# Toward Optimal Use of Biomass in Addressing Climate Change, Oil Supply Insecurity, and Biodiversity Concerns

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# OUTLINE

- Biofuels dilemma
- 2-part photosynthetic C storage strategy to address dilemma
- Outlook for storing $CO_2$ in geological media
- Modeling coal & coal/biomass plants to make synfuels
- Tilman research on mixed grasses with soil/root C storage
- Implications of proposed coal/biomass synfuels strategy for biodiversity loss concerns
- Economic analysis of synfuel production exploiting two-part photosynthetic C storage opportunity
- Suggestions for public policy

# DILEMMA FOR CONVENTIONAL BIOFUELS

- Advantages:
  - Carbon neutrality via photosynthetic $CO_2$ removal from atmosphere
  - Renewability
- Downside:
  - Limited availability of high-quality land for dedicated energy crops arising from low efficiency of photosynthesis (*competition with food production*) ➔ conventional biofuels can satisfy only part of liquid fuel demand even with improved conversion technologies
  - Biodiversity loss concerns about high levels of development of monoculture crops grown for energy

# TWO PART C-STORAGE STRATEGY FOR ADDRESSING DILEMMA

- ***Shift biomass from C-neutral → C-negative*** via two-part C-storage strategy for biomass to help address land-use constraint posed by conventional biofuels:
  - *First part*, based on biomass conversion via gasification, involves separating out/storing underground (*in geological formations*) as $CO_2$ most C in biomass not needed in final energy products. This part of strategy is made economically feasible by coprocessing biomass with coal to make synfuels with $CO_2$ capture and storage (CCS) in large conversion plants. "Negative $CO_2$ emissions" from photosynthetic $CO_2$ storage offset coal $CO_2$ emissions from plant and from eventual release of $CO_2$ from coal as result of synfuel combustion.
  - *Second part,* growing biomass as *mixed grasses on C-depleted soils*, leads to substantial additional storage of photosynthetic $CO_2$ as soil C and root C.
- Second part of strategy also addresses effectively biodiversity challenge posed by conventional biofuels

# KEY QUANTITATIVE ASPECTS OF BIO-C STORAGE STRATEGY

- Up to ~ 90% of C in biomass can be routinely stored underground as $CO_2$ along with $CO_2$ derived from coal if biomass and coal are gasified to make synfuels and electricity

  R. Williams, E. Larson, and H. Jin, "Synthetic Fuels in a World with High Oil and Carbon Prices," *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies*, 19-22 June 2006 (*forthcoming*)

- If biomass is mixed prairie grasses grown on C-depleted soils, biomass growth would be accompanied by C-buildup in soils/roots at rate up to ~ 60% of C in harvested biomass

  D. Tilman, J. Hill, and C. Lehman, "Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass," *Science*, **314**, 1598-1600, 8 December 2006

