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The Bio-based Economy

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The bio-based economy can and should be to the 21st century what the fossil-based economy was to the 20th century. Agriculture will be core to the bio-based economy, providing source materials for commodity items, e.g. liquid fuels and value-added products such as chemicals and materials. For example, a hectare (2.47 acres) of biomass crop converted to 16,800 L (4,450 gallons) of ethanol at a cost of $0.13/L ($0.50/gallon), grown on 20 Mha (50 million acres) of non-prime agricultural land would, along with domestic petroleum, enable national self-sufficiency in gasoline. At the same time, agriculture will continue to provide food and feed that are even more healthful and safe.

The public-good benefits that will accrue from the bio-based economy are compelling (Fig. 1). They include national and homeland security, economic advantages to farmers, industry, rural communities, and society, environmental benefits at the global, regional, and local levels—including sustainability—and other benefits to society in terms of human health and safety.

New crops and new uses are central to the bio-based economy. A combination of aggressive facilitating, national policy, public and private investment, and development of the necessary science and technology is needed to realize these benefits in a reasonable time frame.

THE ROOTS

The bio-based economy has historical roots in the 1920s and 1930s in the chemurgic movement. Henry Ford thought that ethanol, not gasoline, would fuel the automobile. Also, he made car bodies from soybeans [*Glycine max* (L.) Merr., Fabaceae]. Agriculture had the problem of overproduction for limited food and feed markets then as it does today. New agricultural markets were needed then as they are today. The Agriculture Research Service established centers for new uses at Albany, New Orleans, Peoria, and Philadelphia, which have made significant contributions. We now need a much-expanded federal initiative with internal and external funding to realize the opportunity of the bio-based economy.

There has been momentum-building activity over the past 20 years for the bio-based economy. The New Uses Council was born in the 1980s, as was the Association for the Advancement of Industrial Crops. The Alternative Agriculture Research and Commercialization (AARC) Center was established in 1992 and the Alternative Agriculture Research and Commercialization Corporation in 1996. AARC made venture-capital investments in private corporations commercializing bio-based industrial products. Several AARC investments include those in companies now producing and marketing new fibers for building materials, furniture, comforters, etc., plant-based lubricants and cleaning agents, and high-value-added nutraceuticals, as well as developing novel high-yield, low-cost processes for bio-ethanol. AARC had many novel features, but the risk/return aspect of venture capital—where most investments fail and a few generate very large returns was not understood by government agencies and was unfamiliar to many politicians. AARC was a great idea, but its concept is probably still beyond the range of government, which is familiar with grants and loan guarantees, but not with venture capital. Unfortunately, current private-sector venture capital is focused almost exclusively on medical and information technologies and not on agricultural technologies for the bio-based economy. The private venture-capital industry needs to recognize this emerging major opportunity.

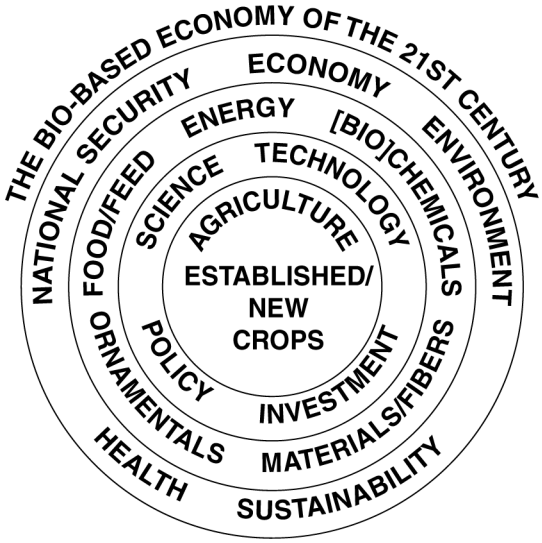

Fig. 1. An integrated overview of the bio-based economy from its basis in agriculture to its products and benefits.

