Where will Biofuels and Biomass Feedstocks Come from?

By Vinod Khosla

When it comes to biofuels we have a few choices and options – we can do it poorly, with short-run approaches with no potential to scale, poor trajectory, and adverse environmental impact, or we can do it right – with sustainable, long-term solutions that can meet our biofuel needs and our environmental needs. We do need strong regulation to ensure land use abuses do not happen. A recent report published by the Royal Society highlights some of the factors that need to be balanced – they note that some changes in land use (such as clearing tropical forest or adapting peatlands for crop cultivation) can do more harm than good. To counter these potential abuses, we have suggested each cellulosic facility be individually certified with a LEEDS (international certification program for "Leadership in Energy and Environmental Design", a green building rating system) like "CLAW" rating and countries that allow environmentally sensitive lands to be encroached be disqualified from these CLAW rated fuel markets. We think a good fuel has to meet the CLAW requirements:

C – COST below gasoline
L – low to no additional LAND use; benefits for using degraded land to restore biodiversity and organic material
A – AIR quality improvements- i.e., low carbon emissions
W – limited WATER use.

Cellulosic ethanol (and cellulosic biofuels at large) can meet these requirements. The Royal Society notes that the uncertainty of some biofuels do not obscure the main benefits of cellulosic fuels: "(1) biofuels from cereals, straw, beet and rapeseed are likely to reduce GHG emissions, though the estimated contribution varies over a wide range, from 10 to 80% (averaging about 50%) depending on crop, cropping practice and processing technologies; (2) biofuels from lignocellulose material are likely to show a twofold or more improvement in average abatement potential when compared with biofuels derived from food crops."[1] Our research and data suggests that cellulosic ethanol can reduce emissions on a per-mile driven basis by 75-85%, with limited water usage for process and feedstock as illustrated later. Range, Coskata and other companies currently have small scale pilots projecting 75% less water use than corn ethanol, and energy in/out ratio between 7-10 (Energy returned on energy invested or EROI, even though we consider this a less important variable than carbon emissions per mile driven). The question that eventually comes to the forefront is land use and biomass production – how much will we need? What will it take? Is it scalable enough to make a meaningful positive impact? To be conservative, we assume CAFE standards in the US per current law though we expect by 2030 to have much higher CAFE and fleet standards (hopefully up near 54 miles per gallon (mpg) or 100% higher than 2007 averages), thus dramatically reducing the need for fuel and hence biomass. For, this to happen, we need a combination of factors, including lighter vehicles, more efficient engines, better aerodynamics, low cost hybrids and whatever else we can get the consumer to buy that increases mpg.

What do we believe? As we will cover in this paper, we believe that given reasonable assumptions on technologies, biofuel yields, and adoption of better agronomic practices, most of our biofuel needs can be met with fairly limited land usage. From a technology perspective, the advances and continuing research into thermochemical processes offers potential far exceeding that of standard biochemical approaches. From an agronomic perspective, a greater understanding about the benefits of crop rotations and conservation practices combined with an ability to use generally underutilized land offers us the ability to vastly increase our biofuel producing abilities without cultivating additional land. In particular, we think the potential for winter cover crops as a biofuel source has been greatly understated, and that even modest yield assumptions would allow them to meet a significant portion of our biofuel needs. In the long run, the combination of these multiple factors (an example of the innovation ecosystem at play) will allow us to sever our dependence on oil – for good. Hybrid vehicle technologies will help but not materially on a worldwide basis at current costs.

A note about evaluating alternatives – when looking at a potential solution, it's important not to evaluate a technology/approach in isolation; rather, we ought to compare it relative to other viable approaches to determine its actual feasibility. For example, every nuclear plant that we did not build over the last 50 years (due to environmental concerns) was almost certainly replaced by a coal plant, whose environmental footprint was significantly worse. We are in danger of doing it again, by going after pie-in the sky or uneconomic solutions to replace oil. That could lead to even more problems - the alternative (as a long run transportation fuel solution) may well be oil shales (Canada is moving aggressively in this direction), which are even worse environmentally. **Letting the perfect be the enemy of the good is irrational – marginal analysis counts.**

Part I: What are the sources for biomass and biofuels?

There are many approaches to production of feedstocks for biofuels. To make a material impact in replacing gasoline, major feedstocks need to collectively produce more than a hundred billion gallons annually in the US and preferably more than 150 billion gallons to replace gasoline. Replacing gasoline and replacing diesel involve different technologies and markets. The focus here is principally on gasoline replacement in America's cars and light trucks though we do briefly touch upon diesel feedstocks.

We believe that a sustainable biofuel needs yields of at least 2,000 gallons (ethanol equivalent) per acre (hopefully 3,000!) in the long run to meet the worlds oil replacement needs on a manageable amount of land (with the exception of winter cover crops that use no additional lands). We believe, as estimated in our papers elsewhere, that 2,500 gallons of ethanol equivalent per acre annually is a reasonable assumption. (Assuming corn grain yields of 140 to 170 bushels/acre that are typical of the mid-Western corn belt today, and 2.8 gallons of ethanol from a bushel of corn, the range in ethanol production from corn is only 392 to 476 gallons/acre.) Chemical and water inputs and the effect on biodiversity should be minimal, if any. Cost should be below that of oil. Feedstock production should not materially increase the land under annual cultivation nor affect food security materially but should enhance energy security, reduce poverty and increase rural incomes. None of the "food/feed crop" based biofuels (corn or sugar based) or classic biodiesel sources (vegetable oils) comes close to these targets. Is such a fantasy possible? Yes! Part I covers sources of biomass, Part II will cover agronomy practices for yield, biodiversity, water and chemical efficiency, and Part III discusses the rationale of yield assumptions that lead to 2,500 gallons per acre. Our calculations later show that if we can increase engine and automobile efficiency significantly at the same time, we will need no additional land for biofuels.

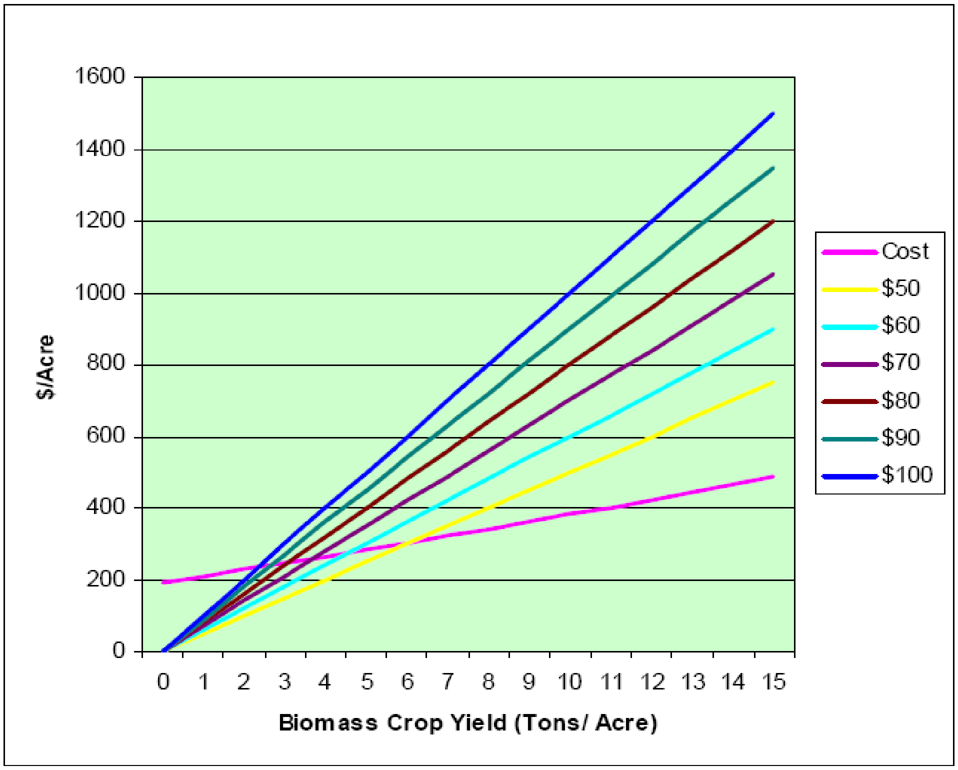
Currently there are two primary feedstocks for the production of renewable biofuels to replace gasoline (almost entirely ethanol) to replace gasoline – sugar from sugar cane (primarily used in Brazil) and starch from corn (the source of most US-based ethanol). In Asia and Africa, tapioca, potatoes and other starch crops are being used (sadly!). Amongst feedstocks, there has been significant discussion regarding both corn stalks and wheat straw. We are not huge fans of wheat straw or corn stalks, though they are possibilities. In our opinion, cellulosic ethanol plants need to reach production levels of 100m gallons per year per plant to achieve economies of scale (expensive fuels don't sell! A local conversion plant near the field and distributed supply would be ideal and we continue to investigate technologies that might make this possible). That would dictate feedstock needs of around 1,000,000 tons - per year, per plant In the short and medium term, at biomass yields of 10 tons/acre (by 2030 we expect about 20-25 tons/acre), 100,000 acres of land would be needed per cellulosic ethanol plant or 40,000 acres by 2030. With yields of approximately 2 tons/acre, the usage of either corn stalk or wheat straw would effectively quintuple land usage and substantially increase transportation distances and costs, hence our skepticism. In addition, there is value to plowing corn stalks and wheat straw under to minimize the need for commercial fertilizer. Winter cover crops like legumes and winter rye (no biomass optimized winter cover crops have been developed but grasses are a good candidate), grown on row crop lands during their idle period during winters, can yield 3-5 tons/acre with no additional land usage and may actually improve land ecology where row crops are grown anyway. In conjunction with winter cover crops, annual crop residue may become a viable supplement to winter cover crops annual/biomass yields per acre. To quote Prof Bransby, a renowned agronomist from Auburn University in a personal communication:

> “Regarding water and fertilizer needs of cover crops: The answer is that no irrigation is needed, and fertilizer needs are about 30% of the fertilizer requirements of corn. Also, there are multiple benefits from cover crop/traditional crop rotations (compared to traditional crops with no cover crops), including better soil protection/less soil erosion, improved soil organic matter, better water holding capacity, suppression of crop pests, etc. Provided this is done with conservation tillage practices, there should be no serious negative environmental impacts.” He states further: “It is reasonable to assume that winter cover crops can be grown on the same land that our summer traditional crops are grown, and summer cover crops can be grown on land where traditional winter crops (mainly winter wheat) are grown. As far as I know, most of this land is currently idle/fallow at the time when these cover crops would be grown. From the USDA National Agricultural Statistics website the 2007 acreage (in millions) for our major traditional crops is as follows: corn, 93; soybeans, 63; cotton, 11; sorghum, 8; winter wheat, 44; Total = 219. At a modest estimate of 3 tons/acre/year, this would provide 657 million tons of biomass annually. With research and genetic improvement, I believe the yield could be increased to 5 tons/acre within 10 years, for a total of 1.1 billion tons/year. Acreage for all annual crops is 317 million. For various reasons, it is unrealistic to assume that 100% of land in traditional crops could be planted to cover crops to produce biomass. Maybe 70%?”

While cover crops have been utilized historically for the agronomic benefits (more on the benefits of crop rotations later), increased biomass yield has not always been a primary area of focus. While many traditional cover crops such as legumes (clovers, vetches, medics, field peas) offer limited potential for biomass yields, other cover crops like small grains (winter rye, wheat, oats, triticale) offer substantial potential – we’re confident that they can achieve the 3-4.6 ton yields that we project, and perhaps even go further. Currently, these crops (and rye in particular) achieve yields of up to 4-5 tons per acre[2]. These crops today are generally managed for forage or grain - managing for forage is perhaps closest to managing for total biomass, but there are still differences in practices that offer potential for substantial yield improvements, along with plant breeding and many of the improved agronomic practices (we discuss these later in the paper). Our research leads us to be optimistic about this area, and we believe further investigation is called for.

In our most likely scenario, we have chosen to use 50% of the annual acreage of traditional annual crops for winter cover crops and about 70% of forest waste in our estimates. Each of these sources offers benefits. The DOE noted that major primary sources for forest biomass would be logging residues and fuel treatments, and that much of the forest material we project to use “has been identified by the Forest Service as needing to be removed to improve forest health and to reduce fire hazard risks.”[3] With regards to winter crops, our estimates suggest that any feedstock transportation beyond about 50-75 miles (preferably under 30 miles) will reduce its competitiveness, unless the crop is very low cost (like winter cover crops), in which case a maximum 100 mile radius might make sense. Energy crops and winter cover crops will reduce the need of substantial transport infrastructure for biomass and answer critics’ questions about infrastructure. If these plants were distributed around the country it would substantially reduced need for infrastructure. Smaller pipelines will be needed if most of the biofuels are not concentrated in the Midwest. Biomass crops will be widely distributed and will minimize the need for this infrastructure.

What are the price points needed for biomass to be profitable for farmers? Professor David Bransby notes that his communication with farmers suggests $60 per ton for switchgrass and similar crops would be reasonable, with the breakeven price decreasing as yields increase. Based on a switchgrass price model developed at the University of Auburn, the graph below highlights (one set of estimates) farmers’ breakeven points for given yields and prices. Its worth nothing that even at a $50 per ton price point, yields of as low as 7-8 tons/acre (which we are exceeding now) would allow farmers to be profitable.



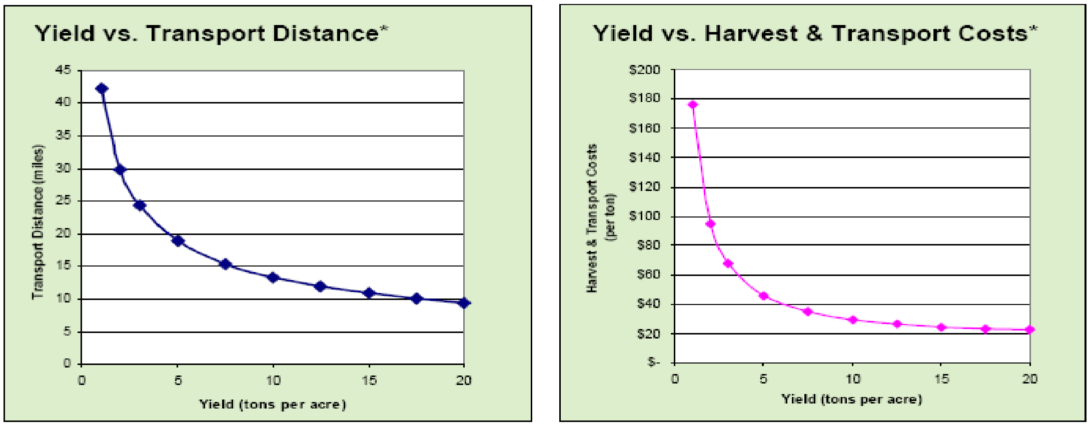
What is the competitiveness of biomass vis a vis a oil? Since an air dry ton of biomass contains about 2.5 times the energy content of a barrel of oil (14.5 million btu vs. 5.8 million btu), $50/barrel oil could theoretically be competitive with $125/ton biomass. However, given the high cost and nascent nature of biomass processing, we believe a more conservative estimate is needed initially – as biomass processing costs decrease, we will see increases in the price of biomass (towards the 2.5 times oil price point) for farmers even as it remains competitive with oil. Today, we think a competitive feedstock cost based on current conversion efficiencies (which are subject to improvement), delivered to the factory, has to be below $50/ton of dry biomass (plus or minus 25% depending upon feedstock type) to compete with $50/barrel oil (which we are unlikely to see again without significant reduction in demand).

As per the pricing constraints above, we limit (in our estimates) potential incremental land using feedstocks to crops that yield over 10 tons/acre in the mid-term – effectively, “energy crops”. The Royal Society’s “Sustainable Biofuels”[4] report notes the following:

> “a significant advantage of developing and using dedicated crops and trees for biofuels is that the plans can be bred for purpose. This could involve development of higher carbon to nitrogen ratios, higher yields of biomass or oil, cell wall lignocellulose characteristics that make the feedstock more amenable for processing ... Several technologies are available to improve these traits, including traditional plant breeding, genomic approaches to screening natural variation and the use of genetic modification to produce transgenic plants. Research may also open up new sources of feedstocks from, for example, novel non-food oil crops, the use of organisms taken from the marine environment, or the direct production of hydrocarbons from plants or microbial systems.”

We should also note that a number of “biomass densification” technologies are being investigated that may ultimately reduce biomass transportation costs even further but are currently in early research stages. For example, one approach is the production of “bio-oil” at small-scale localized biomass pyrolysis units. This bio-oil can then be transported to a centralized facility for conversion and up-grading to ”biocrude” that can go into an existing refinery or used as-is for applications like home heating oil (Kior).

Yield density both reduces transport distance (thereby reducing transport cost) and improves economy of scale for use of harvesting equipment



* Assumes a 10,000 ton/day processing facility with 50% of surrounding land used for biomass

Source: David Bransby & Ceres [5].

As discussed earlier, we estimate feedstock costs need to be under $50 per ton delivered within the next decade (and lower in the short run) to compete with $50/barrel oil. Switchgrass and miscanthus-like grasses (C4 photosynthetic grasses) and certain trees are the most likely feedstocks to provide our liquid fuel requirements in the long run. Tree crops developed for the paper pulp business will also make for good sources of biomass. Many client paper mills have recently gone out of business and these communities are crying for local economic stimulus and jobs. Given these prices, biomass has the potential to substantially increase farm income and reduce the need for farm subsidies.

The DOE Billion-Ton report confirms many of our conjectures. It notes: “It is assumed that significant amounts of land could shift to the production of perennial corps if a large market for bioenergy and biobased products emerges.” It further notes that studies have shown that “if a farmgate price of about $40 per dry ton were offered to the farmers, perennial grass crops producing an average of 4.2 dry tons per acre (a level attainable today) would be competitive with current crops on about 42 million acres of cropland and CRP land.”[6] We do note that this report was published in 2005, and fuel and fertilizer costs have increased rapidly since then – updated research is needed. We also believe yields of 2-6 times these estimates are feasible by 2030.

Waste Feedstocks?