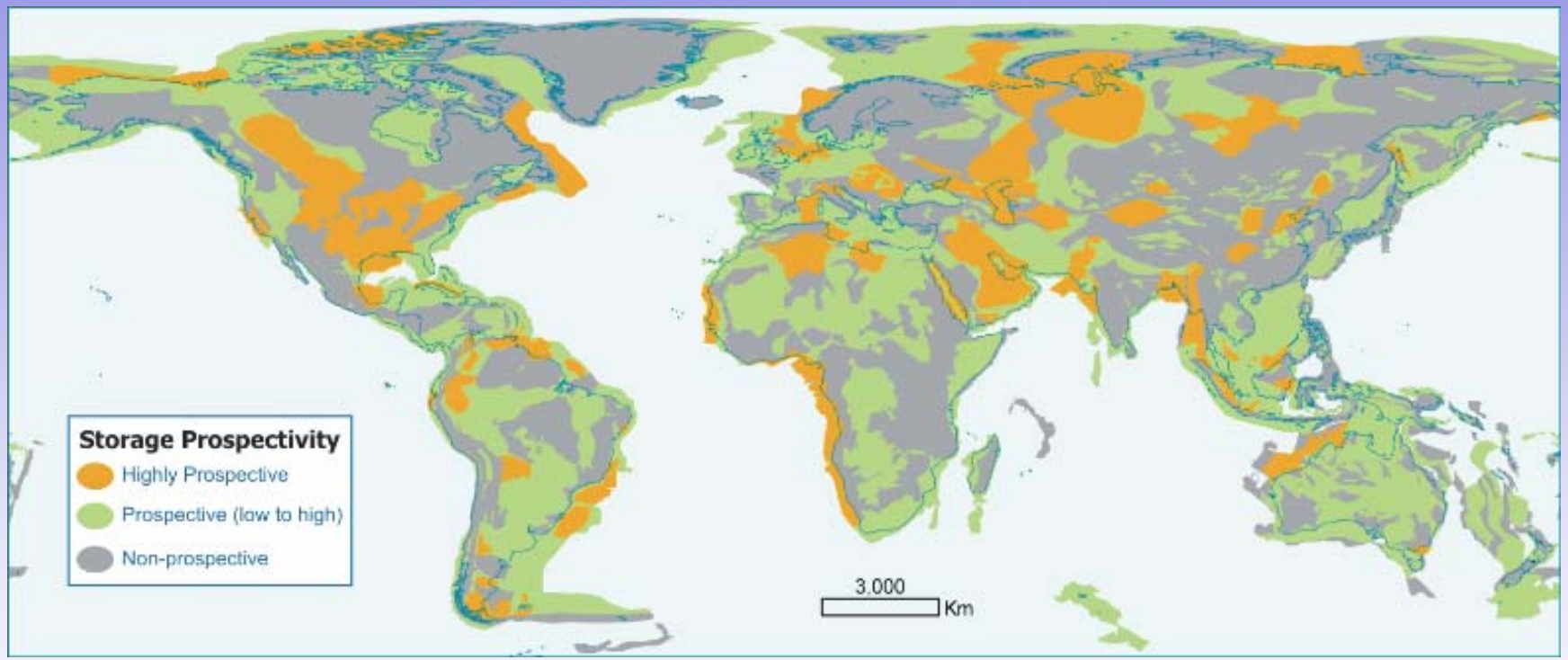
- ➔ total C storage rate up to 150% of C in harvested biomass

- Two-element C-storage strategy makes it feasible for biomass to play much greater role in mitigating climate change than with any conventional biofuel—and to do so without biodiversity loss concerns posed by conventional biofuels based on growing monocultures