In 1998, the Council of the NABC produced a *Vision Statement for Agricultural Research and Development in the 21st Century* for food, feed, and fiber, but also for energy, chemicals and materials (Fig. 2) (NABC 1998). NABC's Year 2000 Annual Meeting focused on the bio-based economy, with the presentations and dialog published as NABC Report 12 (Fig. 3): *The Bio-based Economy of the Twenty-First Century: Agriculture Expanding into Health, Energy, Chemicals, and Materials* (Eaglesham et al. 2000).

The National Research Council's report—*Bio-based Industrial Products: Priorities for Research and Commercialization* (NRC 2000) provided scientific legitimization for the concept of the bio-based economy, and proposed conservative targets (Table 1). I believe that the targets should be much more aggressive in date achievement. Other reports include *Plant/Crop-Based Renewable Resources 2020* (Anon. 1998). National impact has resulted from these momentum builders. Executive Orders and legislation are promoting government use of bio-based industrialized products, and a modest start on focused national funding of needed research.

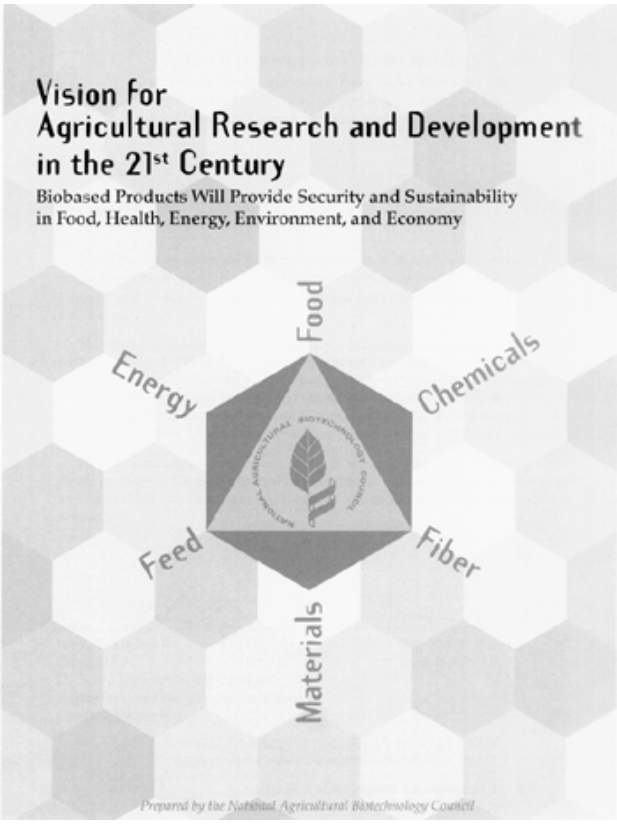

Fig. 2. The cover of the NABC vision statement for agricultural research in the twenty-first century (NABC 1998).

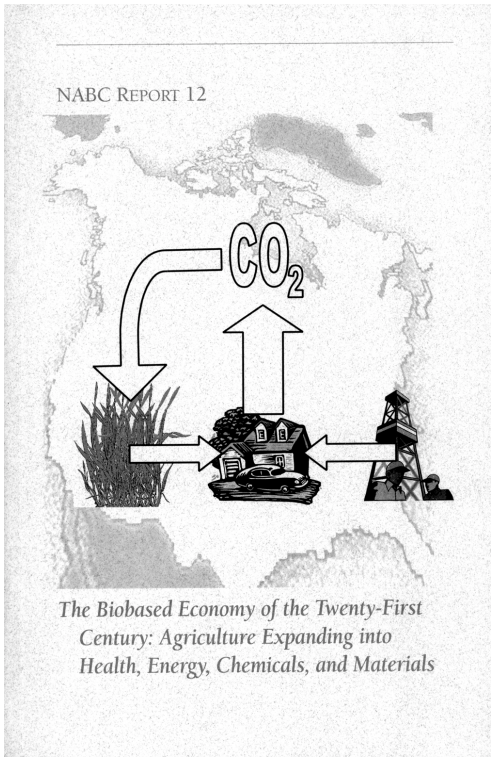

Fig. 3. The cover of NABC Report 12 illustrating the combined use of domestic petroleum and biosources for energy, chemicals, and materials, and for reduced net CO_2 emissions (Eaglesham et al. 2000).