While we believe that energy crops will meet most of our feedstock needs, we have invested our time and money in the potential of waste feedstocks as we think they can make a material impact and reduce the above cited biomass needs by an additional 10-20% or more! Promising waste feedstocks include municipal sewage even municipal solid waste - the paper, wood, construction waste, even lawn clippings that are brought to a landfill. Something that has been a problem (especially with disposal) may soon become an opportunity! There is sufficient municipal waste to produce tens of billions of gallons of ethanol. The waste is available in large enough quantities (in most major cities) to justify waste-specific plants and actually has a negative cost (usually a tipping fee). We’re also intrigued by the possibility of using farm organic waste One of our favorites is a proposal to take all the waste carbon monoxide from steel mill flue gases (already collected and piped, available to go into a process!) to make ethanol. There is enough carbon monoxide coming out of today’s steel mills to produce over fifty billion gallons of ethanol![7]. Forest waste could be treated similarly and is discussed below.

Scenario Planning

Now to the numbers. How much biomass can we get to convert to biofuels without subsuming other uses for land and biomass? More than enough! There are four principal sources of biomass and biofuels we consider (1) energy crops on agricultural land and timberlands using crop rotation schemes that improve traditional row crop agriculture AND recover previously degraded lands (2) winter cover crops grown on current annual crop lands using the land during the winter season (or summer, in the case of winter wheat) when it is generally dormant (while improving land ecology) (3) excess non-merchantable forest material that is currently unused (about 226 million tons according to the US Department of Energy), and (4) organic municipal waste, industrial waste and municipal sewage.

For the US, the world’s most oil intensive economy, our calculations show that a small dose of vision, two decades of agricultural development, and process technology that is in pilots today, with less than 5% of our annual crop and timberlands could more than supply our biofuels needs to replace most of our light-vehicle gasoline usage by 2030. The table below shows one of many possible scenarios – in the scenario below, we assume about 50% of the total annual crop acreage (317M acres) is used with winter cover crops; approximately 70% of excess forest waste identified by the DOE is used, and assume that waste-based (municipal organic waste, sewage, steel mill flue gases, industrial waste, etc) ethanol accounts for 10% of total demand by 2030 – resulting in dedicated energy crop usage of approximately 15M acres (The assumptions are covered in Appendix A).

Scenario 1

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	102.3	48.9	4.1	3.4	20.8	10.9	14.0	10.9	1.3	1.7	2.6
2020	30.0	3.0	107.5	251.1	42.9	3.8	68.3	15.4	19.4	15.4	1.3	1.7	2.5
2025	87.6	8.0	110.0	724.1	142.5	4.2	125.5	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	15.0	110.0	1227.3	158.5	4.6	158.0	24.5	334.2	24.5	13.6	18.2	27.3

How Do We Get There?

Total Biomass	=	Winter Cover Crops:	Forest Excess Waste:	Dedicated Crop Land:
2015: 49M tons	=	14M tons	21M tons	14M tons
2020: 251M tons	=	163M tons	68M tons	19M tons
2025: 724M tons	=	599M tons	126M tons	0M tons
2030: 1227M tons	=	735M tons	158M tons	334M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	13.6	18.2	27.3
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-1.9M acres**	**2.7M acres**	**11.8M acres**

While our projections above are based on our most likely scenario, other scenarios are possible. We project a range of scenarios using 50% or 70% of our annual crop lands for winter cover crops, using 50%, 70%, 100% of sustainable, harvestable forest waste, energy crop yields 12,18,24 tons/acre with and without usage of waste like municipal sewage and organic waste, and yields of 110 and 130 gallons ethanol equivalent fuel per dry ton. Early experimental data have shown that other biofuels may produce yields equivalent to 150 gallons of ethanol equivalent biofuels per ton (as opposed to the 110 projected in the table above), long before 2030; (based on data disclosed confidentially to us). In this (optimistic) scenario, ALL of our light-vehicle transportation needs would be met without using any additional devoted energy cropland! Going further, the USDA projects corn ethanol production of 9.3 billion gallons in 2008 – at 2.8 gallons per bushel and 150 bushels per acre, that suggests that 22M acres of corn crop is being devoted to corn ethanol today – 70% of this land could be "released" and reused for other purposes (we assume that all ethanol production by 2030 will be cellulosic). We have outlined six potential scenarios in Appendix A (a summary is provided here – scenario 1 is highlighted above).

Scenario	Waste Resources (% of total ethanol demand in 2030)	Winter Cover Crop - % of annual crop land/ acres	Winter Cover Crop Yield (Tons Per Acre)	Excess Forest Biomass (Millions of Dry Tons)	Biofuel Yields (Gallons per Ton)	Dedicated Land Use @ 24/18/12 tons/acre (Millions of Acres)	Net Land Use @ 24/18/12 tons/ acre (Millions of Acres)
1:	10%– 15B gallons	50% – 159M	3-4.6	70% -158Mt	90-110	13.6 / 18.2 / 27.3	-1.9 / 2.7 / 11.8
2:	-	50% – 159M	3-4.6	50% -113Mt	90-110	21.0 / 28.1 / 42.1	5.5 /12.6 /26.6
3:	-	50% – 159M	3-4.6	50% -113Mt	90-130	12.5/16.6/25.0	-3.0 / 1.1 / 9.5
4:	-	50% – 159M	3-4.6	70% -158Mt	90-130	10.6/14.2/21.3	-4.9 / 1.3 / 5.8
5:	-	50% – 159M	3-4.6	100% -226Mt	90-130	7.9/10.5/15.7	-7.6 / -5.0 / 0.2
6:	10% –15B gallons	70% – 221M	3-4.6	100% -226Mt	90-130	0	-15.5

We should also note the point about water usage – cellulosic ethanol has come under attack recently for excessive water usage, again without doing an apples-to-apples comparison with gasoline. Producing one gallon of gasoline uses 2-2.5 gallons of water[8]; producing one gallon of cellulosic ethanol (through the Range/Coskata processes) uses 1 gallon on water. Even account for the mileage discount of ethanol vs. gasoline (which we expect to decrease from 25% in 2020 to about 15% by 2030), the water usage of cellulosic ethanol is significantly lower than that of gasoline on a per mile driven basis! We assume that energy crops will grown as rainfed unirrigated crops.

Take Scenario 1: the key assumption here is recovering 3 tons/acre of biomass additionally per year from winter cover crops (growing to 4.6 tons/acre, or just over a 1.5% a year productivity increase). For conservation, we have not separately provided for summer annual crop biomass residue. Using crop residue plus winter crops will provide for higher yields and allow substantial biomass to be plowed back into the soil for sustainability. Based on point data reports on energy crop yields and detailed in part III, we assume that 24 tons/acre of energy crop yields can be achieved by 2030, starting at 7 tons/acre in 2008.. However, the net land use requirements are immaterially affected if yields are assumed to be 25% or 50% lower, since winter cover crops provide the bulk of the biomass. It should be noted that the 3 tons/acre of biomass from winter cover crops could be made up of actual winter cover crop yields and use of parts of the biomass (corn stover, wheat straw, etc) from annual food crop cultivation. And that's only the beginning – one of our investments is working to improve the mileage efficiency of the standard ICE (Internal Combustion Engine) by 50-100% for ethanol and gasoline dramatically reducing biomass needs! Increased CAFE standards will help too. Additional degraded land can be recovered if our 10 year by 10 year biomass crop rotation scheme is followed (described in Part II), though we have not modeled this. In combination with the other factors listed above, we are confident that our biomass needs will not be a limiting factor by 2030. Furthermore, they will neither encroach on land needed for food production, nor cause destruction of tropical rain forests that are vitally important resources for carbon sequestration and control of green house gases.

Diesel Replacement

While gasoline is the primary focus of much of this research, a diesel replacement is also a vital goal. Today, an alternative fuel like "classic" biodiesel (diesel produced mostly from vegetable oil) can meet some needs, but its inability to scale and its vegetable oil source will prevent it from being a relevant scale replacement for petrodiesel in the long run – it lacks trajectory. And it creates a food versus fuel controversy. We are very negative on classic biodiesel (see our Biodiesel paper). The primary feedstocks for classic biodiesel are vegetable oils such as rape seed, soybean and palm oil, with sources such as jatropha being used in India and other parts of the world. Unfortunately, none of these sources has high enough yields per acre - soybean oil yield is around 40-50 gal/acre, rape seed around 110-130, and jatropha at 170-180, while palm oil reaches as 630-650 gal/acre[9]. Jatropha does have the benefit of growing on non-food crop lands, limiting any food vs. fuel conflicts. Because food grains are well-optimized crops (with the exception of jatropha and algae), we don't expect vegetable oil yields to increase significantly over time (a 2X is projected for corn by 2015). As mentioned earlier, we believe that a sustainable biofuel needs yields of at least 2,000 gallons per acre (hopefully 3,000!) in the long run to produce the worlds oil replacement needs on a manageable amount of land. Unfortunately, none of the classic biodiesel sources comes close to these targets.

A source that can achieve these minimum yields is algae, which has not been optimized. However, there are many challenges for producing diesel from algae. Growth can be in open ponds or in enclosed bioreactors. Open ponds are the simpler, more economic approach. Enclosed bioreactors can be used to achieve higher yields but with increased capital and operating costs and we are skeptical about their economics. Methods such as the tools of synthetic biology can be used to improve the productivity of algae; however, these genetically engineered organisms are going to be controversial in open oceans. Hence we are cautious about investing in bioengineered algae. Our preferred source to replace petrodiesel is to use cellulosic biomass based "cellulosic diesel". Companies such as our investments in Amyris, LS9, Kior, and others believe they can produce diesel and jet fuel replacement at substantially lower costs than food oil based diesel (below $1.75 per gallon) while getting all the high yield benefits of cellulosic biomass sources. At 2,500 gallons per acre and approximately 40 billion gallons of diesel usage (for on-road transportation[10]), we will need roughly an additional 16M acres to meet our transportation diesel needs in the US.

