Biofuels—a critical part of America's sustainable energy future

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Coming to terms with biofuels

What do we mean when we talk about "biofuels"? There is no simple answer to that question. Figure 1 gives a sense of how diverse and numerous the options are for biofuels production. And, as complex as this figure looks, it does not capture all of the possibilities and permutations that exist for mixing and matching biomass feedstocks, conversion technologies and optional fuel forms.

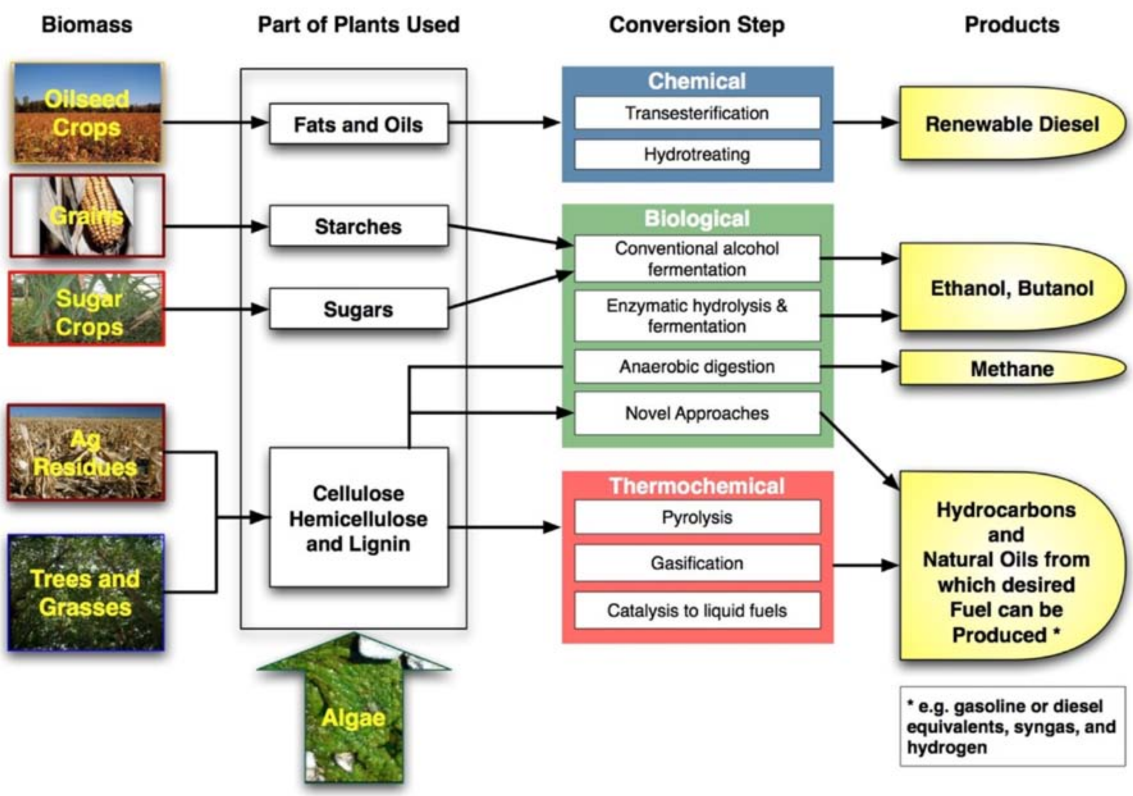

Figure 1 Biofuels—Variations on a theme

I define biofuels as any transportation fuel that can be produced from plant matter. Broadly speaking, the technology used to convert biomass into fuel can be classified as chemical, biological and thermochemical. The fuels can take any form—from electricity to gases to liquids. And there is no limit to the diversity of types and sources of plant materials that we can process. This diversity has its advantages and its disadvantages. On the one hand, it creates plenty of opportunities for biofuels to address the ever-changing demands placed on fuel suppliers. On the other hand, the variety of choices can be daunting and confusing to technologists, investors, regulators and policy makers.

