Lifecycle Carbon Footprint, Bioenergy and Leakage: Empirical Investigations

Bruce McCarl, Texas A&M

Agriculture may help mitigate climate change risks by reducing net greenhouse gas (GHG) emissions (McCarl and Schneider, 2000). One way of doing this is that agriculture may provide substitute products that can replace fossil fuel intensive products or production processes. One such possibility involves providing feedstocks for conversion into consumable forms of energy, where the feedstocks are agriculturally produced products, crop residues, wastes or processing byproducts. Such items may be used to generate bioenergy encompassing the possibilities where feedstocks are used

- To fuel electrical power plants
- As inputs into processes making liquid transportation fuels e.g. ethanol or biodiesel.

Employing agriculturally produced products in such a way generally involves recycling of carbon dioxide because the photosynthetic process of plant growth removes carbon dioxide from the atmosphere while combustion releases it. This has implications for the need for permits for GHG emissions from energy generation or use (If we ever have such a program). Namely

- Direct net emissions from biofeedstock combustion are virtually zero because the carbon released is the recycled atmospheric carbon. As such this combustion may not require electrical utilities or liquid fuel users/producers to have emissions permits.
- Use of fossil fuels for power and liquid fuels, releases substantial carbon dioxide and would require emission rights.

This would mean that the willingness to pay for agricultural commodities on behalf of those using them for bioenergy use would rise because their use would not require acquisition or use of potentially costly/valuable emissions permits. This means biofeedstocks may be a way that both (a) energy firms can cost effectively reduce GHG liabilities and (b) be a source of agricultural income. But, before wholeheartedly embracing biofuels as a GHG reducing force, one fully account for the GHGs emitted when raising feedstocks, transporting them to a plant and transforming them into bioenergy. This is the domain of lifecycle accounting and the subject of this conference.

However lifecycle accounting can provide biased accounting of such phenomenon. Lifecycle accounting is typically done assuming where nothing changes elsewhere in the economy or world. The reality is that large biofuel programs embody many violations of such an assumption. For example, ask yourself whether the recent corn boom has induced changes in exports, reactions from foreign producers and changes in livestock herds. I think that is the case. Such issues involve a concept called leakage in the international GHG control discussion as covered below. In addition, the issues imply that a full analysis needs to conduct a broader sectoral level partial (or perhaps economy wide general) equilibrium form of lifecycle accounting as also discussed herein. Finally, another issue worth mentioning is that biofuel opportunities embody differential degrees of GHG offsets as apparent by the widespread belief that cellulosic ethanol has a "better" net energy and GHG balance than does corn ethanol.

This paper addresses the issues raised in the above paragraph discussing lifecycle accounting relative to different fuels, leakage concepts and full greenhouse gas accounting in a partial equilibrium setting.

1 Lifecycle accounting and Biofuels

Over the last couple of years I have tried to do a fairly comprehensive life cycle accounting across the full spectrum of agricultural biofuel possibilities including possibilities for biofuels to go into ethanol, biodiesel and electricity. The method for this is as follows

- GHG emission estimates of the carbon dioxide, methane and nitrous oxide emitted when making fertilizer, lime, and specific pesticides were adapted from EPA assumptions.
- GHG emission estimates embodied in gasoline, diesel, natural gas and electricity (regionalized) use were adopted from EPA and GREET work.
- IPCC default emission rates were adopted for fertilizer related nitrous oxide emissions.
- A consistent regionalized set of crop budgets were developed based on extension service budgets and USDA ARMS data.
- Crop soil sequestration rates were incorporated based on CENTURY runs.