It is worth noting that unless we dramatically reduce carbon emissions and stop global warming, millions of acres of land will be "dislocated" from its current uses and must be figured into the "net land use" equation. Though many technologies will contribute to displacing oil based fuels, we don't believe any other technologies are pragmatically likely to achieve as large a reduction in emissions from transportation fuels as cellulose-based processes. A recent Booz Allen Hamilton study noted that worldwide, there is up an additional 6 billion acres of rain-fed land that is available for agricultural production (clearly, there would be opportunity cost associated with this land use). Farmers will make more money, we will sell less subsidized crops (an issue over which the Doha round of trade talks have broken down as developing countries demand fewer agricultural subsidies in the west. Organizations like Oxfam now oppose the dumping of subsidized US food crop in Africa, where agriculture is often the only means of income generation). We will import less oil and export fewer crops allowing farmers in poor countries to make a living (helping reduce third world poverty) while we in the US improve our trade balance.

Part II: Better Agronomy for Energy Crops

We believe improved crop practices are a vital aspect in meeting our cellulosic feedstock needs. There are a few areas that offer significant potential – (i) crop rotation, (ii) the usage of polyculture plantations, (iii) perennials as energy crops, and (iv) better agronomic practices. We address all four issues here. Though none of these have been extensively studied, early studies and knowledgeable speculation point to their likely utility. Further study of these techniques is urgently needed; especially the use of grasses or other biomass optimized winter cover crops.

(i) We have proposed the usage of a 10 year x 10 year energy and row crop rotation. As row crops are grown in the usual corn/soy rotation, lands lose topsoil and get degraded, need increased fertilizer and water inputs and decline in biodiversity. By growing no-till, deep rooted perennial energy crops (like miscanthus or switchgrass - see below) for ten years following a ten year row crop (i.e. - corn/soy) cycle, the carbon content of the soil and its biodiversity can be improved and the needs for inputs decreased. The land can then be returned to row crop cultivation after ten years of no-till energy crops. Currently unusable degraded lands may even be reclaimed for agriculture using these techniques over a few decades. A University of North Dakota study[11] highlights some of the benefits for food crops. We expect similar or even greater benefits for food crop/energy crop long cycle (ten year) rotations, especially in soil carbon content: (1) Improved yields –a crop grown in rotation with other crops will show significantly higher yields than a crop grown continuously. (2) Disease control– changing environmental conditions (by changing crops) changes the effect of various diseases that may set in with an individual crop, and crop rotation can limit (and often eliminate) diseases that affect a specific crop. (3) Carbon content - Energy crops in the rotation can increase soil carbon content and reduce the impact of top soil loss materially. (4).Better land: the study notes farmers practicing crop rotations comment on improvements in soil stability and friability. In addition, crop rotations have the potential to increase the efficiency of water usage (by rotation deep-rooted and more moderately-rooted crops or rotation of perennials in long cycles with row crops)

One manifestation of the crop rotation approach is the idea of utilizing cover crops – crops such as grasses, legumes, or small grains that are grown between regular crop production periods (i.e.

– the winter for most crops, and the summer for winter specific crops such as winter wheat). As Part I details, Professor David Bransby has noted that such crops require no additional irrigation, and use about 30% of the fertilizer of regular crops like corn. Elsewhere, Professor Greg Roth at Penn State is studying the usage of specific winter cover crops (like hulless barley), and has noted it could be used to increase biofuel yields per acre[12]. In communication, Professor Roth notes that "One factor to consider for future research and thinking in this area is that winter cover crop yields are increased with earlier planting, especially in northern states. Planting is often delayed because we are waiting for the primary crop to dry down. If the primary crop can be harvested just after physiological maturity, then yield of both the primary and winter cover crops can be maximized." He further noted that the system as a whole provides an excelling living ground cover. In addition to providing biomass, winter cover crops provide the benefits of crop rotation – adding organic matter to the soil (even if top growth is removed to produce energy, root systems remain in the soil), recycling nutrients, and more efficient usage of soil and water resources. Research cited by the National Sustainable Agriculture Service notes that the replenishment of organic matter is substantial – "The contribution of organic matter to the soil from a green manure crop is comparable to the addition of 9 to 13 tons per acre of farmyard manure or 1.8 to 2.2 tons dry matter per acre"[13]. They also note that the soil conservation benefits of cover crops are immense – not only do they protect the bare soil when the major crop is not being grown, but "the mulch that results from a chemically or mechanically killed cover crop in no-till plantings increases water infiltration and reduces water evaporation from the soil surface. Soil cover reduces soil crusting and subsequent surface water runoff during rainy periods." Further study of these winter cover crops as a potential biomass source is needed, but they could provide a significant portion of our biofuels land needs while improving the land's ecology over just planting row crops and leaving the land unused during the winter. This will also improve row crop agriculture during the summer. It is even possible that winter cover crops could eliminate the need for most additional lands to meet our biofuels needs in the US. We summarize the benefits of winter cover crops in Appendix B.

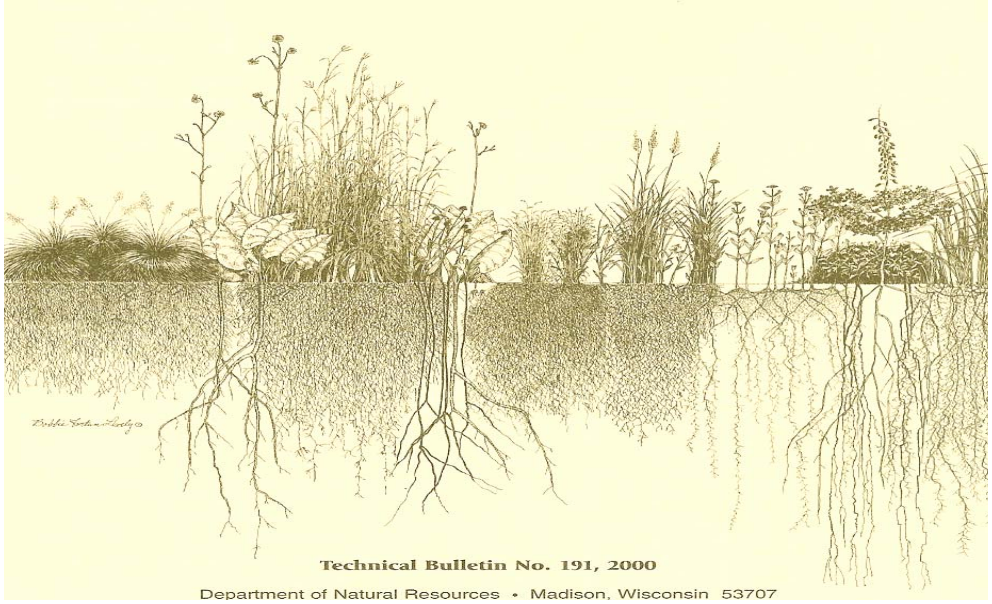
In addition to winter cover crops, we are intrigued by the possibility (though further research is clearly needed) of short rotation coppice, which the Royal Society describes as a "system of semi-intensive cultivation of fast-growing, woody species as coppice, over rotations that are short compared with cultivation of high forest, although lengthy by comparison with the annual cycle of most agricultural crops. SRC is established with different species and hybrids." In particular, the emphasis to this point has been on poplars, which are "recognized model systems for woody species, with a broad genetic base for breeding, an extensive understanding of genetics, the availability of a sequenced genmore and a well-established set of molecura tools that can be used for improvement of tree species."

(ii) Another important crop practice is the idea of utilizing polyculture species instead of monocultures. This is particularly possible for energy crops as many processes can accept a mixture of biomass types. The Land Institute notes that polycultures (and the resulting plant diversity) have significant benefits – from the provision of an "internal supply of nitrogen, management of exotic and other harmful organisms, soil biodiversity, and overall resilience of the system." Further research shows that grasslands that suffer from overgrazing or drought tend to recover faster if there is greater biodiversity. The Australian Rural Industries Research and Development Corporation notes that "Polyculture is shown to offer the proverbial 'free lunch' by producing more from less."[14]The report goes on to note that polycultures yield in greater amounts from smaller areas, and their yields are generally more stable than monocultures (with regards to income level and general risk). Furthermore, polycultures were found to be more efficient in gathering resources such as light, water, and soil nutrients. Other researchers have found similar potential in the yields and environmental benefits of polyculture crops. Though it is hard to extrapolate data from low production potential areas (where these studies were conducted) to the high production potential areas that are needed, we think this is an area that requires further exploration and study. These benefits are starting to gain recognition - Ceres Corporation has proposed an alternative approach they call polycultivation.