Today's biofuels industry

The first three boxes on the left in Figure 1 represent the major sources of biomass used by today's industry. Fats and oils from soybeans, waste fats and greases, and other oilseed crops can be converted into fuels suitable for diesel engines using well-established chemical technology. To make "biodiesel," fuel processors chemically combine these oils with methanol using a chemical reaction known as "transesterification." The oleochemicals industry has been practicing this kind of chemistry for many decades. The process is cheap, reliable and efficient.[1]

A new way to process fats and oils has been introduced commercially both in the US and abroad. It comes from an unexpected place—petroleum refiners. Refiners have borrowed from their own well-established tool set for converting petroleum to fuels to introduce a new fuel known as renewable or "green" diesel. By hydrotreating and hydrocracking fats and oils, refiners are able to make a bio-based diesel fuel virtually indistinguishable in performance and handling requirements from ultra low sulfur clean diesel—and perhaps even better. The largest source of biofuels in the US is corn. In Brazil, sugarcane is fermented to fuel grade ethanol at a level only slightly less than that of corn ethanol in the US.

Emerging and future biofuels technologies

The remaining biomass sources shown in Figure 1 represent the future of biofuels, based on so-called "advanced biofuels" technologies. Trees and grasses are the largest source of organic carbon in the biosphere. Advanced biofuels technologies are designed to convert this organic carbon into useable forms of liquid fuels, heat, power and other chemical products. These vast resources of organic carbon are what Senator Richard Luger and former CIA director James Woolsey once referred to as "the New Petroleum" because, in combination with advanced biofuels technologies, they represent the largest renewable alternative to petroleum as our dominant source of liquid organic carbon feedstocks for production of transportation fuels.[2]

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[1] Sheehan, J., Camobreceo, V., Duffield, J., Graboski, M., & Shapouri, H. (1998). *Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus*. Golden, CO: National Renewable Energy Laboratory.

[2] Lugar, R.G. & Woolsey, R.J., 1999, "The New Petroleum." *Foreign Affairs,* 78(1), pp. 88-102.

Leading technologies for converting trees and grasses to biofuels

Biological processes

Cellulosic ethanol is likely to be the first of the advanced technologies to hit the commercial scene in the next few years. Cellulosic ethanol is made by fermenting the sugars locked up in the cellulose polymers of trees and grasses into ethanol. Releasing those sugars has been one of the greatest hurdles facing the industry, but the recent large private and public sector investment in new enzymes and new microbes that can break down cellulose into its component sugars is rapidly eliminating this roadblock. Meanwhile, biotechnology tools are being brought to bear to create microbes that can turn these sugars into other, potentially more interesting, fuels—such as butanol and even bio-gasoline.

Thermochemical processes

Thermochemical conversion of biomass includes gasification and pyrolysis. Gasification involves the use of high temperature and high pressure to bust up biomass into simple chemical building blocks. These chemicals can then be converted to hydrocarbons and almost any other chemical you can think of—including alcohols such as ethanol and butanol. Pyrolysis uses milder conditions to convert biomass into a complex chemical soup that can be upgraded to a fuel grade liquid. The advantage of thermochemical processing is that it is “omnivorous.” Biological processes need sugars. By contrast, thermochemical processes will take organic carbon in virtually any form. This has two important implications: 1) thermochemical processes can yield higher amounts of liquid fuels because, unlike biological processes, they can use the non-sugar part of the biomass (primarily lignin); and, 2) they are not limited to high sugar-containing biomass.

Biological versus thermochemical technology—why choose?

The picture I have just painted of advanced technology for biofuels actually offers a false dichotomy. Technologists tend to identify themselves with one or the other of these two camps. Investors and policy makers are often bombarded with competing claims of superiority about these two technologies. But the truth is that each has their place, and (more importantly) each can and must be used together. The ideal integrated biorefinery is (as shown in Figure 2) one in which both types of technologies are used to optimize fuel production from all of the components in biomass. It lets the microbes do what they do best—convert sugars into products without going through the step of destroying these chemicals, and it allows heat and pressure to convert the rest. And there is an added benefit to this approach. Thermochemical processes often produce a lot of excess (often viewed as waste) heat. In an integrated process, the “waste” heat can be used to supply heat and power to the biological processing side of the facility. This reduces overall cost and improves the energy efficiency of the facility.