- The above data were unified on a regional basis using 11 regions as defined in FASOM (Adams et al, 2008) to get regional average GHG emissions per acre and per unit (e.g. bushel) of crop.
- Biofuel processing budgets were drawn together based on the literature for a wide variety of agricultural feedstocks for transformation into ethanol, cellulosic ethanol, biodiesel and electricity including alternative electricity co firing rates. These budgets contained assumptions about the fuel being replaced (typically, gasoline, diesel and coal), the foregone fossil emissions and emissions from transforming feedstocks into bioenergy.
- Hauling cost was computed based on feedstock density in a region, crop yields and processing plant feedstock needs following the formula in French (1960) as in McCarl et al (2000).
- Total GHG emissions per unit of energy output were computed unifying the emissions per unit crop input, per unit hauled and per unit transformed on a regional basis and then were computed to percent net savings in emissions per unit of fuel displaced.
- A national set of results was generated using the regional results favoring areas where the acreage of the biofeedstock was the largest or where the prospect is commonly referred to (e.g. Cornbelt and south for switchgrass).

The resultant data appear in Table 1. In these data, the net GHG contributions of a biofuel depend upon the amount of fossil fuel used in (a) producing the feedstock, (b) making production inputs, (c) hauling and (d) processing transformation.

	Liquid Fuels			Co fired Electricity				Elec
Commodity	Crop Ethanol	Cell Ethanol	Bio Diesel	5 %	10 %	15 %	20 %	fire 100%
Corn	17.2							
Hard Red Winter Wheat	16.1							
Sorghum	27.8							
Sugarcane	64.9							
Soybean Oil			95.0					
Corn Oil			39.1					
Switch Grass		56.7		86.3	86.5	86.2	86.0	75.1
Hybrid Poplar		52.6		84.1	84.4	84.1	83.8	71.3
Willow		62.8		90.9	91.0	90.8	90.7	83.4

Softwood Log Residue	79.3	99.2	99.1	99.1	99.0	97.3
Hardwood Log Residue	79.4	99.0	98.9	98.8	98.8	96.3
Corn Cropping Residue	69.8	89.2	89.4	89.2	89.0	80.1
Wheat Cropping Residue	56.4	93.3	93.4	93.2	93.1	87.2
Manure		99.5	99.4	99.2	99.1	96.4
Bagasse	95.7	98.1	98.1	98.1	98.0	96.5
Lignin		91.3	91.5	91.3	91.2	85.8
LigninHardwood		91.4	91.5	91.4	91.2	85.7
LigninSoftwood		96.2	96.3	96.2	96.2	94.1

Table 1. Percentage offset in carbon dioxide equivalent emissions from the usage of a biofeedstock.

For example, the 17.2% for corn-based ethanol is the carbon reduction relative to using gasoline. The lifecycle accounting indicates 83.8% of the potential emissions savings from replacing gasoline with ethanol are offset by the emissions from the use of fossil fuels in transforming corn into ethanol. On the other hand, many of the electricity based technologies use relatively little fossil fuel, mostly in transporting the products to the power plant and so the carbon credit is on the order of 85% with it being higher for co fired plants rather than ones solely fueled on biomass.

Broadly across the table, we see

- Relatively low rates for liquid fuels as opposed to electricity.
- The lowest liquid fuel offsets arising for corn ethanol with relatively higher values from cellulosic ethanol sources and biodiesel from soybean oil.
- Results that reflect differential offset rates due to the differential use of
  - Emission intensive inputs in producing feedstocks (corn is a large fertilizer user)
  - Emission intensive transformation processes in making ethanol along with successively less so processes to make cellulosic ethanol, biodiesel and electricity.

2 Leakage and other International Negotiation Issues

In the domestic and international policy discussion directed toward net GHG emission reductions a number of concepts have arisen that are likely to differentially characterize

the contribution of alternative possible offsets within the total regulatory structure. These involve:

- Leakage
- Permanence
- Additionality
- Uncertainty
- Heat trapping ability of different gases involved (as commonly called global warming potential or GWP).

In all likelihood grading standards will differentiate based on the characteristics listed above between a certified offset price and the price for potential offsets from a number of sources. Biofuels are likely to be subject to some of these concerns. Here we only cover leakage. Coverage across most of these items appears in Smith et al (2007) with all covered in McCarl (2007) or in Post et al(2004).