# OPTIONS FOR $CO_2$ STORAGE

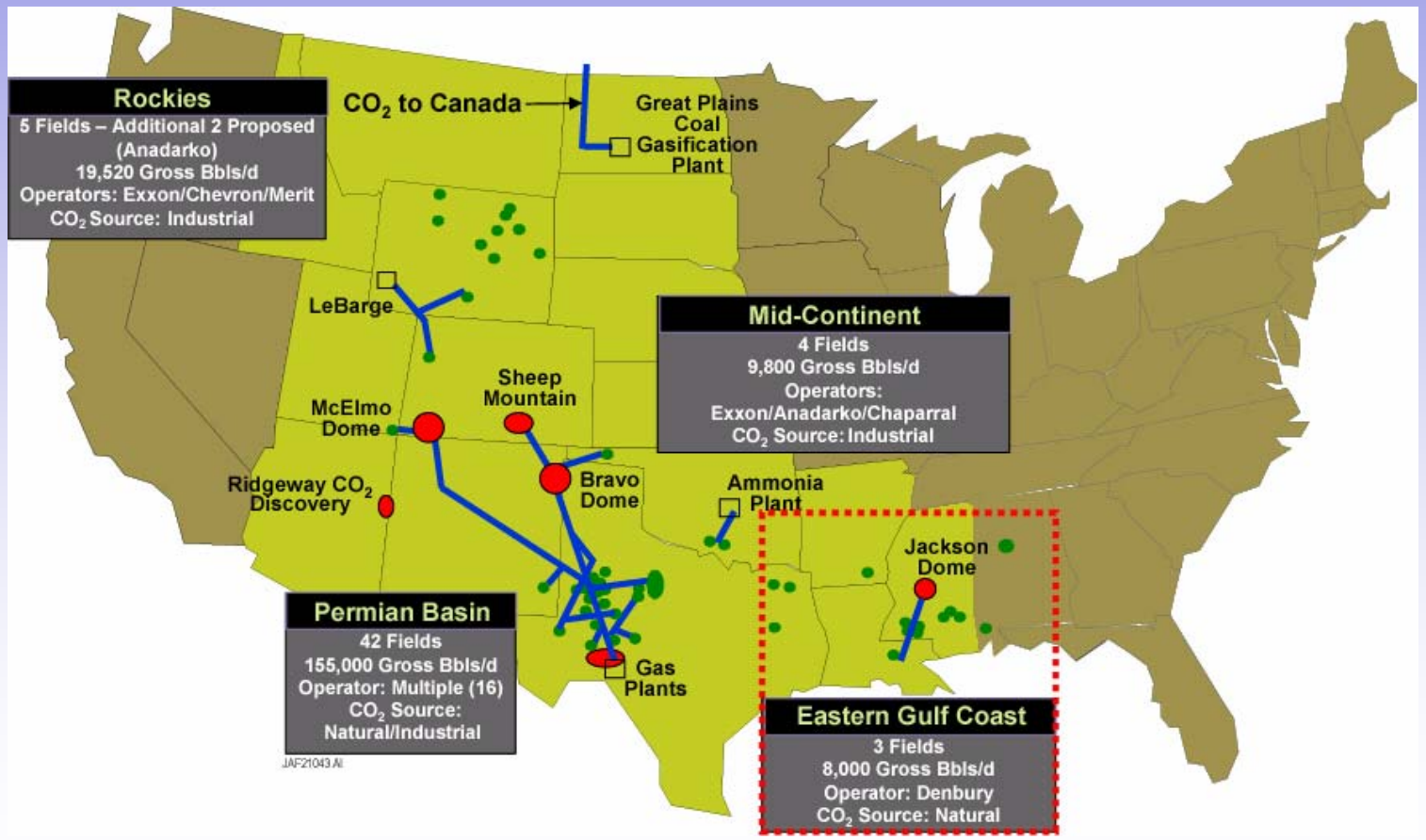
- Goal: store 100s to 1000s of Gt $CO_2$ for 100s to 1000s of years
- Major options, disposal in:
  - Deep ocean (*concerns about storage effectiveness, environmental impacts, legal issues, difficult access*)
  - Carbonate rocks [*100% safe, costly (huge rock volumes), embryonic*]
  - Disposal in geological media (*focus of current interest*)
    - Enhanced oil recovery (*30 million tonnes $CO_2$/y—4% of US oil production*)
    - Depleted oil and gas fields (*geographically limited*)
    - Beds of unminable coal (*$CO_2$ adsorbed in pore spaces of coal*)
    - Deep saline aquifers—huge potential, ubiquitous (*at least 800 m down*)
      - Such aquifers underly land area = ½ area of inhabited continents (*2/3 onshore, 1/3 offshore*)
  - Most large anthropogenic $CO_2$ sources within 0-200 km of geological disposal sites (*800 km = longest US $CO_2$ pipeline for EOR*)
  - Already some experience with aquifers, gas fields (*e.g., Sleipner, North Sea; In Salah*, *Algeria*) and extensive experience with $CO_2$-EOR