Lush green alfalfa[15]

Cover crop growth[16]

Illustration of Polyculture Prairie[17]



(iii) Perennial crops: As opposed to standard, annual crops which need to be replanted yearly, perennial crops (hopefully in polyculture prairies) will produce for multiple years before requiring replanting. As the Land Institute notes, the perennial plants provide significant advantages – from cover against wind and soil erosion, to improved soil quality over time. They note that “it has been shown that restoring former cropland to perennial vegetation can actually return much of the soil structure and function characteristic of original prairie ecosystems.”[18] The Royal Society notes that “the use of perennial crops and trees may reduce N_2O emissions and provide large yields with the addition of nitrogen." Similarly, the DOE's Office of Science notes that "perennial grasses and other bioenergy crops have many significant environmental benefits over traditional row crops. Perennial energy crops provide a better environment for more-diverse wildlife habitation. Their extensive root systems increase nutrient capture, improve soil quality, sequester carbon, and reduce erosion."[19] Plowing releases an enormous amount of carbon from the soil into the atmosphere. So, by simply eliminating tillage perennial energy crops sequester vast quantities of carbon, in addition to the carbon added to the soil in their roots. The NRDC (National Resources Defense Council) study, "Growing Energy" points out the advantages of a perennial crop (switchgrass) over most traditional row crops – "on average, switchgrass requires less fertilizer, herbicide, insecticide, and fungicide per ton of biomass than corn, wheat, and soybeans."[20] In addition, the study shows the cultivating switchgrass reduces soil erosion and improves soil carbon. The advantage of increased soil-carbon is two-fold – a higher sequestration of carbon in the soil (and thus reducing carbon dioxide in the air), as well as an improvement of soil organic matter levels – truly a win-win scenario. Infact the NRDC shows that negative carbon emissions per mile driven are possible with biomass crop based fuels!

Annual vs. Perennial Root Systems[21]

The extensive roots of perennials and subsequent access to nutrients reduces the need for fertilizer (and thus farmer costs), while their evolution in naturally-occurring ecosystems has provided them with a greater resiliency to stresses such as droughts, diseases, and insects. Today, perennial grasses like switchgrass offer significant potential as energy crops. While this has been difficult for row crops, energy crops are most suited to perennial, polyculture cultivation.

Importantly, the usage of these crop practices around perennial, crop rotated energy crops will offer significant benefits to farmers themselves. One example of the usage of perennial crops is highlighted in a 2002 University of Illinois study[22] – (along with other research by Ceres) – on strictly economic terms, farmers are likely to be better off with miscanthus (a perennial grass) farming vs. a standard corn/soy rotation. The study in question pointed out that a 10 year rotation was likely to yield negative income (based on historical prices) for the corn/soy farmers (hence the need for subsidies) as opposed to a significant profit when growing the energy crop, with improving soils and reduced needs for water and fertilizer even during the row crop phase of the rotation. We do note that corn prices have changed significantly since this study, and results are probably different today. In light of this opportunity, companies like Bical (UK) have been setup to provide “renewable and profitable diversification for farmers and landowners.”[23] Today, it is Europe’s largest miscanthus developer and commercial producer.

(iv) Improved Agronomic Practices: In addition to the changes highlighted here, the usage of better agronomic practices can also have a significant impact in raising yields. More than 85% of all corn grown in the US is non-irrigated, leading to efficient water usage.[24] Elsewhere, the previously cited University of North Dakota study notes that practices like no-till or minimum till farming with crop rotations have been shown to reduce wind and water erosion. The NCGA (National Corn Grower’s Association) notes that no-till farming is “a practice whose time has arrived.”[25] The CTIC (Conservation Tillage Information Center) notes that 20% of all corn surveyed is now grown utilizing no-till practices. These practices have bourn fruit – even as the corn harvest has increased rapidly over the past 20 years, farmers have reduced soil erosion by 44% using a combination of conservation tillage and other soil-caring practices.[26] Energy crops will accelerate these trends dramatically because they make the farmer more money. Other benefits to conservation practices exist: Professor David Montgomery of the University of Washington notes that “No-till farming can build soil fertility even with intensive farming methods. It could prove to be a major benefit in a warming climate. By stirring crop residue into the soil surface, no-till farming can gradually increase organic matter in soil, as much as tripling its carbon content in less than 15 years."[27]

Some concern has been raised about the risk of candidate biomass crops becoming invasive. We strongly oppose the use of species that are already invasive for production of biomass feedstocks, including plants like giant reed (*Arundo donax*), johnsongrass (*Sorghum halapense*) and water hiacynth (*Eichhornia crassipes*), since it is not necessary to use such species when others that have no record of being invasive are available. The current top priority candidate biomass crops include switchgrass (*Panicum maximum*), sugarcane and energy cane (*Saccharum* spp), high producing annual sorghums (*Sorghum* spp) and miscanthus (*Miscanthus x giganteus*). Switchgrass is native to North America, and is recommended for planting on Conservation Reserve Program (CRP) land where it occupies millions of acres and has shown no evidence of becoming invasive. Sugarcane and sorghum have been grown commercially on millions of acres throughout the world for over a century, also without evidence of becoming invasive. Miscanthus does not have as long an agricultural history, but has been under evaluation in Europe for over 2 decades where it is now in commercial production. Since it is similar to sugarcane, in that it does not produce seed, it is reasonable to assume that it is not invasive. The top priority woody species are hybrid poplar (*Populus* spp.) and willow (*Salix* spp), and these species have also shown no sign of becoming invasive.

As biomass crops are developed further, new genetic material needs to be evaluated for its invasive potential prior to being released. This will require development of procedures to conduct such evaluation, as well as a regulation process to prevent use of crops with clear invasive potential from being cultivated on a commercial scale. It is assumed that the recently formed Council for Sustainable Biomass Production (www.csbp.org) will guide the development of such a process, along with addressing several other environmental issues related to the emerging cellulosic bioenergy industry.

Part III: Yields – The most critical Assumption

Our most critical assumption with cellulosic biofuels is on land efficiency (tons of biomass per acre and hence gallons of fuels produced per acre – or more accurately, miles driven per acre) – we believe biomass yields per acre will improve 2-4 times from today's norms. The lack of genetic optimization and research on cultural practices, harvesting, storage and transport with would-be energy crops (like miscanthus, sorghum, switchgrass and others) means that there is significant potential for improvement. The Royal Societies report notes that miscanthus is " can be cultivated with low inputs in marginal land, but biomass yield is linked to inputs and may improvements will be required. As yet, there is little molecular understanding of the crop, its genetics and its agronomy and a number of additional issues, including the optimization of harvesting processes remain to be resolved." The application of advanced breeding methods like genetic engineering and marker assisted breeding, limiting water usage through drought resistant crops, and large-scale application of biotechnology (i.e., optimizing the process by which plants conduct photosynthesis, or reducing stress-based yield losses) will also contribute to increased yields with fewer inputs. More importantly, different energy crops are likely to be optimal for different climates- jatropha makes sense on degraded Indian land, but not in the American Midwest. Algae are discussed under Biodiesel energy crops. Rather than a single dominant energy crop, we are likely to see a variety of feedstocks that allow specialization to local conditions, mixes and needs while mitigating the risks. [28]

Some reported examples and data points of biomass yields speak to the feasibility of our estimates of yields between 18-24 tons per acre by 2030:[29]

- Miscanthus averaged 16.5 dry tons per acre per year, where switchgrass averaged 4.6 at 3 Illinois sites, with data taken over 3 years. Research in Europe notes yields ranging up to 16 dry tons per acre.[30]

- Sugarcane ventures in Brazil (Allelyx is using GMO techniques, Canavalis is using more traditional plant breeding) are breeding energy cane that will likely result in a yield of 25 dry tons per acre/year of harvestable biomass. Similar progress is being made by USDA sugarcane geneticists in Louisiana.[31]

- Megaflora Corp. has measured productivities of 28 dry tons per acre per year from crossing North American Hardwoods with the paulownia tree in North Carolina.[32]

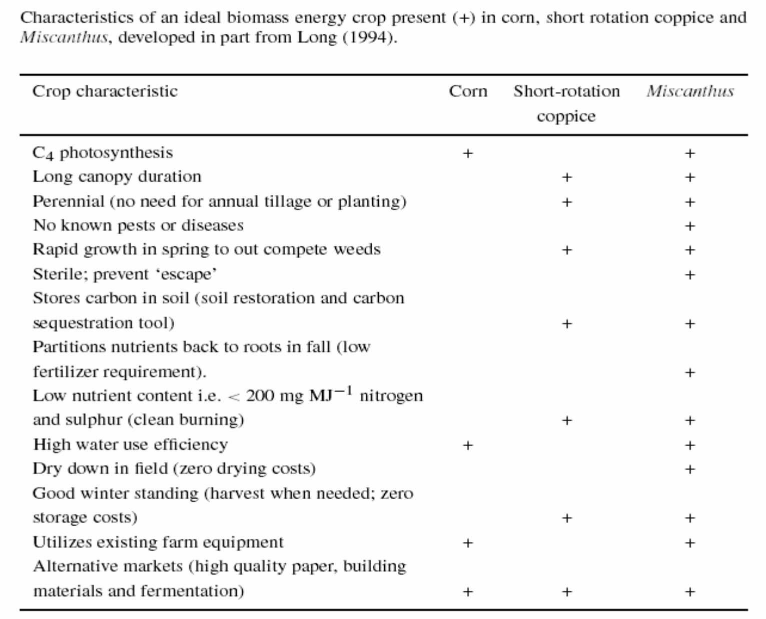
- Anagenesis Corp trees quotes "one acre can yield 48x times as much ethanol as an acre of corn".[33]

- DOE estimates suggest that collecting existing biomass with only a small change in agricultural practices could generate 1.3 billion dry tons of biomass in the US (most of our biomass needs) and still be able to meet all food, feed, and export demands.[34]

- High yield sorghum can be grown in 35 US States and produce yields as high as 25 dry tons per acre/year with low water usage[35]

- Researchers at Texas A&M have developed new “freakishly tall sorghum plants” that reach heights of nearly 20 feet – more than double the height of regular sorghum and yielding double the amount of crop per acre.[36] They use little water, and have been bred to prevent flowering (thus trapping more energy), and can be grown on marginal crop lands.