Market forces coupled with less than global coverage by biofuel or a GHG program can cause net GHG emission reductions within one region to be offset by increased emissions in other regions. For example, the international Kyoto Protocol GHG reduction effort has a component called the Clean Development Mechanism (CDM). Under the CDM proposals palm oil plantations for biodiesel production have been proposed where plantation development involved rainforest destruction. In such a case changes in land management would occur in the name of bioenergy development and GHG management resulting in increased biofuel production. But the development would cause substantial emissions due to the lost rainforest sequestration. More generally increased commodity prices can cause expanded production in other areas of the world perhaps greatly offsetting the GHG gains. Today it is common to hear about many forms of this leakage phenomena including

- US forested acres being removed to permit increased corn production,
- Possible reversion of Conservation Reserve Program lands into cropland or
- Expansions of crop acres in Brazil and Argentina at the expense of grasslands and rainforest.

Consideration of leakage implies that biofuel project GHG offsets need to be evaluated under broad national and international accounting schemes so that both the direct and indirect implications of project implementation are examined including offsite stimulated leakage. In such a context a leakage discount will be manifest in either

- Reduction of the quantity of potential offsets that can be credited and thus sold so that the creditable quantity reflects adjustments for external leakage.
- Reduction in the price per ton paid by the purchaser so it is multiplied by one minus a leakage discount factor. That leakage discount factor would reflect the external leakage.

2.1 Leakage in the literature

Leakage has been addressed in a number of different circumstances as reviewed in McCarl (2007). Here looking at the agricultural context Wu finds that under the United States conservation reserve program, that moving crop lands into the CRP, that about 20% of the reserved acres were replaced by additional acreage moving into the cropland category, again a finding of leakage. Leakage findings have also appeared in the context of slippage rates estimated with respect to farm program land set asides. Hoag, Babcock, and Foster (1993) , Brooks, Aradhyula, and Johnson (1992) and Rygnestad and Fraser (1996) all found that acreage reductions were larger than total production reductions because of retirement of less productive lands in a heterogeneous landscape. Wu, Zilberman and Babcock (2001) show that such problems make cost benefit analysis of individual projects misleading and argue for more comprehensive treatment.

Leakage has been examined internationally. Lee et al (2007) show in a modeling context that unilateral implementation of agricultural GHG offsets including biofuels leads to a decline in host country exports and an increase in international production.

2.2 A leakage discount

Suppose that project activity simulates emissions (leakage) elsewhere and thus that only parts of the offsets are global GHG offsets. Consequently, the quantity of offsets is not only the life cycle quantity. In such a case, we can express the proportion of GHG offsets that are achieved after adjustment for leakage in year t using the formula

$$\text{ProportionNotLeaking}_t = \frac{\text{ProjectOffsets}_t - \text{OffsetingLeakedEmissions}_t}{\text{ProjectOffsets}_t}$$

Further, if we assume the proportion of leaking offsets does not vary over time this can be solved to yield

$$\text{LeakageDiscount} = 1 - \text{ProportionNotLeaking}$$

2.3 Formulae for leakage estimation

Formulae estimating leakage rates have been developed based on the theoretical economic deductions by Murray, McCarl and Lee (2004) and Kim (2004). The Murray, McCarl and Lee approach is based on diverted production in the commodity markets. The Kim approach is based on the amount of land diverted. Both will be presented.

Murray, McCarl and Lee (2004) develop the following estimation formula for leakage

$$L = \frac{e * C_{out}}{[e - E * (1 + \phi)]\, C_{proj}}$$

where

- L — provides an estimate of the leakage discount which is proportion of the potential offsets offset by leakage. This is derived so it equals the amount of emissions released through induced expansions in offsite emissions divided by the amount of potential offsets saved by the project.
- e — is the price elasticity of supply for off project producers such as the supply elasticity of corn by rest of world producers.
- E — is the price elasticity of demand for the consumption of the final commodity produced like the global price elasticity for corn.
- C_{out} — is the amount of GHG emissions produced per unit of increased commodity production outside the project area.
- C_{proj} — is the amount of potential GHG offsets produced per unit of reduced commodity production in the project area.
- ϕ — is a measure of relative market share and is the total quantity of the commodity produced by the project divided by the amount produced elsewhere like the US share of the global corn market.