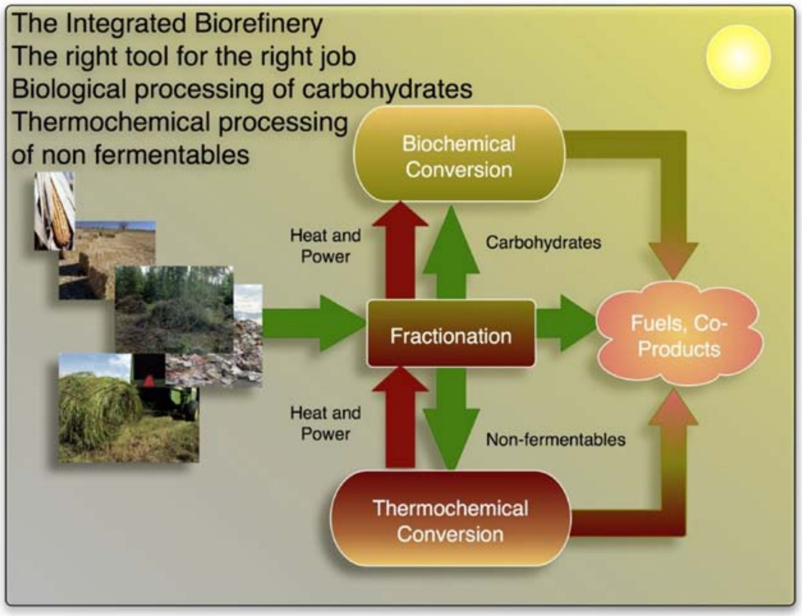

Figure 2. The ultimate integrated biorefinery

The economics of a mature biofuels industry

The peer-reviewed journal *Biofuels, Bioproducts, and Biorefining* recently dedicated an entire issue to analysis of the future mature state of technology for biofuels. The papers in this issue came from a project entitled "The Role of Biomass in America's Energy Future," which I co-lead with colleagues at Dartmouth College, Princeton University, and the Natural Resources Defense Council while I was at the National Renewable Energy Laboratory.[3] We looked at the future prospects for economic and environmental performance of 14 different combinations of biological and thermochemical process technologies. Figure 3 shows the range of biofuels prices we found for a range of biomass feedstock costs.[4] The lowest cost options are for bioethanol facilities that coproduce thermochemical fuels. Even when feedstock costs rise to levels of over $100 per metric ton, the processes will be able to deliver fuel at prices that compete with oil priced at $50 to $125 per barrel. One of the limitations of analyses published by the Department of Energy and others is that they often assume biomass costs of $30 to $40 per metric ton. While such low prices may be feasible in the early days of the industry, they are unsustainable for a large industry. The ability to compete at higher feedstock prices is vital to a future biofuels industry if it wants to play a large role in our energy supply.

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[3] Lynd, R. ; Larson, E.; Greene, N.; Laser, M.; Sheehan, J.; Dale, B.; McLaughlin, S.; Wang, M. "The role of biomass in America's energy future: framing the analysis." *Biofuels, Bioproducts, and Biorefining*, 3:pp 113-123.

[4] Laser, M.; Larson, E.; Dale, B.; Wang, M.; Greene, N.; Lynd, R. (2009). "Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios." *Biofuels, Bioproducts, and Biorefining*, 3:pp 247–270.