A wide variety of crops have potential as feedstocks for cellulosic ethanol. Bical notes that “The criteria for the ideal energy crop are high dry matter yield, perennial growth, and efficient use of nitrogen, water, other resources, and pest and disease resistance.” The previously cited U of Illinois study compared corn, short-rotation coppice, and miscanthus versus a set of idealized criteria for energy crops and found miscanthus (and by extension, other C4 photosynthetic grasses) to meet most of the requirements (see charts below).[37] Of particular interest to us is miscanthus that “partitions nutrients back to the roots in the fall just before harvesting”. We figure crops that provided (and survived) energy for mammals in the prairies can now provide energy for humans!



Characteristics of an ideal biomass energy crop present (+) in corn, short rotation coppice and *Miscanthus*, developed in part from Long (1994).

Crop characteristic	Corn	Short-rotation coppice	*Miscanthus*
C_4 photosynthesis	+		+
Long canopy duration		+	+
Perennial (no need for annual tillage or planting)		+	+
No known pests or diseases			+
Rapid growth in spring to out compete weeds		+	+
Sterile; prevent ‘escape’			+
Stores carbon in soil (soil restoration and carbon sequestration tool)		+	+
Partitions nutrients back to roots in fall (low fertilizer requirement).			+
Low nutrient content i.e. < 200 mg MJ^{-1} nitrogen and sulphur (clean burning)		+	+
High water use efficiency	+		+
Dry down in field (zero drying costs)			+
Good winter standing (harvest when needed; zero storage costs)		+	+
Utilizes existing farm equipment	+		+
Alternative markets (high quality paper, building materials and fermentation)	+	+	+

Many of the advantages of miscanthus are also applicable to some of the other proposed feedstocks. The new, higher-yielding strains of sorghum developed at Texas A&M use less water than conventional sorghum (making them more drought-resistant), and are sterile (not flowering prevents the escape of energy) - their 20-feet heights mean that yields have effectively doubled. The table below (from Ceres) highlights the advantages and disadvantages of various feedstocks-

-however, it is notable that most non-cellulosic sources (example, vegetable oils) would fail on the vast majority of the criteria.

Crop Traits[38]	Energycane	Miscanthus	Poplar	Sorghum	Switchgrass
Efficient photosynthesis	■	■		■	■
Long canopy duration	■	■	■	■	■
Nutrients recycled to roots		■			■
Low crop inputs		■	■	■	■
Low fossil fuel inputs		■	■		■
Adapted to marginal land		■	■	■	■
Minimal pests/plant diseases		■			■
Non-invasive or sterile	■	■	■	■	■
Easily removed	■	■		■	■
Winter standing		■	■		■
High water-use efficiency	■	■		■	■
Planted by seed				■	■
Harvest first year				■	

Examples abound of people in action on energy crops. Ceres has been attacking the problems from a multitude of angles, and is utilizing biotechnology in combination with better crop practices (such as those highlighted earlier). Firstly, they are attempting to increase the usable land available, by working on crops that can deal with problems such as drought tolerance (and recovery), heat tolerance, salt tolerance, and even cold germination. They are also working on increasing yields with plants that have shorter flowering times, greater photosynthetic efficiency, and greater shade tolerance Additionally, they are attempting to reduce the costs per acre by increasing the efficiency of nitrogen utilization, improving the efficiency of photosynthesis with lower nitrogen usage, increasing the biomass present in the root of the plant, and reducing costs through enzyme production while working to increase the gallons per acre that result from various feedstocks. They are also proposing better agronomy techniques like polycultivation (plots of monoculture crops interleaved together) as opposed to a polyculture (mixed crop cocktails). As a whole, the company is developing genetically modified, commercial energy crops, and expects to have proprietary commercial varieties ready for market in 2-3 years and transgenic varieties in 5-7 years. There are others with similar efforts.

Criticism – Science Article

Recently, the production of biofuels has come in for considerable criticism from sources. While there has been a tendency for much of this criticism to originate from sources with a vested interest in bashing biofuels, there has been significant attention to a recent article published by Professor Timothy Searchinger in Science. In summary, Professor Searchinger's article attempts to model the effect of converting land from other purposes to feedstock production for biofuels production and conclude that significant greenhouse gas emissions are associated with this conversion.

We disagree with Professor Searchinger's specific conclusions, while finding areas of agreement. Our key difference lies in his assumptions of yields – his assumptions analyzed land emissions with the usage of switchgrass and assumed yields of 18 tons / hectare and 660 gallons of biofuels per acre – levels that can we exceed today (using dedicated energy crops). Furthermore, they assume production levels of corn ethanol reaching 30 billion gallons – a quantity more than double of the maximum considered likely for corn ethanol. Additionally, while the paper project carbon debt for vast periods, it fails to quantify yield improvements in terms of tons per acre, gallons of ethanol per ton, and the adoption of newer technologies. The potential for waste outline in the US Department of Energy biomass study is completely ignored. The study points out that with no material additional land use up to 1.3 billion tons of sustainable biomass "without a significant change in agricultural practices". With regards to carbon emissions, its clear that biofuels can be done right, or they can be done poorly, as Prof Searchinger reinforces – but there is a significant difference between Malaysian palm-oil based biodiesel and cellulosic ethanol, and the assumption that widespread biofuel usage would lead to deforestation (as a result of the former) is unlikely if right policies are enacted– no serious proponent of biofuels believes clearing forest land for palm oil is a desirable long-term proposition. As we note at the beginning of this paper, we propose a "CLAW"-like rating for fuels to be acceptable on the marketplace that should help assess the actual environmental impact of various fuels and feedstocks.

While we did find these areas of disagreement with Professor Searchinger, personal communication suggested areas where we do agree. He notes that "I am particularly excited about the prospects for making substantial quantities of biofuels from waste products and cover crops", and notes that their papers should have discussed the cover crops as a viable biomass source. In addition, we agree with his belief that there should be a focus on utilizing unproductive lands – he cites tropical grazing land as one source that is unproductive relative to their potential (although still substantial sources for the world's agricultural expansion). Professor Searchinger also notes that "a key question therefore is whether these wetter grazing lands can be used to produce biofuels, which depends both on the technical capacity to dramatically increase annual biomass production and on policies to assure that the loss of these grazing lands does not trigger additional conversion to replace them either for commercial meat product or subsistence." We are convinced that the answer is positive, especially through the usage of new technology, such as the thermochemical processes being utilized by Range and Coskata. While fundamental areas of disagreement remain, we are confident that the approach we propose eliminates many of the standard criticisms of biofuels (excessive land use, the food v. fuel discussion, environmental impact) while offering significant upside.

Research and Policy – What Need To Be Done?

As we've highlighted in the paper, we believe that we can replace most of our gasoline usage with biofuels within the next 25 years. However, we believe that there are a few areas of research focus that are vital to getting there. In addition, specific policy steps must be taken in order to help achieve these goals. While we disagree with some of the policy conclusions of the Royal Society report (next section), it does highlight issues key goals of research going forward.

Royal Society:

- " increased yield per hectare of feedstock while reducing negative environmental impacts;

- development of new feedstocks that can, for example, be grown in more hostile environments, be more readily processed and be capable of generating a variety of products;
- improved methods of processing, in particular for lignocellulose feedstocks;
- new physicochemical systems for biofuel synthesis;
- development and demonstration of integrated biorefineries;
- integration of the supply chain to gain the maximum efficiencies;
- integration of biofuel development with engine development;
- internationally agreed methods of assessing sustainability."

While these are valuable areas of focus, we have highlighted specific practices and areas that we consider to be the most promising

- development and research into the viability of winter cover crops as long-term biomass sources
- research into sustainable, environmentally beneficial agronomic practices such as crop rotations
- increased study of the biomass/agronomic potential of natural systems such as polycultures and perennial crops
- development of crops/systems that help restore soil nutrients and thus help restore degraded land

From a policy perspective, The Society notes that a coherent approach will:

- "avoid the unintended consequence of solving one problem at the expense of exacerbating another;
- see biofuels as part of a portfolio of approaches that also includes, for example, greater energy efficiency, electric vehicles, hydrogen and fuel cells, and price and tax incentives such as carbon pricing based on avoided greenhouse gas emissions;
- balance growth of feedstock supply against other existing and potential uses of land;
- deploy an assessment of sustainability that encompasses the complete cycle from growth of the raw material to end use irrespective of where each stage in the cycle takes place;
- commit to adequate public and private investment in the required research and development (R&D);
- provide aptly targeted regulatory and fiscal incentives;
- develop a process for effective public engagement on biofuel issues"

While we agree with the idea of avoiding unintended consequences to the best of our abilities, we should not understate the problem at hand – our current oil usage is not sustainable on an environmental or economic basis; action has to be taken now, as opposed to at some future date. The principle of "primum nil nocere" (first, do no harm) is vital in individual medicine – it is less so when it comes to the planet at large. While the adoption time of new technologies has continued to increase rapidly (economists/econometrics use regressive data going forward – unlike technologists/entrepreneurs), replacing oil will still require substantial effort – and this is an effort that must start now. We recognize that there are risks with these approaches, but these are manageable technology risks, not market risks – furthermore, the risks of the status quo persist. **From a policy perspective, we reiterate the question – what risks do we wish to take?**