Kim (2004) set up a leakage estimation formula based on the amount of acreage diverted by a project. That formula follows

$$\text{Leak} = \frac{e\, EL_{proj}}{[e - E * (1 + El_{out}\phi)]} \frac{LCR_{out}}{LCR_{proj}}$$

where

e, E, and ϕ	are as defined for the commodity dependent Murray, McCarl and Lee formula presented above.
EL_{proj}	is the elasticity of commodity production with respect to changes in project land use. Namely, it is the percentage decrease in commodity production per one percent increase in project land used for the GHG offset project.
EL_{out}	is the elasticity of commodity production with respect to changes in offsite land use. Namely, it is the percentage increase in commodity production per one percent increase in offsite land used for commodity production.
LCR_{out}	is the GHG emission increase per acre that arises when additional acres are used to produce the commodity outside the project area.
LCR_{proj}	is the GHG potential offset per acre in the project region created by developing the project.

Once number are plugged into these formulae one gets an estimate of the amount of leakage. Murray, McCarl and Lee (2004) find leakage numbers as large as 85% for certain types of projects. If we do a quick numerical exercise using the Murray formula under an assumption that the world demand for corn the US faces has an elasticity of -2 and that in some other region like South America the supply elasticity is a 1 plus the US corn market share is 40% and that per bushel emission increases overseas when expanding production relative to the savings from diverting corn to biofuels

- Are equal (i.e $C_{out}/C_{proj} = 1$) then leakage is 45%
- Are twice the US ones (i.e $C_{out}/C_{proj} = 2$) we get a 91% leakage
- Are half the US ones then we get 23% leakage.

Clearly overseas leakage will be an important offset and perhaps we should make an attempt to discount for leakage for example with a rate of 50% crediting no more than ½ of the estimated emissions offsets.

3 Equilibrium Life Cycle Accounting

As mentioned above the accounting of greenhouse gas offsets may be further affected by changes in emissions from other sources. To test this, runs were made with the FASOMGHG (Adams et al 2008) model with 15 billion gallons of corn ethanol produced

in 2015 and later with 18 billion gallons. The changes in greenhouse gas emissions in million metric tons CO2 equivalent from generating this extra 3 billion gallons appear in table 2. The main results show that while there is a substantial offset in the GHGs offset by the ethanol where the ethanol replaces gasoline (labeled ethanol from grains) there is also

- increased emissions from agricultural soil as land is converted from grass, and tillage is intensified
- reduced emissions from animals and the form of lower manure and enteric fermentation related emissions largely due to dropping animal populations because of more expensive feedstuffs
- Increased crop non CO2 emissions largely in the form of increased fertilizer use
- increased agricultural fossil fuel usage emissions because of expanded land use and changes in management.
- Reduced emissions from electricity generation and biodiesel production

	Offsets generated
Soil carbon sequestration	-7.39
CH4 and N20 from animals	+7.18
CH4 and N20 – from crops	-5.98
Ag CO2 from Fossil fuel use	-3.80
Net offset when making Ethanol from grains	+80.6
Net offset when making Electricity from ag feedstocks	-7.65
Net offset when making Biodiesel from ag feedstocks	-2.55
Other miscellaneous	-0.08

Table 2 : Expansions in carbon dioxide equivalent emission offsets when corn ethanol production in 2015 is increased from 15 to 18 billion gallons tabled in million metric tons.

