed countries (OECD, 2001).

125. Some common underlying threads in these substitutions of biotechnology for existing processes or approaches have emerged. Biotechnology is in general less expensive and environmentally superior to existing systems because: biotechnology for molecular transformations can be more specific than chemical or physical transformations, thereby

- Increasing desired product yields (the key process parameter).
- Reducing the temperature and pressure required by non-biological catalysts to perform adequately.
- Reducing waste treatment costs.
- Enabling the substitution of less expensive renewable carbon sources for other raw materials.

126. It is crucial to note that essentially every economic reason for substituting biotechnology is accompanied by a corresponding environmental reason for the substitution. Increasing product yields in particular is crucial for the economic success of commodity products, and I have previously listed the many linkages between increasing product yields and simultaneously improving environmental performance.

127. Thus there is ample reason, based on both underlying fundamental principles and industrial experience, to believe that what is true for individual products or processes will be true for whole collections of processes and products. That is, if biotechnology has been shown to be an economic and environmental success in these specific applications cited above, that biotechnology will also be an even
greater economic and environmental success when it is applied across an entire economy, that is, in the biobased economy.

**Biotechnology in the biobased economy- a sector by sector sketch**

128. **Product selection** Biotechnology gives us the ability to produce both entirely new products as well as existing products in new ways. Using molecular biology and other emerging technologies, entirely new classes of proteins, lipids and carbohydrates can in principle be produced. Furthermore, desired products can be produced directly within plants or microbes, giving us additional flexibility in our overall system design. Non biotechnology approaches (e.g. nanotechnology) has very limited capacity to deliver such results.

129. **Crop production** Biotechnology can alter the composition of the plant raw material, increasing its content of desired components and/or diminishing its content of less desirable components. Specifically, biotechnology can make the crop raw materials easier to process in the biorefinery. This is an enormous advantage not enjoyed by the petroleum based economy. Biotechnology can also improve the other desirable plant properties including total yields, enhance salt, temperature and drought resistance, improve the efficiency of nitrogen uptake, insect resistance, etc…all properties with environmental as well as economic benefits. Plants do exist, and can also be developed or improved to better fix atmospheric nitrogen. Commercially fixed nitrogen is a very large, and arguably unsustainable, input of fossil energy into modern agriculture. Finally, crops can be bred or engineered to efficiently use waste streams, including waste streams recycled from the biorefinery.

130. While many of these benefits can be obtained by traditional plant breeding, the new tools of molecular biology allow such benefits to be obtained more certainly, with greater speed and at lower cost. I fully recognise that use of genetically modified organisms is controversial, particularly in Europe. However, any barriers placed in the way of the biobased economy will slow its progress and reduce the associated benefits, both economic and environmental. Societies and individuals must have a clear picture of both risk and rewards if they are to make rational decisions. The rewards of the biobased economy seem to be insufficiently appreciated, and its real risks, particularly those connected with genetically modified organisms, exaggerated beyond recognition.

131. **Biorefinery operations** Within the biorefinery, biotechnology will find its greatest applications in developing biocatalysts, both micro-organisms and enzymes. These improved biocatalysts will generate higher yields of desired products, lower production of undesired compounds, at higher concentrations and higher rates than available by chemical catalysis alone. (However, the integration of chemical and biochemical catalysis will certainly be an important feature of biorefineries.) Furthermore, these biocatalysts will be directed toward desirable transformations of abundant, renewable carbon resources.

132. **Use of biotechnology in waste treatment** Biotechnology has always played a central role in waste treatment, particularly for organic waste streams. However, it appears that the potential of biotechnology to contribute to waste treatment in the biobased economy has scarcely been tapped. For example, anaerobic digestion has long been used to treat mixed organic wastes, but more with the objective of waste disposal than of energy production or efficient resource utilisation. Biotechnology ought to be fully exploited within the biorefinery to produce energy products and/or recapture carbon for reuse in the biorefinery.

133. **Product end of life considerations** Finally, biotechnology can contribute to the ultimate fate of biobased products. For example, composting approaches can be used to ensure environmentally sound ultimate disposal and perhaps recapture some value from biobased materials at the end of their life. Stability of the biobased product might possibly be designed into the molecule to provide sequestered
carbon for greenhouse gas mitigation. The ultimate biological end product, carbon dioxide, can of course be recaptured as plant biomass, thereby completing the cycle and generating a new round of useful products, wealth and environmental benefits.

What can we reasonably expect of the biobased economy?