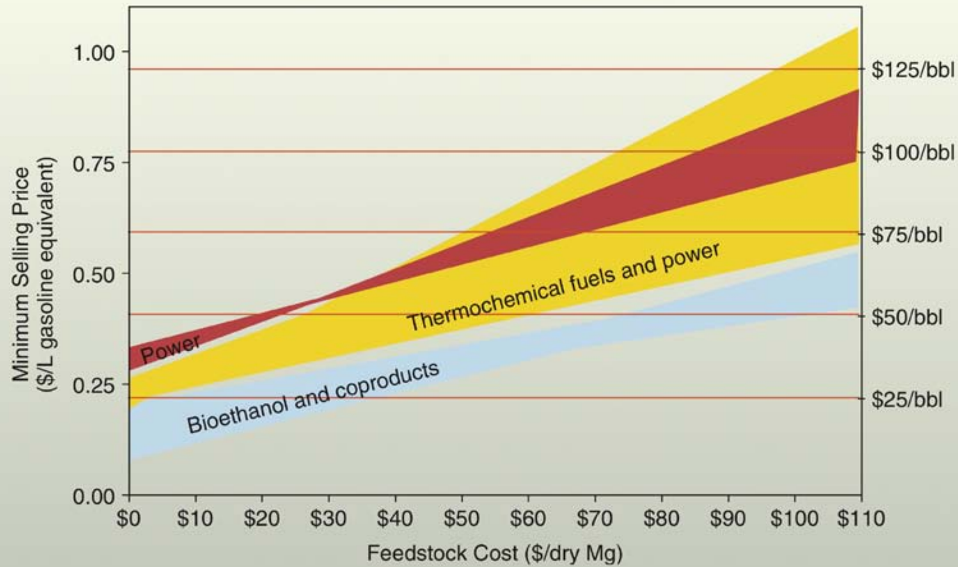

Figure 8. Minimum energy selling price as a function of feedstock cost for categories of mature biorefinery scenarios. Electricity price = $0.05/kWh (fuel scenarios); protein coproduct price = $0.44/kg; debt/equity ratio = 35/65; loan rate = 7.0%; IRR = 12%.

Figure 3. Biofuels prices for future mature state of technology scenarios

Biofuels—How much by when?

The limiting factor for domestic biofuels production is biomass supply. Many estimates of supply are available. Among the most often cited is a joint study of the U.S. Department of Energy and the U.S. Department of Agriculture—the so-called "Billion Ton Study."[5] As the title suggests, it was intended to evaluate the feasibility of producing one billion tons of biomass for fuel production in the US. In round numbers, such a level of production could correspond to around 100 billion gallons of ethanol per year if all of the biomass were converted to ethanol.

My own preliminary modeling work evaluating the dynamics and economics of biomass production and biofuels industry growth suggest that this level of production is achievable in the next 30 years, depending on the price of oil and the kinds of policies that are put in place. Figure 4, for example, shows a scenario in which a renewable fuel standard of 20 billion gallons per year, in conjunction with a carbon mitigation value of $40 per ton and sustained high oil prices, could lead to 100 billion gallons per year of ethanol production by around 2039. (Note that this

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[5] Perlack, R., Wright, L., Turhollow, A., Graham, R., Stokes, B., & Erbach, D. (2005). Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. Oak Ridge, TN: Oak Ridge National Laboratory.

work was done in 2006, when DOE's high oil price scenario showed prices reaching $100 per barrel by 2030).[6]