# STORAGE POTENTIAL FOR $CO_2$ IN SEDIMENTARY BASINS OF THE WORLD

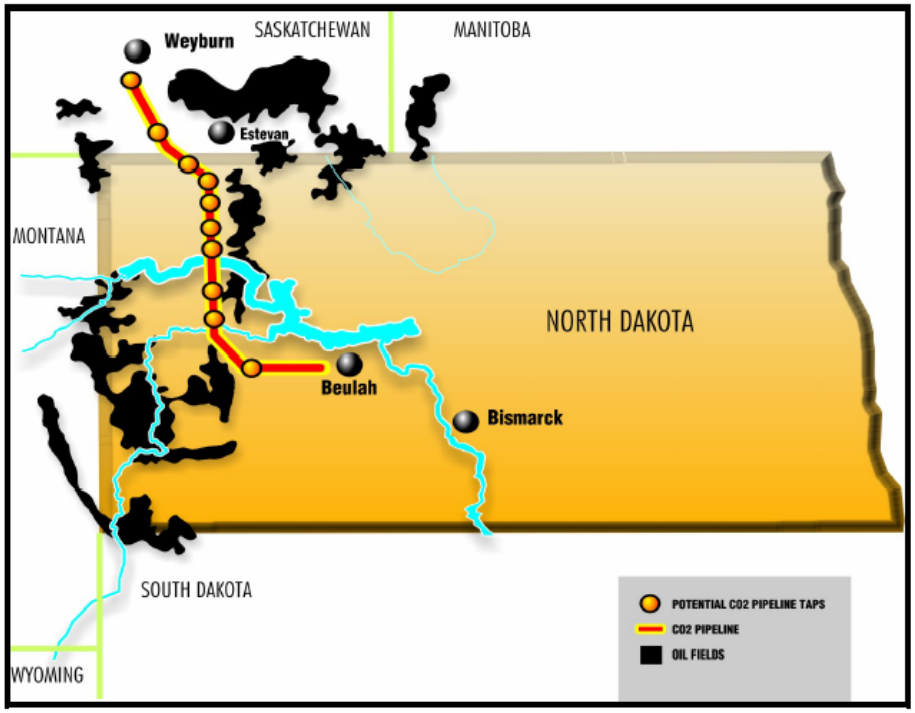



Source: J. Bradshaw and T. Dance, 2004: Mapping geological storage prospectivity of $CO_2$ for the world's sedimentary basins and regional source to sink matching. *Proceedings of the 7th International Conference on Greenhouse Gas Technologies*, September 5-9, 2004, Vancouver, Canada.

# EXTENSIVE US EXPERIENCE WITH $CO_2$ TRANSPORT FOR ENHANCED OIL RECOVERY …SOME $CO_2$ IS ANTHROPOGENIC



# FIRST PROJECT TO EXPLOIT COAL SYNFUEL-DERIVED $CO_2$ FOR ENHANCED OIL RECOVERY




- Synfuel plants are source of cheap $CO_2$ that can be used for EOR
- The $2.1 billion Great Plains Synfuels Plant at Beulah, ND, with capacity to produce up to 170 million cubic feet of methane daily from 18,500 tons of lignite, went on line in 1984.
- The GPSP generates as coproduct up to 200 million cubic feet per day of nearly pure $CO_2$.
- Since 2000 the GPSP has sold 95 million cubic feet of $CO_2$ per day to Encana Corporation for $CO_2$-EOR at the Weyburn oil field in Saskatchewan, Canada.
- The $CO_2$ is transported 205 miles to the $CO_2$-EOR site via pipeline.

# INTERGOVERNMENT PANEL ON CLIMATE CHANGE (2005) ON $CO_2$ STORAGE

- On geological storage capacity for $CO_2$:

  …worldwide, it is virtually certain that there is 200 Gt $CO_2$ of geological storage capacity and likely that there is at least about 2000 Gt $CO_2$…

- On geography of sources and sinks for $CO_2$:

  …there is potentially good correlation between major sources and prospective sedimentary basins, with many sources lying either directly above, or within reasonable distances (*less than 300 km*) from areas with potential for geological storage…

- On security of $CO_2$ storage:

  …based on observations and analysis of current $CO_2$ storage sites, natural systems, engineering systems, and models, the fraction [*of injected $CO_2$*] retained in appropriately selected and managed reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1000 years…

# "POLYGENERATION" SYSTEMS ANALYZED

- Feedstocks:
  - Coal (*high S bituminous*)
  - Biomass (*switchgrass*)
- Conversion systems analyzed:
  - C-FT-V
  - C-FT-C
  - C-FT-CoC
  - C/B-FT-CoC
  - B-FT-V
  - B-FT-C
- Alternative $CO_2$ storage modes:
  - $CO_2$-AqS = saline aquifer storage
  - $CO_2$-EOR = enhanced oil recovery
- Acronyms defined:
  - C- = coal
  - B- = biomass
  - C/B- = coal/biomass coprocessing
  - -FT- = Fischer-Tropsch liquids + electricity
  - -V = $CO_2$ vented
  - -C = $CO_2$ captured
  - -CoC = $CO_2$ & $H_2S$ co-captured

# MODELING TOOLS & MAJOR SYSTEM ELEMENTS MODELED

## Modeling Tools

- AspenPlus software for mass/energy balances
- AspenPinch software for system heat integration
- Princeton costing model

## Major Elements of Synthetic Liquid Fuel Systems Modeled

- GE entrained flow quench gasifier for coal
- GTI fluidized bed gasifier for biomass—*not commercial*
- Rectisol (*physical solvent*) for acid gas removal
- Liquid-phase reactors for synthesis (*iron-based catalyst*)

# CATALYTIC SYNTHESIS OF FUELS FROM SYNGAS

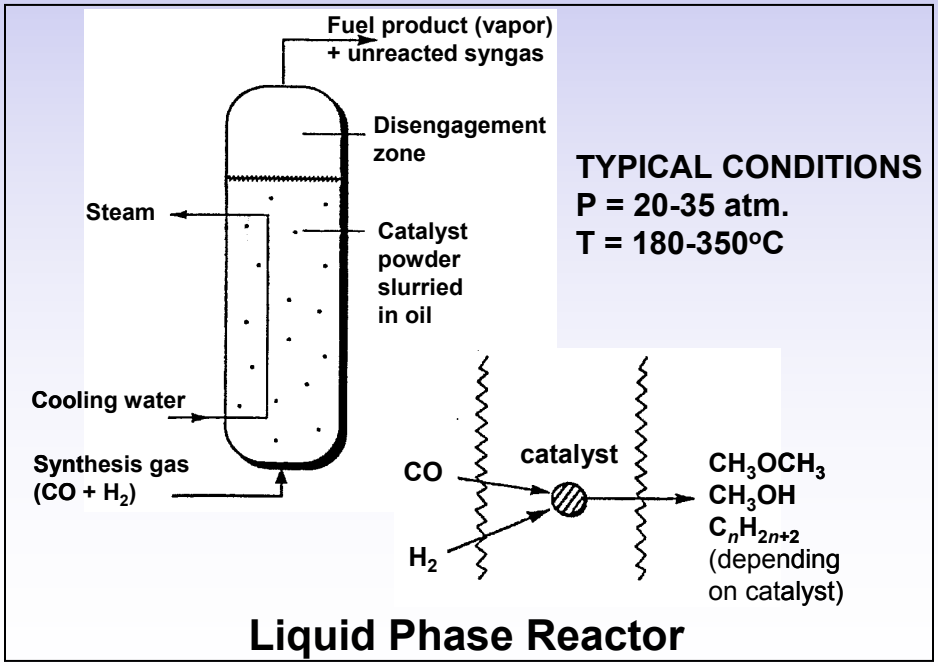
- **Basic overall reactions**:

$$CO + 2H_2 \Leftrightarrow -CH_2- + H_2O$$ Fischer-Tropsch liquids (FTL)