Summary

Our conclusions are surprising:

- With biofuel yields of 110 gallons per dry ton of biomass modest to little dedicated land is required. With yield at 130 gallons/dry ton (or 65% of the maximum theoretical yield of 198.4 gallon/ton), the land use issue becomes minimal. If other well optimized chemical processes are used as a guide, yields between 76-80% of theoretical processes should be achievable, but were not assumed in the scenarios.
- The potential for winter cover corps has been largely ignored as a feedstock source for biofuels production.
- With modest assumptions about winter cover crops (on 50% of annual crop lands) and forest waste use (70% of sustainable harvestable biomass per the Department of Energy study) and no use of biomass from today's annual crops (the use of corn stover, wheat straw, etc) a surprisingly small amount of land will be required to replace most US gasoline consumption for light vehicles
- Using transrespiration based maximum yield estimates (in a 40 inch per year rain region) and derating them by 60% (a level historically achieved in other crops), yields of 24 tons per acre seem achievable by 2030 using plant breeding and genetic engineering techniques. Incidental data on biomass crop yields in actual practice (from a number of crops in a variety of regions tends to validate this assumption)
- Even assumptions of energy crop yields at 25% and 50% lower than the numbers estimated would not materially change the land acres needed.
- The scenarios assume modest engine efficiency improvements over today's automobile engines. If developments already underway (Transonic, Ecomotors– targeting 50-100% improvements each, hybrids – 25-50% improvements, vehicle attributes like weight, drag, size etc, HICCI engines, improved CAFE mandates by 2030) bear fruit, the above scenarios could be dramatically changed for the better.
- Significant potential exists in improving the ecology and yields of annual crop lands using winter cover crops, long rotation (ten year) row crops/energy crop rotations, in recovering degraded agriculture lands with good energy crop agronomic practices like perennial crops, polyculture cultivation, etc. The net result of improving row crop agriculture ecology, reducing input costs, recovering degraded lands replacing most gasoline in the US is possible if the right practices are followed and the right technologies are developed.

We have highlighted some of the feedstocks that (we believe) are likely to meet feedstock needs, but there are many other potential sources that have not yet been researched (or discovered!). In time, some feedstocks may prove to be more efficient than others, but local needs and transportation costs mean that cellulosic biofuels (utilizing local feedstocks) can be produced in many locations in the US and worldwide**.** The innovation ecosystem will ensure that over time, new ideas will continue to be developed- the better ideas will persist as more and more intelligent people, resources, and capital join the field, and the best ideas will eventually rise to the top. While some oil companies are starting to recognize and investigate the potential of biofuels, traditional oil interests (OPEC) will continue to fight this trend with the hundreds of billions of dollars at their disposal - state-owned oil companies control almost 80% of the world's oil resources. There is plenty of biomass available (computed here for the US but similar calculations are possible for other world geographies).

In the short term, we need to accelerate (not slow down) the deployment of biofuels. In order to prevent adverse outcomes we suggest implementation of the following policies (1) focus on non-food sources without additional land use such as winter cover crops, forest waste, and other organic waste sources (2) Aggressively pursue energy crop research and development including crop rotations, perennials, assessment of invasive species, land and water use etc (3) Prohibit the import of agricultural products from countries where deforestation rates don't decline to negotiated targets, either directly or through the WTO.

Biomass from energy crops can replace oil while improving traditional agriculture and biodiversity while reducing needs for chemicals and water for both the energy crops and the row crops that we use today. Far from being a food versus fuel battle that many tunnel visions critics have imagined, biomass based income may be one of the few fundamental economic tools we may have to solve poverty issues in Africa. Of course, biofuels can be produced as defined above or we can produce biomass on land from cut-down rain forests. They can be done well or done poorly. It behooves us to regulate each biofuels facility and qualify its feedstock sources as being eco-qualified (a LEEDS like rating for each biofuels factory!). Such regulation will cut off the abuses that will necessarily happen if we don't regulate them.

Appendix A: Potential Scenarios for Land Use

Scenarios – Summary

Scenario	Waste Resources (% of total ethanol demand in 2030)	Winter Cover Crop - % of annual crop land/ acres	Winter Cover Crop Yield (Tons Per Acre)	Excess Forest Biomass (Millions of Dry Tons)	Biofuel Yields (Gallons per Ton)	Dedicated Land Use @ 24/18/12 tons/acre (Millions of Acres)	Net Land Use @ 24/18/12 tons/ acre (Millions of Acres)
1:	10%– 15B gallons	50% – 159M	3-4.6	70% -158Mt	90-110	13.6 / 18.2 / 27.3	-1.9 / 2.7 / 11.8
2:	-	50% – 159M	3-4.6	50% -113Mt	90-110	21.0 / 28.1 / 42.1	5.5 /12.6 /26.6
3:	-	50% – 159M	3-4.6	50% -113Mt	90-130	12.5/16.6/25.0	-3.0 / 1.1 / 9.5
4:	-	50% – 159M	3-4.6	70% -158Mt	90-130	10.6/14.2/21.3	-4.9 / 1.3 / 5.8
5:	-	50% – 159M	3-4.6	100% -226Mt	90-130	7.9/10.5/15.7	-7.6 / -5.0 / 0.2
6:	10% –15B gallons	70% – 221M	3-4.6	100% -226Mt	90-130	0	-15.5

General Notes:

1. We estimate that 150B gallons of cellulosic ethanol are needed in 2030 to replace most light-vehicle gasoline usage. How do we get there? The EIA energy outlook (published BEFORE the recent energy bill passage) projects light-vehicle usage of 11.15M [39] barrels/day of oil equivalent in 2030 – or about 171B gallons annually. We assume a 20% discount on this demand to reflect updated CAFE standards, and an ethanol mileage discount of 15% - giving us equivalent ethanol demand of 160B gallons (if every car was a Flex Fuel Vehicle). We assume that by 2030, 90% of the fleet consists of FFV's, leading to ethanol demand of 144B gallons (we have thus used 150B gallons to be conservative). In some scenarios, we exceed this projection without dedicated crop land, and production numbers reflect that.
2. Biomass from waste production is modeled in some scenarios. Waste refers to organic waste, municipal waste, industrial waste, flue gases from steel mills, and other biomass waste.
3. Current CAFE laws are assumed to reduce gasoline demand. Additional ICE engine efficiency/higher CAFE could substitute for higher efficiency on ethanol assumed by 2030. Any of the efficiency breakthroughs mentioned here but not assumed the calculations could dramatically improve all the scenarios.

4. Yield projections (tons per acre) are based on fertile, rainfed (40 inch rain region) land. The usage of degraded land will result in lower yields. Crop variety and yield variations are averaged for modeling purposes.
5. We assume that the primary source of dedicated land for energy crops will be cropland, but commercial reduction in today's forest resource usage (i.e. - more paper mill closures) could be offset by using it for biofuels - while also reducing the amount of cropland needed.
6. We believe that replacing diesel may require an additional 20M acres in cropland, but it is not modeled here. Many of the gasoline use scenarios result in excess biomass that could be used for diesel production and other purposes.
7. No recovery of degraded land is assumed because of good perennial growth; long cycle crop rotation practices are assumed, but no increase in yields from such practices is modeled.
8. In 2008, the USDA projects corn ethanol production of 9.3B gallons. At 150 bushels per acre and 2.8 gallons per bushel, this equates to 22.1M acres of expected corn production for biofuels. We assume only 70% of this land is recovered because 30% of corn ethanol byproduct is used as feed, and that demand still needs to be met.
9. Gasoline takes approx 2-2.5 gallons of water to produce 1 gallon (as per NREL[40]) - production of 1 gallon of cellulosic ethanol (using Range/Coskata like thermochemical processes) would use 1 gallon of water. Assuming an ethanol mileage discount of 15% in 2030, net water usage per mile driven with cellulosic ethanol is approximately 47-58% that of gasoline refining.
10. Our yield assumptions assume adoption of thermochemical processes (such as those of Range and Coskata), as opposed to standard bio-fermentation. The maximum theoretical yield (for switchgrass) is 111 gal/ ton for biochemical processes, and 198.4 gal/ton for thermochemical processes ("Cellulosic Biofuel Technologies", Professor David Bransby). Though historical chemical processes often reach 75-80% of theoretical maximum yield, the most optimistic scenario here (130 gallons/ton) for biofuel yield is modeled at 65% net efficiency.

Scenarios

Scenario 1

	KV Cellulosic Ethanol Production Estimates (Gallons - Billions)	Waste Ethanol Production Estimates (Gallons - Billions)	Ethanol Yield (Gals/Ton) (best tech)	Total Biomass Needed (Tons - Millions)	Winter Cover Crop Acres (Acres - Millions)	Winter Cover Crop Yield (tons/ac)	Forest Excess Biomass (Tons - Millions)	Forest Biomass Yield (tons/ac)	Biomass needed from dedicated cropland (Tons - millions)	Expected Yield (Tons/ac) (Tons - millions)	Acres needed at projected yield (Tons - millions)	Acres needed at 75% of projected yield (Tons - millions)	Acres needed at 50% of projected yield (Tons - millions)
2015	5.0	0.0	102.3	48.9	4.1	3.4	20.8	10.9	14.0	10.9	1.3	1.7	2.6
2020	30.0	3.0	107.5	251.1	42.9	3.8	68.3	15.4	19.4	15.4	1.3	1.7	2.5
2025	87.6	8.0	110.0	724.1	142.5	4.2	125.5	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	15.0	110.0	1227.3	158.5	4.6	158.0	24.5	334.2	24.5	13.6	18.2	27.3

How Do We Get There?