4 Economics and Portfolios

Finally I turn attention to the issue of considering which bioenergy opportunities make sense in a world that is trying to control GHG emissions but also facing higher liquid energy prices. Specifically, we examine agricultural sensitivity to variations in

- Carbon dioxide equivalent GHG emissions offset prices ($ per metric ton of emissions reduced).
- Liquid fuel prices ($ per gallon gasoline with linked prices for ethanol and biodiesel).

Large-scale GHG trading seems likely to emerge in the near future but has not been an opportunity historically. As such its full implications cannot be observed in today's world. Consequently, we employ procedures that simulate the effects of carbon dioxide equivalent prices and higher energy prices. In doing this we follow a number of previous studies and use an agricultural sector simulation model.

4.1 Modeling background

The agriculture sector is complex and highly interrelated. The sector and GHG issue exhibit a number of features that need to be considered in any analytical approach to reasonably assess GHG mitigation potential. Among these are

- Multiple gases (Carbon Dioxide, Nitrous Oxide, Methane) arising from agricultural activities,
- Simultaneities between mitigation activities where undertaking some mitigation options precludes or otherwise affects other mitigation options i.e. one cannot take land and harvest corn residue for biofuel feedstock while simultaneously establishing trees for sequestration.,
- Environmental co-benefits of GHG mitigation where for example strategies affect fertilizer use, tillage practices, and livestock numbers which in turn alter runoff and erosion,
- Commodity availability and prices along with farm income and consumer welfare from food purchases
- Offset rates that vary across different mitigation activities and across space based on their effectiveness in reducing carbon emissions and local conditions.

The way that each of these issues is addressed in the modeling work is briefly addressed below.

Multiple gas implications. GHG mitigation practices and strategies in agriculture independently and jointly impact emissions of carbon dioxide, nitrous oxide, and methane. To compare these different gases that each have different climate effects100 year Global Warming Potentials (a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming also abbreviated GWP) are used to put them in common, carbon dioxide-equivalent terms following standard IPCC practices.

Mitigation alternative interrelatedness. Actions that influence, for example, the quantity of livestock produced also influence crop demand, and land allocation which in turn influences the carbon sequestered on crop lands, the nitrous oxide released when fertilizers are used and the methane emitted from livestock production. This interdependence needs to be accounted for in order to understand the full implications of any mitigation strategy. At the simplest level, for example, if wheat or corn land is converted to switchgrass or to a grass cover crop, then it is no longer available for converting to forest or for the harvest of crop residues. This study utilizes an analytical approach that simultaneously depicts crop and livestock production, the feeding of crop products to livestock, grazing, product substitution, and competition for land, among other factors across the agricultural sector.

Environmental Co-Benefits. Agricultural mitigation alternatives are frequently cited as win-win approaches as a number of the strategies generate GHG offsets while at the same time as achieving environmental quality gains in terms of reduced erosion and improved water quality. This study will try to develop quantitative information on the magnitude of such effects.

Commodity Market and Welfare implications. US agriculture produces large quantities of a number of commodities relative to domestic needs and total global market volume. Variation in US production influences prices in these markets. This in turn affects farm income and consumer well being collectively called welfare. Thus it is possible that US GHG mitigation policies will also affect domestic and world market prices along with the welfare of producers and consumers in those markets. The analytical approach used here includes a representation of domestic agricultural markets and their links to foreign markets.

Differential offset rates. Agricultural strategies exhibit substantially different GHG offset rates. For example, tillage changes produce about 0.84 metric tons of carbon dioxide offsets per acre while still producing crops. Biofuel energy crops can produce offset rates above 2.5 tons, but with no complementary crop production. At low GHG prices, complementary production is likely to be favored. The model-based approach used here will be used to simulate agricultural effects across a continuum of carbon dioxide prices, thus showing the conditions under which different mitigation strategies dominate. Also offsets vary from place to place due to differential growing potential for the various crops and livestock involved. Thus the model has 63 US production regions with different GHG net emission rates and different crop and livestock production possibilities.