Economic performance

134. In principle, biomass can supply every function now provided by fossil sources of carbon, including chemicals, fuels and materials. In addition, biomass can provide foods and feeds that cannot be provided by fossil carbon. In the aggregate, these industries providing fuels/chemicals/organic materials from fossil carbon are worth in the U.S. and the E.U. several trillions of dollars annually. Biomass is already less expensive than petroleum per unit of energy or mass. Therefore it is entirely reasonable to believe that we can eventually replace most or all fossil carbon based services with services based on renewable carbon. To do so, we must learn how to efficiently convert renewable carbon into products that provide the services now provided by fossil carbon. And we must do so in ways that tend to enhance the natural environment. This is also an entirely reasonable goal.

Environmental performance

135. The environmental performance of the biobased economy will improve over time as we learn better technology and apply better management approaches, as illustrated above. LCA is a critical part of this process. LCA will help us benchmark the environmental performance of existing and potential biobased products, and then guide our choices as we strive to improve these processes and products. But we must be careful to rigorously apply LCA according to established standards if it is to have its desired effect. We must also be demanding of ourselves and use the latest data and best tools to model and describe the biobased economy and its subsystems.

136. An entirely reasonable objective is to provide services based on biomass that a) enhance the fertility of soil over time, and b) achieve order of magnitude improvements in environmental metrics compared with current fossil carbon based sources of these same services. I strongly believe these are feasible goals and that we should commit ourselves to achieve them as the biobased economy grows over the next few decades.

Some suggested policies to achieve these objectives

137. I realise that suggested policies are not really part of my job description in this report. However, I am going to take the opportunity to at least outline a few key policy measures that, from my perhaps limited perspective, OECD might take to hasten the adoption of the biobased economy and ensure its economic and environmental success. These suggestions and their underlying rationale are as follows:

- Support research aimed at large increases in the amount of biomass produced per hectare of land under environmentally sound conditions. Yield increases are fundamental to improving biorefinery economics. High yields will simultaneously reduce the amount of land needed to supply the biobased economy while meeting other human needs and providing animal habitat. High yields, particularly of grasses and perennials, will tend to increase soil carbon over time—the key criterion of agricultural sector sustainability within the biobased economy. Interesting opportunities exist to simultaneously increase yield while improving environmental performance, e.g. by planting winter cover crops to reduce nitrogen losses and increase soil organic matter.
• Support research aimed at improving the yields (kg of value added products/kg of raw materials consumed) of biobased products within the biorefinery. Yield is also the dominant economic and environmental factor within the biorefinery. For biorefineries based on lignocellulosic biomass, achieving this objective of increased yields means learning to overcome the recalcitrance of biomass.

• Increase the attention paid to nitrogen-containing species in environmental performance of biobased products.

• Support or independently perform your own LCA studies according to strict ISO standards to establish feasible pathways toward the biobased economy. These pathways will outline environmentally sound methods of developing this economy so that industries involved in the biobased economy can intelligently choose among their development options.

Summary

138. Huge and growing societal demands exist for organic chemicals, materials and organic liquid fuels. Biomass is abundant enough and inexpensive enough that it undoubtedly will be called on to meet at least a portion of these societal needs. This is especially true in an era of declining cheap petroleum and increasing potential for petroleum supply interruptions. There is every reason to believe the biobased economy will grow rapidly over the next few decades. For perhaps the first time, we have the ability to design a new industry so that it meets not only economic requirements, but also achieves very large environmental improvements. LCA coupled with correct policies and intelligent engineering design of integrated biobased systems can achieve these very large environmental benefits versus the current petroleum economy.
REFERENCES


S. Kim and B. E. Dale, Life Cycle Assessment Study of Biopolymers (Hydroxyalkanoates) Derived from No-Tilled Corn Grain. 2004 Int. J. LCA


Figure 1. Cost of plant biomass relative to petroleum on mass and energy bases

Figure 2. Cost of corn grain in constant and nominal dollars per bushel
Figure 3. Framework for Life Cycle Analysis

Figure 4. Industrial Ecology Model for Integrated Biorefining Systems
Figure 5. Systems View of Biobased Products in Life Cycle Context

- Plant Raw Material:
  - Grains
  - Crop Residues
  - Oilseeds
  - Sugar Crops
  - Woody & Herbaceous Crops

- Pre-processing:
  - Carbohydrates
  - Protein
  - Oil
  - Lignin
  - Ash

- Final Processing:
  - Fuels
  - Chemicals, etc.
  - Polymers
  - Feeds & Foods
  - Monomers
  - Lubricants
  - Electricity
  - Steam
  - Fertilizer