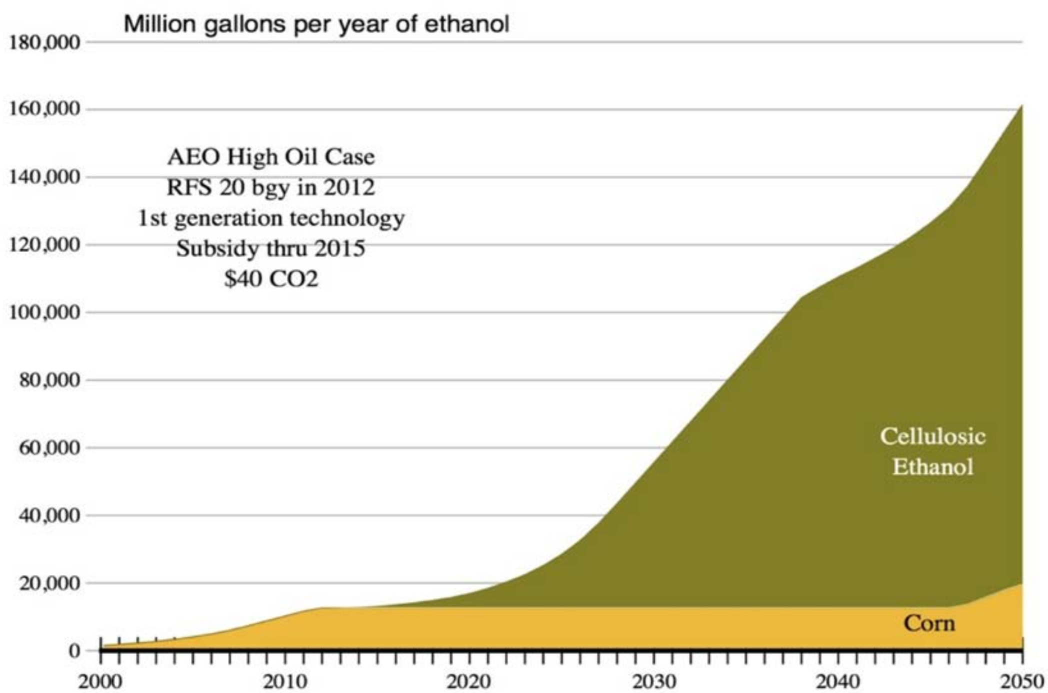

Figure 4. System dynamics modeling of biofuels industry growth

Biofuels and the conundrum of sustainability

Beyond the complexity of characterizing the technology is the tougher question of how to define sustainability. As a concept, sustainability has a long and checkered history. Its roots go back to the controversial writings of Thomas Malthus, who dared to suggest (albeit prematurely with regard to both technology and human reproductive behavior) that the planet had reached the limit of its ability to support human population and the needs of society.[7] In the 1970s, the Malthusian perspective returned with public concern about the environment and population growth. Its essence was captured in the computer modeling work at MIT that led to the controversial "Limits to Growth" report.[8,9] Today, the Malthusian question continues to influence the debate over the sustainability of biofuels and society in general, leading to often-acrimonious debate in both the public sector and the technical community—particularly with respect to the question of "food versus

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[6] A description of the modeling approach I have used is available in:
Bush, B.; Duffy, M.; Sandor, D. (2008). *Using System Dynamics to Model the Transition to Biofuels in the US.* Conference Paper NREL/CP-150-43153. National Renewable Energy Laboratory, Golden, CO.

[7] Malthus, T.R. (1798). *An Essay on the Principle of Population*. Oxford University Press; 1798.

[8] Cole, H.S.D. (1973). *Models of doom: A critique of the limits to growth*. Universe Books.

[9] Meadows, D., et al (2004). *Limits to Growth: The 30-Year Update.* Chelsea Green Publishing Co.

fuel." Unfortunately, one of the greatest challenges facing analysts in the nascent field of sustainability is the pace with which policy makers are moving forward with laws to promote sustainability. The field is struggling to keep up with these demands.

Direct benefits of advanced biofuels

There is a growing literature supporting the benefits of advanced biofuels in terms of greenhouse gas reductions and petroleum savings—both important metrics of a sustainable energy supply. The work we have done under the "Role of Biomass in America's Energy Future" shows that, regardless of what combination of biological and thermochemical technology we considered, biofuels can achieve 80 to 90% savings in both petroleum and carbon emissions (see Figure 5).