Total Biomass	=	Winter Cover Crops:	Forest Excess Waste:	Dedicated Crop Land:
2015: 49M tons	=	14M tons	21M tons	14M tons
2020: 251M tons	=	163M tons	68M tons	19M tons
2025: 724M tons	=	599M tons	126M tons	0M tons
2030: 1227M tons	=	735M tons	158M tons	334M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	13.6	18.2	27.3
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-1.9M acres**	**2.7M acres**	**11.8M acres**

Scenario 2

	KV Cellulosic Ethanol Production Estimates (Gallons - Billions)	Waste Ethanol Production Estimates (Gallons - Billions)	Ethanol Yield (Gals/Ton) (best tech)	Total Biomass Needed (Tons - Millions)	Winter Cover Crop Acres (Acres - Millions)	Winter Cover Crop Yield (tons/ac)	Forest Excess Biomass (Tons - Millions)	Forest Biomass Yield (tons/ac)	Biomass needed from dedicated cropland (Tons - millions)	Expected Yield (Tons/ac) (Tons - millions)	Acres needed at projected yield (Tons - millions)	Acres needed at 75% of projected yield (Tons - millions)	Acres needed at 50% of projected yield (Tons - millions)
2015	5.0	0.0	102.3	48.9	4.1	3.4	19.2	10.9	15.6	10.9	1.4	1.9	2.8
2020	30.0	0.0	107.5	279.0	42.9	3.8	47.7	15.4	67.9	15.4	4.4	5.9	8.8
2025	80.0	0.0	110.0	727.3	142.5	4.2	76.1	20.5	52.6	20.5	2.6	3.4	5.1
2030	150.0	0.0	110.0	1363.6	158.5	4.6	113.0	24.5	515.5	24.5	21.0	28.1	42.1

How Do We Get There?

Total Biomass		Winter Cover Crops	Forest Excess Waste	Dedicated Cropland
2015: 49M tons	=	14M tons	19M tons	16M tons
2020: 279M tons	=	163M tons	48M tons	68M tons
2025: 727M tons	=	599M tons	76M tons	53M tons
2030: 1364M tons	=	735M tons	113M tons	516M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	21.0	28.1	42.1
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**5.5M acres**	**12.6M acres**	**26.6M acres**

Scenario 3

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	104.9	47.7	4.1	3.4	19.2	10.9	14.4	10.9	1.3	1.8	2.6
2020	30.0	0.0	113.0	265.6	42.9	3.8	47.7	15.4	54.5	15.4	3.5	4.7	7.1
2025	82.1	0.0	121.7	674.7	142.5	4.2	76.1	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	0.0	130.0	1153.8	158.5	4.6	113.0	24.5	305.7	24.5	12.5	16.6	25.0

How Do We Get There?

Total Biomass		Winter Cover Crops	Forest Excess Waste	Dedicated Crop Land
2015: 48M tons	=	14M tons	19M tons	14M tons
2020: 266M tons	=	163M tons	48M tons	55M tons
2025: 675M tons	=	599M tons	76M tons	0M tons
2030: 1154M tons	=	735M tons	113M tons	305M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	12.5	16.6	25.0
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-3M acres**	**1.1M acres**	**9.5M acres**

Scenario 4

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	104.9	47.7	4.1	3.4	20.8	10.9	12.8	10.9	1.2	1.6	2.3
2020	30.0	0.0	113.0	265.6	42.9	3.8	68.3	15.4	33.9	15.4	2.2	2.9	4.4
2025	88.1	0.0	121.7	724.1	142.5	4.2	125.5	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	0.0	130.0	1153.8	158.5	4.6	158.0	24.5	260.7	24.5	10.6	14.2	21.3

How Do We Get There?

Total Biomass		Winter Cover Crops	Forest Excess Waste	Dedicated Crop Land
2015: 48M tons	=	14M tons	21M tons	13M tons
2020: 266M tons	=	163M tons	68M tons	34M tons
2025: 724M tons	=	599M tons	126M tons	0M tons
2030: 1154M tons	=	735M tons	158M tons	261M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	10.6	14.2	21.3
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-4.9M acres**	**-1.3M acres**	**5.8M acres**

Scenario 5

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	104.9	47.7	4.1	3.4	22.4	10.9	11.2	10.9	1.0	1.4	2.0
2020	30.0	0.0	113.0	265.6	42.9	3.8	88.4	15.4	13.8	15.4	0.9	1.2	1.8
2025	90.2	0.0	121.7	740.9	142.5	4.2	142.3	20.5	0.0	20.5	0.0	0.0	0.0
2030	150.0	0.0	130.0	1153.8	158.5	4.6	226.0	24.5	192.7	24.5	7.9	10.5	15.7

How Do We Get There?

Total Biomass	=	Winter Cover Crops	Forest Excess Waste	Dedicated Crop Land
2015: 48M tons	=	14M tons	22M tons	11M tons
2020: 266M tons	=	163M tons	88M tons	14M tons
2025: 741M tons	=	599M tons	142M tons	0M tons
2030: 1154M tons	=	735M tons	226M tons	193M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	7.9	10.5	15.7
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-7.6M acres**	**-5M acres**	**0.2M acres**

Scenario 6

	KV Cellulosic Ethanol Production Estimates	Waste Ethanol Production Estimates	Ethanol Yield (Gals/Ton)	Total Biomass Needed	Winter Cover Crop Acres	Winter Cover Crop Yield	Forest Excess Biomass	Forest Biomass Yield	Biomass needed from dedicated cropland	Expected Yield (Tons/ac)	Acres needed at projected yield	Acres needed at 75% of projected yield	Acres needed at 50% of projected yield
	(Gallons - Billions)	(Gallons - Billions)	(best tech)	(Tons - Millions)	(Acres - Millions)	(tons/ac)	(Tons - Millions)	(tons/ac)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)	(Tons - millions)
2015	5.0	0.0	104.9	47.7	4.1	3.4	22.4	10.9	11.2	10.9	1.0	1.4	2.0
2020	31.4	3.0	113.0	251.8	42.9	3.8	88.4	15.4	0.0	15.4	0.0	0.0	0.0
2025	102.0	8.0	121.7	772.4	150.0	4.2	142.3	20.5	0.0	20.5	0.0	0.0	0.0
2030	177.6	15.0	130.0	1251.0	221.0	4.6	226.0	24.5	0.0	24.5	0.0	0.0	0.0

How Do We Get There?

Total Biomass		Winter Cover Crops	Forest Excess Waste	Dedicated Crop Land
	=			
2015: 49M tons	=	14M tons	22M tons	11M tons
2020: 251M tons	=	163M tons	88M tons	0M tons
2025: 772M tons	=	630M tons	142M tons	0M tons
2030: 1251M tons	=	1025M tons	226M tons	0M tons

2030 - How Much Land Do We Need?

	24 t/ac	18 t/ac	12 t/ac
Displaced Land - Due to Dedicated Energy Crops	0.0	0.0	0.0
Reclaimed Land - based on 2008 corn ethanol production, assuming 70% land recovery	-15.5	-15.5	-15.5
Net Land Use (Excluding Winter Cover Crops, Forest Excess Waste)	**-15.5M acres**	**-15.5M acres**	**-15.5M acres**

Appendix B - Winter Cover Crops

Benefits of Winter Cover Crops

Water/Fertilizer Use	Winter cover crops require no irrigation, and significantly less fertilizer than traditional row crops. In addition, cover crops are more efficient users of water resources. Cover crops also increase the water holding and infiltration capacity of the soil.
Soil Protection / Conservation	In the US, soil losses due to erosion exceed 3 billion tons annually due to wind and water erosion. The presence of cover crops sharply reduces soil erosion by physically protecting the bare soil, as well as reducing soil crusting and water runoff during subsequent planting seasons. Their increased water infiltration also helps to reduce soil erosion, and this increased soil moisture helps to allow these crops to better survive short-term drought.
Soil Structure / Fertility	Cover crops are a substantial help in replenishing soil organic matter, and increasing the fertility of the soil. Specific cover crops like legumes can also produce soil nitrogen, reducing the need for external nitrogen inputs. In addition, cover crops can also help fertility by providing energy for the soil biota, and stimulate microbial growth and development, leading to a net gain of nutrient availability in the soil. Some cover crops have extensive rooting systems, which further helps improve the soil by loosening and aerating it.
Pest/Weeds Control	Cover crops take up space/light and reduce the opportunities for weeds to establish themselves; deep rooted cover crops also loosen up the soil, reducing the impact of weed populations that rely on compacted soil. Cover crops can also enhance pest management systems by adding diversity to a cropping system - stable (and diverse) systems generally tend to be better able to handle and control particular pest strains. In addition, data has shown that cover crops tend to increase the number of beneficial insects numbers in the soil, especially when combined with conservative tillage practices.

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