Table 1. Targets for a national bio-based industry, percent derived from bio-based feedstocks (NRC 2000).

		Future target	
Bio-based product	Current level	Intermediate (2020)	Ultimate (2090)
Liquid fuels	1–2%	10%	up to 50%
Organic chemicals	10%	25%	90+%
Materials	90%	95%	99%

THE PUBLIC GOOD

The public benefits or public good from the bio-based economy address many of our major concerns for the twenty-first century—security, economy, environment, health, and safety. National and homeland security require independence from Middle-Eastern petroleum (Woolsey 2000). The bio-based economy provides the potential for liquid-fuel self-sufficiency, utilizing large amounts of bio-based ethanol and modest amounts of biodiesel, and domestic/North American petroleum. In addition to reducing dependency on foreign petroleum, we also need a replacement for depleting domestic and foreign petroleum resources. Domestic petroleum peaked in 1970, foreign petroleum is projected to peak in ten to twenty years, and a speaker at this meeting suggested that the peak is only six years away (Deffeyes 2001).

There are substantial economic benefits from the bio-based economy. Foremost for farmers/growers are major new agricultural markets beyond the traditional food, feed, and fiber. These new markets and additional farm revenues should reduce the need for annual agricultural subsidies of $15–25 billion. Our national balance of payments should improve by reducing the $70–80 billion used for importation of petroleum. The bio-based economy should greatly minimize the economic cost of reducing net CO_2 emissions. Social benefits will accrue to rural communities in terms of jobs created for the processing and distribution of bio-based products made from crops grown in the surrounding communities.

The bio-based economy will provide significant answers to major environmental concerns of the twenty-first century; since it uses the carbon cycle, it is inherently sustainable whereas the fossil-based economy in inherently unsustainable. The bio-based economy will mitigate global climate change by the major greenhouse gas, CO_2. There will be reduced local, regional, and global environmental pollution. For example, 85% of atmospheric pollutants—O_3, CO_2, SO_2, NO_x—result from fossil/petroleum. The bio-based economy will not produce slowly degradable spills of oil on land and water. Most "bio-based" crops will be perennial with low inputs, will be harvested annually, will produce minimum environmental impact and be wildlife friendly, and will not be grown on prime food-producing crop land.

Human health and safety will benefit from the bio-based economy. Improved air, water, and soil quality from bio-based production systems should reduce diseases such as asthma. In addition, there will be improved safety from the higher flashpoints and biodegradability of bio-based products compared to petroleum-based alternatives.

THE COMMUNICATION OPPORTUNITY

The above public-good benefits from the bio-based economy need to be broadly communicated beyond the agricultural community. We need to inform and excite national opinion leaders—"the movers and shakers." An initial example was Disney World's Epcot Millennium Exhibit of Prosperity Village, where ten million or more visitors walked through an interactive display, demonstrating to children and adults that the bio-based economy is based on a sustainable carbon cycle, producing consumables such as automobile bodies and interiors, apparel, and energy. We now need a popular book on *The Bio-based Economy and the Public Good* written by an established, recognized, engaging, professional writer and a co-author with technical experience. An investment of $200,000–300,000 should facilitate this initiative. Stories in such a book would expand understanding of the public good that will accrue from the bio-based economy and thus help garner support for policies and investment necessary for its development.

THE BIOSOURCES

Crops and crop production for the bio-based economy will need to possess several attributes. They will need to be reliably available for industrial plant operation 365 days per year. The crop will need to be competitively priced with respect to imported petroleum, e.g. $33/dry tonne (t) ($30/ton) at the farm gate. They will need to be transportable at minimum cost, storable for at least a year, and processable. The engineering skills for solid sources are less developed than those for liquids.