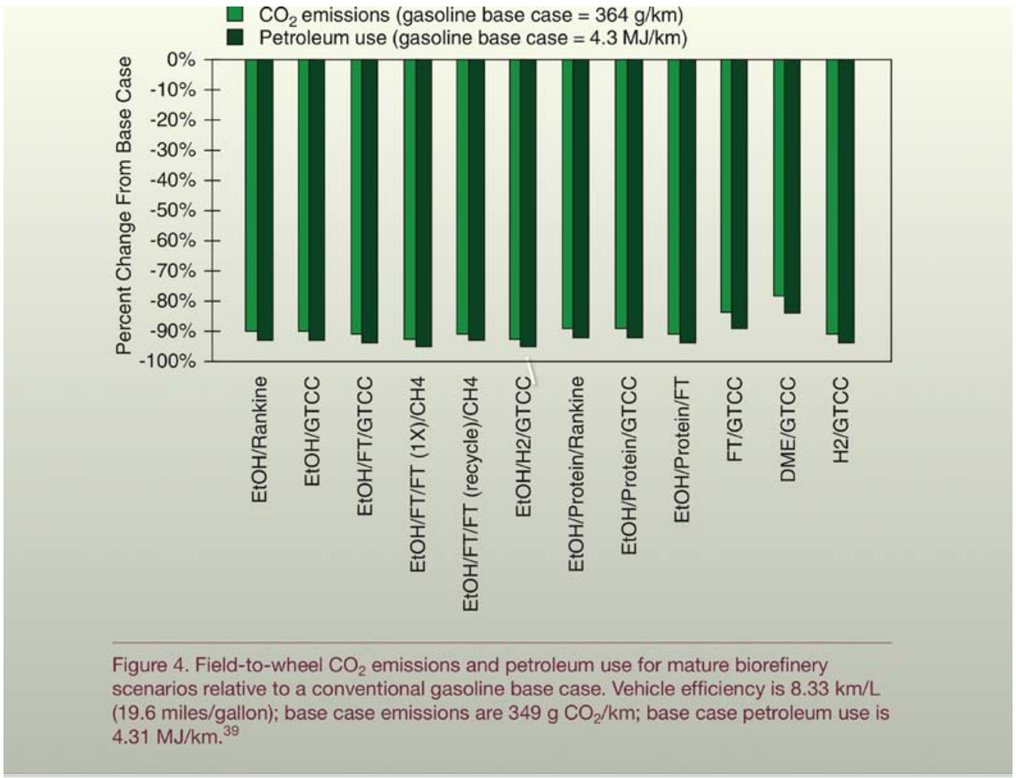

Figure 5. Carbon and Petroleum savings of various biofuels production systems[10]

Biofuels and global land use

The debate about sustainable biofuels production has now expanded beyond the direct effects it has in the US to the broader question of how new demand for biofuels will effect the ability of global land resources to meet the needs for food,

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[10] See footnote 4 for reference. Production system definitions: EtOH=ethanol; Rankine=conventional electric power production; GTCC=gas turbine combined cycle power production; FT=Fischer Tropsch fuel production; FT (1x)= Fischer Tropsch fuel production with "once through" syngas; CH4=methane production; FT (recycle)=Fischer Tropsch fuel production with recycled syngas; Protein=coproduct recovery of protein from biomass; DME=Dimethyl ether production; H2=hydrogen production. FT, DME, H2 and GTCC are all thermochemical conversion processes. Ethanol is a biological process.

feed and fiber. Recently, researchers have posed this question in terms of how much additional carbon emissions could be caused indirectly by the introduction of biofuels as a result of new land clearing that might occur.[11,12] Implicit in these analyses is the assumption that expansion of land for biofuels production must always lead to clearing of new land elsewhere in the world. If such expansion causes tropical deforestation, the added release of carbon could overwhelm any of the direct carbon savings that biofuels may offer.

Our ability to quantify this indirect effect is contingent on our ability to predict how the combination of future yield improvements in agriculture and bioenergy crops, growing population and food demand will effect total demand for land globally. We don't know the answer to that question. My own preliminary analysis suggests that there are plausible scenarios in which continuation of historical yield trends, population growth and per capita food demand lead to a decline in overall demand for agricultural land (see Figure 6). To the extent that this is true (and I in no means can say with certainty that it is), we can add biofuels production without incurring large carbon debts from land clearing. If the scenario I show here is achieved, the decline in land demand could translate to an ability to produce 300 billion to 1 trillion gallons per year of biofuels production without incurring added land clearing.

Furthermore, even if it is true that—assuming business as usual—we will see increasing land demand for food, feed and fuel, why should we accept that future? Why not design a future of sustainable global land use in which we improve global land productivity and land management practices such that we can meet the critical needs of food, feed, fiber *and* fuel? Thus, the more important question may be *how* to ensure sustainable fuel production on our lands.