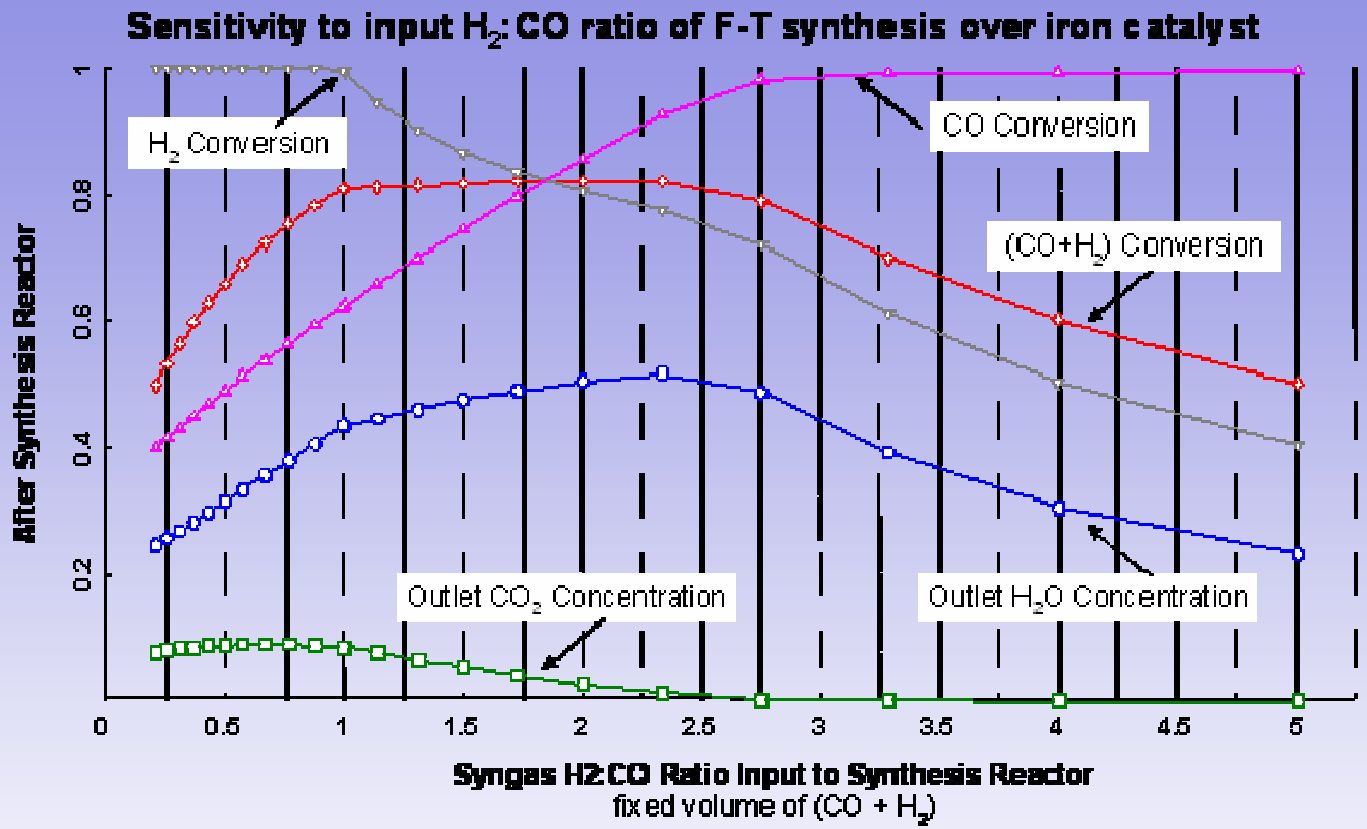
$$3CO + 3H_2 \Leftrightarrow CH_3OCH_3 + CO_2$$ Dimethyl ether (DME)

$$CO + 2H_2 \Leftrightarrow CH_3OH$$ Methanol (MeOH)