The initial biosources will be unused crop residues, waste and add-on uses for existing crops, e.g. starch and oil crops. The intermediate-term sources will be easily domesticated native crops, e.g. switchgrass (*Panicum virgatum* L., Poaceae) and transgenics, e.g. high lauric canola (*Brassica napus* L., Brassicaceae).

In the longer term, there will be dedicated biosources for energy, chemicals, and materials. Examples

are switchgrass and hybrid poplar (*Populus deltoides* Bartr. ex Marsh. × *Populus nigra* L., Salicaceae) for liquid fuels. Cropping or management systems will need to be developed for these industrial crops with production enhancement, as was necessary for food, feed, and fiber crops. Much of the public effort in production agriculture should focus on these crops rather than on the major food, feed, and fiber crops, with which private-sector research now provides the major effort. Productivity targets need to be set. For example, commercial switchgrass production of 18 dry t/ha (8 tons/acre) in two years, 22.5 (10) in five years and 27 (12) in ten years. Ten years of switchgrass yields in Oklahoma have averaged about 18 t/ha (8 tons/acre) for the best cultivars (Fuentes 2002). These dedicated biosources will be combinations of established, transgenic, and new polysaccharide, oil, fiber, and high-value chemical crops. Domestication of new crops is often very high risk, and can take a long time. Public-sector leadership will be necessary for domestication of new crops.

ENERGY

The major commodity opportunity for the bio-based economy is in energy and, within the energy sector, liquid fuels. Two liquid fuels, ethanol and biodiesel—the methyl esters of plant fatty acids—are the most promising. Biodiesel contribution will be limited due to restricted availability of low-cost fats and oils. Ethanol's contribution could amount to 50+% of our gasoline consumption.

Currently, ethanol usage is 1 to 2% of liquid fuels. It is produced mainly from the starch of maize (*Zea mays* L., Gramineae), with animal feed and hot water as by-products. Twenty-five kg (1 bushel) of corn produces 9.8 L (2.6 gallons); an average corn yield of 9.41 t/ha (150 bu/acre) produces 1,480 L (390 gallons). It would require 93 Mha (230 million acres) of maize to produce 340 GL (90 billion gallons) of ethanol, overwhelming the market for animal-feed by-product. Furthermore, ethanol from maize costs $0.33 to 0.40/L ($1.25–1.50/gallon), and is subsidized. Maize ethanol is inadequate on quantity and too expensive utilizing a high-production-cost crop. Maize- and other grain-starch ethanol is not the long-term answer.

A possible intermediate step in liquid-fuel ethanol is the use of cellulosics and hemicellulosics in which 5- and 6-carbon plant sugars are fermented to ethanol. The advantage of this process is low cost in terms of sources, e.g. crop residues and waste. The disadvantage is the need for various pretreatments, most, if not all, of which have limitations. Also the capital cost of construction of processing plants is reported to be up to $1.06/L ($4/gallon) of annual production capacity, which results in high debt service and poor return on capital. Targets of $0.22/L ($0.85/gallon) in 2005 and $0.19/L ($0.73/gallon) in 2010 are proposed.

The ultimate process for ethanol production from plant material must use all of the carbon in the plant—polysaccharides, fats, proteins, and lignin. A combination of a physical and/or chemical process with a chemical or biological process is needed. An example might be gasification followed by biological/enzymatic or chemical catalytic conversion to ethanol. Conversion to hydrogen for fuel cells is another possibility. A thermo-chemical process is another related approach (Kuester 1998). Research and development of such processes are occurring. A cost goal of $0.18/L ($0.70/gallon) in 2005 and 0.13/L ($0.50) in 2010 is suggested. With 27 t biomass/ha (12 tons/acre) and 626 L of ethanol/t (150 gallons/ton) 1 ha would produce 16,800 L of ethanol, compared to 3,650 L from corn (i.e. an acre would produce 1,800 gallons compared to 390 gallons from maize). Some 340 GL of ethanol (90 billion gallons) would be produced on only 20 Mha (50 million acres) of non-prime agricultural land; our current annual consumption of gasoline is 490 GL (130 billion gallons). Energy self-sufficiency in gasoline-type fuel is possible with this ultimate process, without affecting food production on prime agricultural land.