4.1.1 FASOMGHG Model

The approach used to address the issues identified above is to simulate the agricultural sector in a model. We use the agricultural part of the Forest and Agricultural Sector Optimization Model (hereafter referred to as FASOMGHG, Adams et al (2008)). This model has greenhouse gas accounting unified with a detailed representation of the possible mitigation strategies in the agricultural sector as adapted from Schneider (2000), Lee (2002) and McCarl and Schneider (2001) in addition to a number of recent updates that have improved the depiction of biofuel production possibilities.

Geographic scope. The FASOMGHG agricultural sector representation divides the US into 63 regions in the 50 contiguous US states with sub state breakdowns in Texas, Iowa, Indiana, Illinois, Ohio and California.

Links to international markets. The model uses constant elasticity functions for domestic and export demand as well as factor and import supply.

Product scope. The FASOMGHG agricultural component simulates production of the crop, livestock, energy crop, residue, crop processed, livestock, mixed feed and bioenergy commodities listed in Table 3.

Table 3: Modeled Agricultural Sector Commodities

Primary Products

- **Crops:** Cotton, Corn, Soybeans, Soft White Wheat, Hard Red Winter Wheat, Durham Wheat, Hard Red Spring Wheat, Sorghum, Rice, Oats, Barley, Silage, Hay, Sugarcane, Sugar beets, Potatoes, Tomatoes For Fresh Market, Tomatoes For Processing, Oranges For Fresh Market, Oranges For Processing, Grapefruit For Fresh Market, Grapefruit For Processing
- **Animal Products:** Grass-Fed Beef For Slaughter, Grain-Fed Beef For Slaughter, Beef Yearlings, Calves For Slaughter, Steer Calves, Heifer Calves, Beef Heifer Yearlings, Beef Steer Yearlings, Cull Beef Cows, Milk, Dairy Calves, Dairy Steer Yearlings, Dairy Heifer Yearlings, Cull Dairy Cows, Hogs For Slaughter, Feeder Pigs, Cull Sows, Lambs For Slaughter, Lambs For Feeding, Cull Ewes, Wool, Unshorn Lambs, Mature Sheep, Horses/Mules, Eggs, Broilers, Turkeys
- **Biofuels:** Willow, Poplar, Switchgrass
- **Crop and Livestock Residues**: Corn Residue, Sorghum Residue, Wheat Residue, Oats Residues, Barley Residues, Rice Residues, Manure

Secondary Products

- **Crop Related:** Orange Juice, Grapefruit Juice, Soybean Meal, Soybean Oil, High Fructose Corn Syrup, Sweetened Beverages, Sweetened Confectionaries, Sweetened Baked Goods, Sweetened Canned Goods, Refined Sugar, Gluten Feed, Starch, Distilled Dried Grain, Refined Sugar, Bagasse, Corn Oil, Corn Syrup, Dextrose, Frozen Potatoes, Dried Potatoes, Potato chips, Lignin, Starch
- **Livestock Related: Whole** Fluid Milk, Low Fat Milk, Grain-Fed Beef, Grass-Fed Beef, Pork, Butter, American Cheese, Other Cheese, Evaporated Condensed Milk, Ice Cream, Non-Fat Dry Milk, Cottage Cheese, Skim Milk, Cream, Chicken, Turkey, Clean Wool
- **Mixed Feeds:** Cattle Grain, High-Protein Cattle Feed, Broiler Grain, Broiler Protein, Cow Grain, Cow High Protein, Range Cubes, Egg Grain, Egg Protein, Pig Grain, Feeder Pig Grain, Feeder Pig Protein, Pig Farrowing Grain, Pig Farrowing Protein, Pig Finishing Grain, Pig Finishing Protein, Dairy Concentrate, Sheep Grain, Sheep Protein, Stocker Protein, Turkey Grain, Turkey Protein
- **Biofuels:** Mtbtus Of Power Plant Input, Ethanol, Market Gasoline Blend, Substitute Gasoline Blend, Biodiesel

Land Transfers. Within the agricultural component there are period by period land transfer possibilities involving land from: (1) cropland to pasture; (2) pasture to cropland and (c) CRP to cropland. Costs for converting pasture reflect clearing, land grading, drainage installation and other factors. Cost for converting CRP involve its opportunity costs in the existing program.