- **Three reactor designs**:
  - Fixed-bed (*gas phase*): low one-pass conversion, difficult heat removal
  - Fluidized-bed (*gas phase*): better conversion, more complex operation
  - Slurry-bed [*liquid phase* (*LP*)]: much higher single-pass conversion (*e.g., for F-T liquids, 80% with LP vs. 40% with gas phase*)
    - LP-F-T liquids reactors are commercial
    - LP-MeOH commercially demonstrated
    - LP-DME near commercial
  - Focus here on
    - LP synthesis
    - F-T liquids



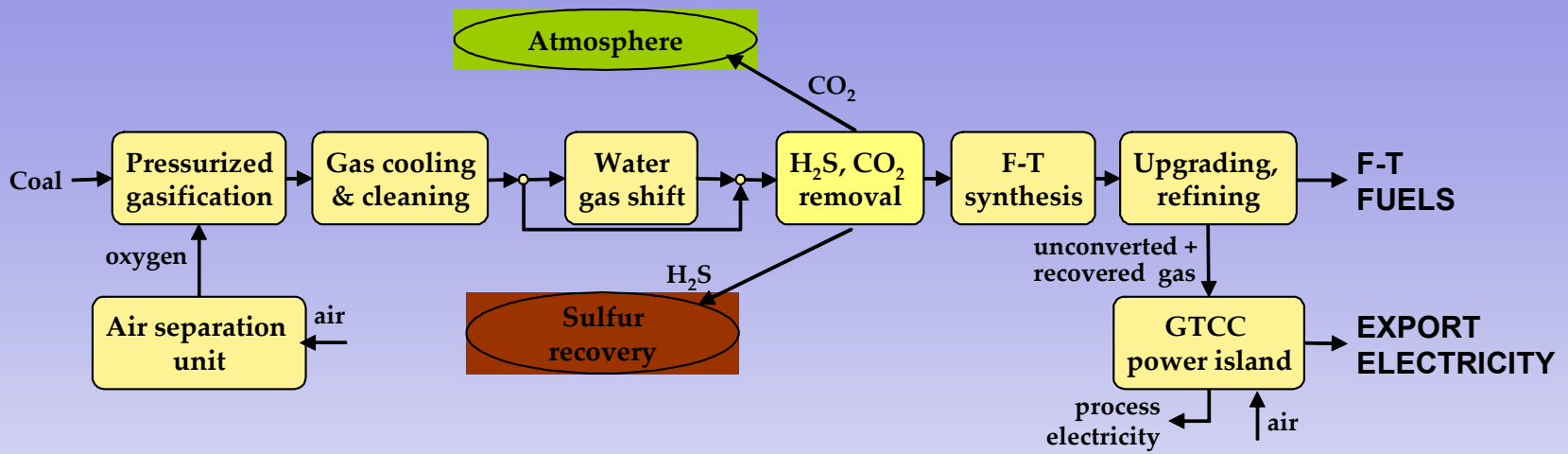
# CHOOSING $H_2$:CO RATIO FOR F-T SYSTEMS




<u>C-FT-V</u>: $H_2$:CO = 2.25 (*maximum syngas conversion*)