Electricity is another energy source. Co-firing of forestry and other wastes is already producing electric power. Dedicated electricity production from biomass is currently too costly. There are hopes that improved gasification and high-efficiency turbines will make biomass competitive, but it will be challenging.

CHEMICALS

Chemicals represent commodity to high-value products. The quantity of petroleum used in their production is only 3% to 10% of that of energy, therefore, bio-based chemicals represent a minor part of energy self-sufficiency. However, the economic opportunity within chemicals is very large, with the NRC Report projecting that we move from 10% of organic chemicals as bio-based to 90%. Low-cost sugars are the key to many bio-based chemicals, especially commodity ones. Corn starch is the current source of "bio-based" sugar, with a

cost of $0.22 to $0.26/kg of sugar ($0.10–0.12/lb). Suggested target costs for sugar are $0.11 to $0.13/kg ($0.05–$0.06/lb) in 2005 and $0.09/kg ($0.04/lb) in 2010. Biomass crops with compositional changes, such as decreased lignin, may be needed.

The list of bio-based chemicals is long. Feedstocks and monomers include ethylene, lactate, β-OH-butyrate, 1,3-propane diol, and succinic acid. Examples of bio-based polymers include polylactate from corn starch produced by the Cargill-Dow joint venture and a new improved polymer, Sorona, being developed by DuPont (Dorsch 2000). Other bio-based chemicals include industrial enzymes, acidulants, amino acids, vitamins, food conditioners, nutraceuticals, pharmaceuticals, and cosmeceuticals. Edible vaccines are in efficacy/safety testing for human and domesticated animal diseases. Oils and lubricants are another major area. Companies like AgroManagement Group, Inc., are producing plant-based engine oils that are showing functionality and emission advantages in the Unites States Postal Service fleets (Johnson et al. 2002). Other products include cleaners, solvents, adhesives, industrial gums, and paints.

The CEO of DuPont has set a challenging target of 25% of revenues from bio-based products by 2010.

MATERIALS

Materials such as lumber, cotton, and silk are 90% bio-based, and the NRC Report target is 99%. We need to develop additional fiber sources that can be used to produce blends or composites with advantageous functionality. Examples of additional fiber sources include crop straws, stover and bagasse, kenaf (*Hibiscus cannabinus* L., Malvaceae), arundo (*Arundo donax* L., Poaceae), syrica (*Asclepias syriaca* L., Asclepiadaceae), flax (*Linum usitatissimum* L., Linaceae), and industrial hemp (*Cannabis sativa* L., Cannabaceae). For example, syrica, the floss of milkweed (*A. syriaca*) is being used by Natural Fibers, Inc., to produce highly insulative, hypoallergenic comforters and pillows. The floss has been used to produce blends with other fibers, and an experimental "Kleenex" equivalent has been made. Domestication of milkweed is needed, as are management systems to enable its high yield and use in these lower-value products. The utility of arundo for production of high-quality paper was reported at this meeting, with greater brightness than that from tan oak [*Lithocarpus densiflorus* (H. & A.) Rehd., Fagaceae] (Lewis 2002). A target in this area should be the development of ten new fibers and production of blends.

Bio-based materials may include paper from crop residues, wheat-straw (*Triticum aestivum* L., Gramineae) based particle board which is being used for furniture manufacture in Canada, South Dakota, and Minnesota, automobile bodies utilizing industrial-hemp fibers, apparel utilizing hemp and polylactate, and shipping and packing materials utilizing starch.

SUMMARY

The Bio-based Economy is a major new opportunity for agriculture—providing the opportunity to take it from its recurring overproduction for limited food, feed, and fiber markets to a more sustainable and profitable balance of production and markets. But the benefits of this bio-based economy will extend beyond agriculture to society as a whole, necessitating broad-based support in terms of public policy and investment.

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