Agricultural Management. Agricultural output is produced using land, labor, grazing, and irrigation water. Once commodities enter the market, they can go to livestock use, feed mixing, processing, domestic consumption, or export. Imports are also represented.

GHG Mitigation Options. Direct GHG mitigation options are those discussed in Schneider (2000) with added bioenergy features discussed below.

Biofuel production and use. Multiple biofeedstocks are represented including conventional crops (e.g. corn, rice, wheat, sorghum, sugarcane), crop residues (e.g. corn stover, wheat straw, rice straw), energy crops (switchgrass, poplar, willow), crop oils (corn oil, soybean oil), manure, and processing byproducts (bagasse, tallow, yellow grease). Across these biofeedstocks there are possibilities to use at least some of them for producing electricity, ethanol from starches and sugars, ethanol from cellulosic material, and biodiesel from oils. Biofuel market penetration is limited by need and facility expansion capability. Need for biofuel electricity is limited by growth in electricity demand and replacement needs for existing facility obsolescence. Ethanol production is assumed to be limited to grow by no more than 1 billion gallons per year due to limits on time to build plants and availability of construction resources..

In this analysis, FASOMGHG is used to simulate the national aggregate response to GHG incentives (in the form of GHG prices) and energy prices. Thus the model results project the most cost-effective mitigation opportunities at the national and regional levels. The GHG mitigation activities in FASOMGHG are accounted for as changes from a zero carbon price business-as-usual baseline. Thus, ***the mitigation results reported here are additional to projected baseline activity and GHG emission or sequestration levels***.

4.2 Results

Now let us examine how mitigation including biofeedstock contributions from agriculture change as prices of carbon dioxide, and gasoline change. Figure 1 shows the national GHG mitigation summary as a function of the carbon dioxide and gasoline prices. These results show that

- Under a situation with low gasoline and low carbon dioxide prices the predominant strategy involves agricultural soil sequestration
- When gasoline prices are low but there are higher carbon dioxide prices the results are dominated by biofuel fired electricity.
- When gasoline prices are higher ethanol production becomes competitive, and to a smaller extent biodiesel. However their GHG contribution in the GHG arena is limited by their lower offset rates. Market penetration is also limited by the ability to build new refineries. In addition, with higher liquid fuel prices the contribution of biofuel-based electricity is slightly reduced.

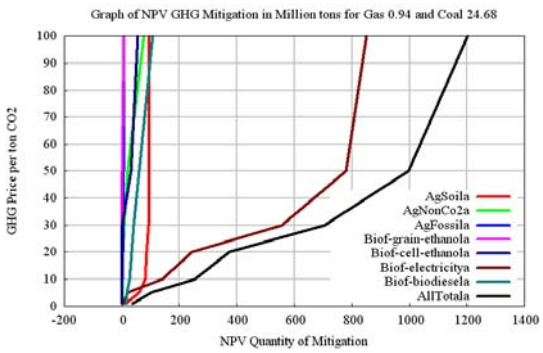
The results also show that increased gasoline prices can cause a reduction in carbon dioxide emissions even at a zero carbon dioxide price, a policy complementarity. Higher gasoline prices, overall, can have a powerful effect by stimulating production of biofuels but if one were really after GHG mitigation the model suggests one would rely mainly on bio-based electricity.\