Final thoughts

Advanced biofuels technology can and, I believe, should be a part of America's (and the world's) energy future. We need the will and the wisdom to make sure that it happens in a sustainable and responsible way. Economically and technologically, the hurdles to success are falling away. And we have an existing industry that can serve as a home for the new technology developments that are coming. We can transform the current debate about biofuels from one of "food versus fuel" to one of "food and fuel."

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[11] Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., et al. (2008). Use of U.S. Croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319(5867), 1238-40.

[12] Fargione, Hill, Tilman, Polasky, & Hawthorne (2008). Land clearing and the biofuel carbon debt . Science, 319, 1235-1238.

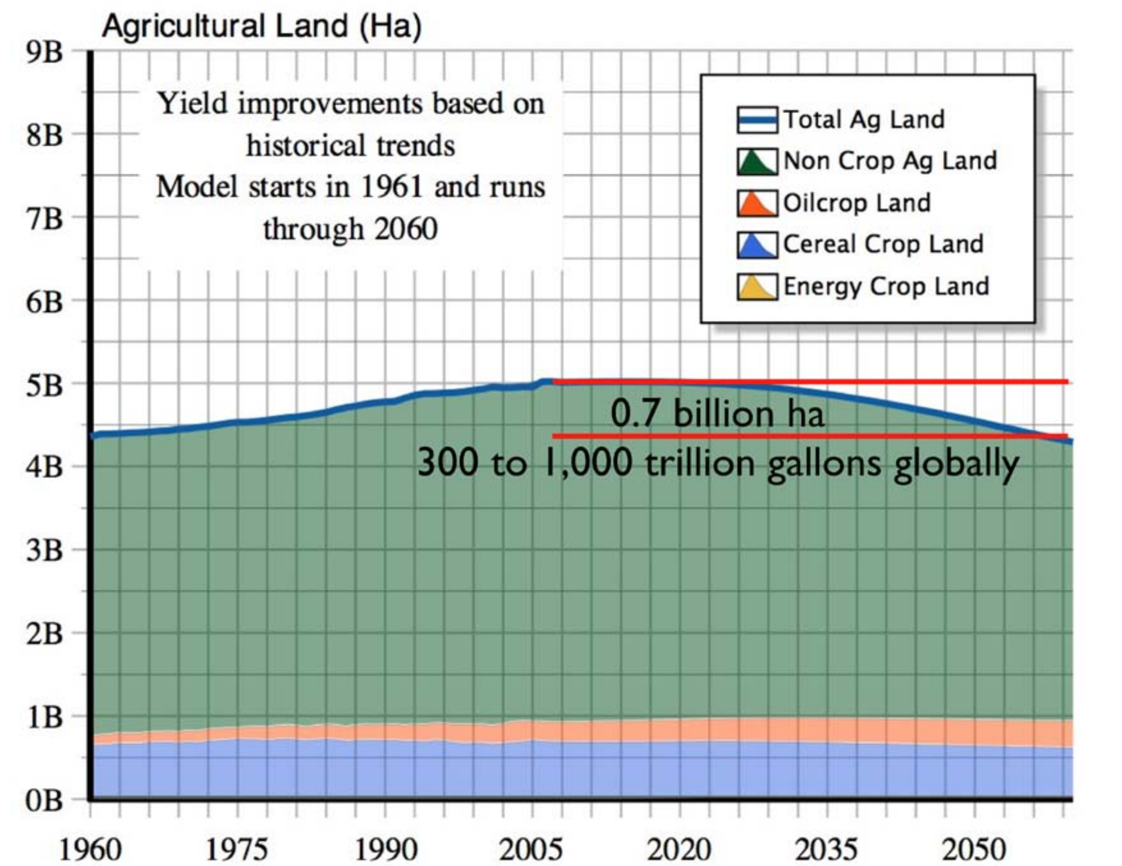

Figure 6. A scenario for declining ag land demand?