- Functional Units:
  - Products to Replace Petroleum Based or Petroleum Dependent Products

- Recycle or Disposal:
  - Recycled within Product System or to Other Product Systems
  - Compost Pile or Landfill

Figure 6. Carbon Flow in the CENTURY Model of Agricultural Ecosystems
Figure 7. Carbon sequestered by corn culture under no–tillage practice

Figure 8. N$_2$O emissions from soil during corn cultivation under no–tillage practice

Figure 9. Typical compositions of selected biomass feedstocks
Figure 10. Net energy of corn ethanol as affected by allocation method

- Dry milling
- Wet milling

Figure 11. Effects of Cropping System, Residue Removal Rates and Cover Crops on Soil Organic Carbon Accumulation for No Till Conditions in Washington County, Illinois
Figure 12. Greenhouse Gas Emissions by Category per Kilogram of Total Carbohydrate Produced Under Various Cropping Systems

Figure 13. Life Cycle Greenhouse Gas Emission Reductions for Ethanol Produced under Different Cropping Systems
Figure 14. Effects of Cropping System on Nitrogen Leaching under No Till Conditions for Washington County, Illinois

Figure 15. Non Renewable Energy Used by Subprocess for PHA as Determined by Different Studies

[Graph showing inorganic nitrogen losses (Kg N/ha) for different cropping systems and non-renewable energy use for PHA production with various subprocesses and studies represented.]
Figure 16. Comparison of Global Warming between PHA and PS
Table 1. Ten Required Biomass Feedstock Properties*

1. **Economical**
2. Stable price & availability
3. Consistent composition
4. **Low cost**
5. Favorable co-products & by-products
6. Multiple product opportunities
7. **Inexpensive**
8. Environmentally benign or beneficial
9. Storable
10. **Cheap**

* Dr. Paul Roessler, Dow Chemical, emphasis added

Table 2. Worldwide Availability of Crop Residues (Kim & Dale, 2004)

<table>
<thead>
<tr>
<th>Material (billion kg)</th>
<th>Africa</th>
<th>Asia</th>
<th>Europe</th>
<th>North America</th>
<th>Central America</th>
<th>Oceania</th>
<th>South America</th>
<th>Subtotal</th>
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</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>0.0</td>
<td>33.9</td>
<td>28.6</td>
<td>134</td>
<td>0.0</td>
<td>0.2</td>
<td>7.2</td>
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<tr>
<td>Barley straw</td>
<td>0.0</td>
<td>2.0</td>
<td>44.2</td>
<td>9.9</td>
<td>0.2</td>
<td>1.9</td>
<td>0.3</td>
<td>58.5</td>
</tr>
<tr>
<td>Oat straw</td>
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<td>0.3</td>
<td>6.8</td>
<td>2.8</td>
<td>0.0</td>
<td>0.5</td>
<td>0.2</td>
<td>10.6</td>
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<tr>
<td>Rice straw</td>
<td>20.9</td>
<td>668</td>
<td>3.9</td>
<td>10.9</td>
<td>2.8</td>
<td>1.7</td>
<td>23.5</td>
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<tr>
<td>Wheat straw</td>
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<td>133</td>
<td>50.1</td>
<td>2.8</td>
<td>8.6</td>
<td>9.8</td>
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<td>Sorghum straw</td>
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<td>0.4</td>
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<td>1.2</td>
<td>0.3</td>
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<td>Bagasse</td>
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<td>19.2</td>
<td>6.5</td>
<td>63.8</td>
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<tr>
<td>Subtotal</td>
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<td>924</td>
<td>217</td>
<td>219</td>
<td>26.1</td>
<td>19.7</td>
<td>106</td>
<td>1549</td>
</tr>
</tbody>
</table>
Table 3. Parameter Assumptions and Acronyms Used for Cropping System Sustainability Analysis

- Basic cropping system
  - Corn (plow till) – soybean (no-till): **CPSN (grain)**

- Effect of winter cover crop under no-till corn continuous cultivation
  - 0 % of corn stover removed: **CC (grain)** (No winter cover crop)
  - Average 56 % of corn stover removed: **CC (56%)** (No winter cover crop)
  - Wheat and oat as winter cover crops with 70 % corn stover removal: **CwCo (70%)**

- Effect of winter cover crop under no-till corn-soybean rotation
  - Wheat and oat as winter cover crops after corn cultivation with 70 % corn stover removal: **CwSCo (70%)**
  - Average 54 % of corn stover removed: **CS (54%)** (No winter cover crop)

- Cover crop **not** harvested