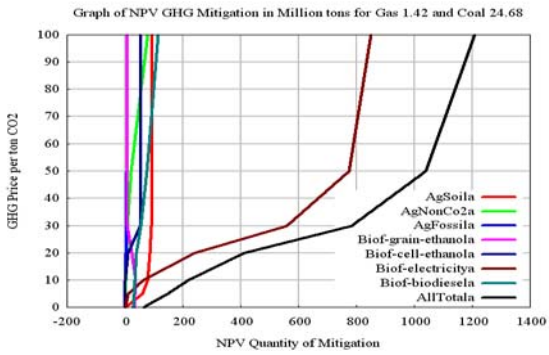
Across all these runs an important finding involves the portfolio composition between bioenergy and agricultural soil sequestration. In particular, at low prices agricultural soil sequestration is the predominant strategy as sequestration can be enhanced by changes in tillage practices that are largely complementary with existing production. However, as carbon dioxide equivalent offset prices get higher then a land use shift occurs. Namely land tends to shift out of traditional production into bioenergy strategies. As a consequence, the gains in sequestration effectively cease, topping out the potential for agricultural soil carbon sequestration. This shift occurs as a result of higher gasoline, coal, or carbon dioxide equivalent offset prices, any of which stimulates a shift of land to biofuels.

The other major result involves the relative shares of cellulosic and grain/crop based ethanol. At low GHG offset prices when the gasoline price is high, the results are dominated by grain/crop based ethanol production but as prices get higher celluosic ethanol production dominates. This is largely due to GHG efficiency.

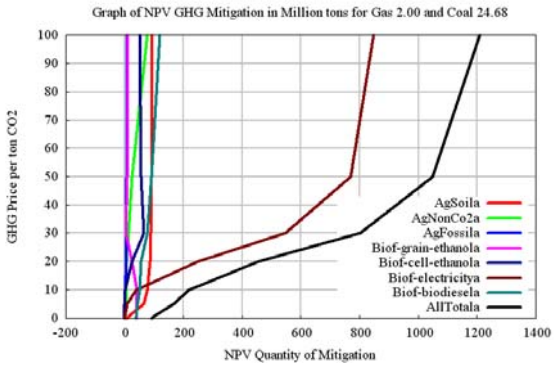
Figure 1: GHG Mitigation Strategy Use For Alternative Gasoline and Carbon Dioxide Prices

Panel a Gas Price $0.94 / Gallon Panel b Gas Price $1.42 / Gallon

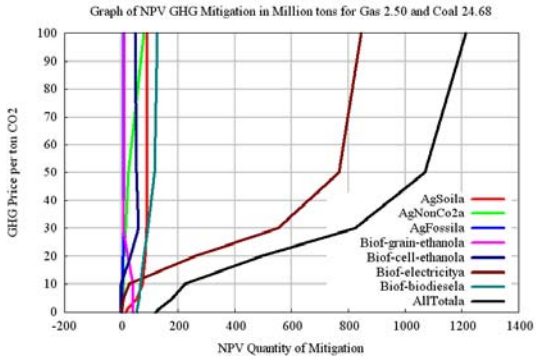




Panel c Gas Price $2.00 / Gallon



Panel d Gas Price $2.50 / Gallon



5 Concluding remarks

Several major points arise from this paper

- Not all biofuels have equal greenhouse gas offset effects generally crop ethanol is the least then cellulosic then biodiesel then electricity
- Leakage created in the commodity markets by replacement production overseas is an important factor and can offset domestic GHG emission reduction gains substantially
- Lifecycle greenhouse gas accounting will likely omit a number of land and commodity based substitution induced emission increases and offsets. Changes in the herd due to feed prices and changes in crop production intensification would seem to be hard to cover perhaps we should leave the lifecycle behind and do more systems analysis.
- Economically as GHG prices rise the more desirable bioenergy forms become bioelectricity and cellulosic ethanol.

- While not fully demonstrated here boundaries are important, considering
  - crops but not livestock,
  - domestic but not international
  - agriculture not forestry ; or
  - no other parts of the total economy

  can all bias the evaluation of the GHG implications of mitigation strategies.

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