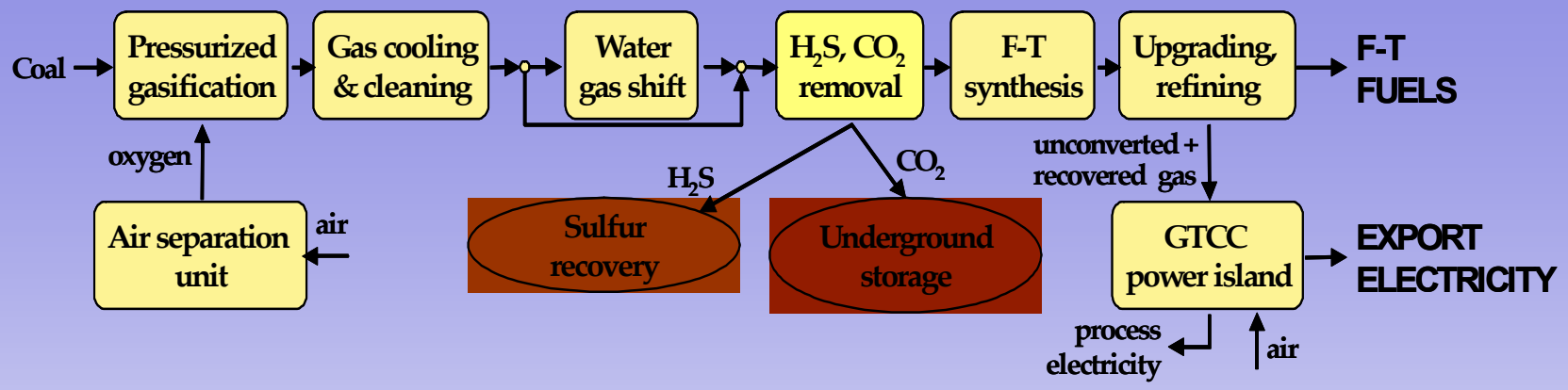
<u>C-FT-C, C-FT-CoC, C/B-FT-CoC</u>: $H_2$:CO = 2.75 (*i*) near maximum conversion; (*ii*) $CO_2$ level essentially zero, and (*iii*) CO conversion almost complete…but there are still minor $CO_2$ emissions from power plant

# F-T FUELS + ELECTRICITY FROM COAL w/$CO_2$ VENTED (C-FT-V)



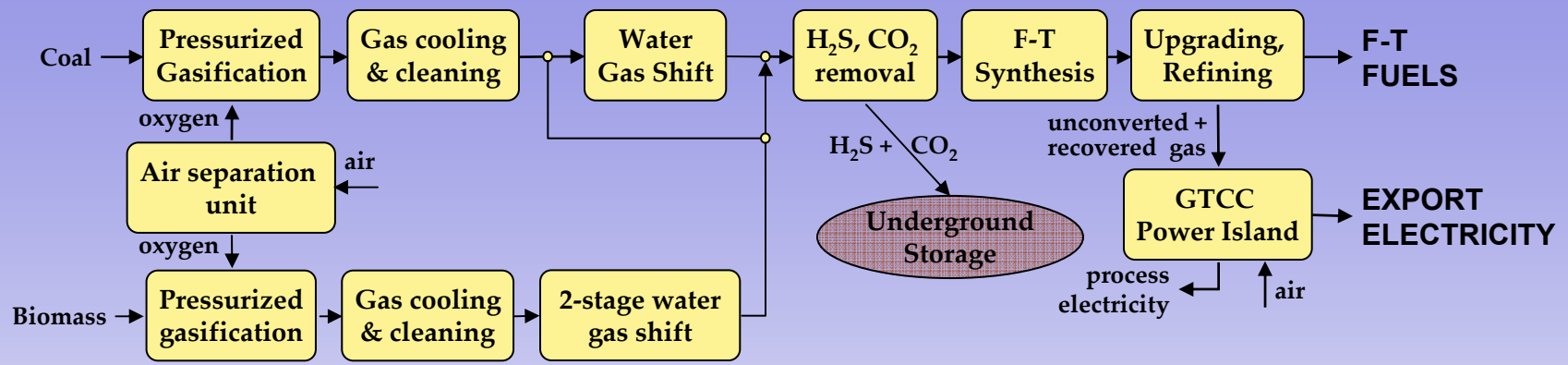

- Technologies for making F-T fuels from coal are commercial
- Least-costly fuels will often be those from "polygeneration" plants that also make co-product electricity
- Using low-cost Western coals, such plants can provide fuels that can compete with diesel/gasoline from \$40-\$50/barrel crude oil
- If the relatively pure stream of $CO_2$ recovered upstream of synthesis is vented, GHG emission rate from plant + F-T combustion ~ 1.8 X GHG emission rate for crude-oil-derived diesel/gasoline

# F-T FUELS + ELECTRICITY FROM COAL w/CCS (C-FT-C)



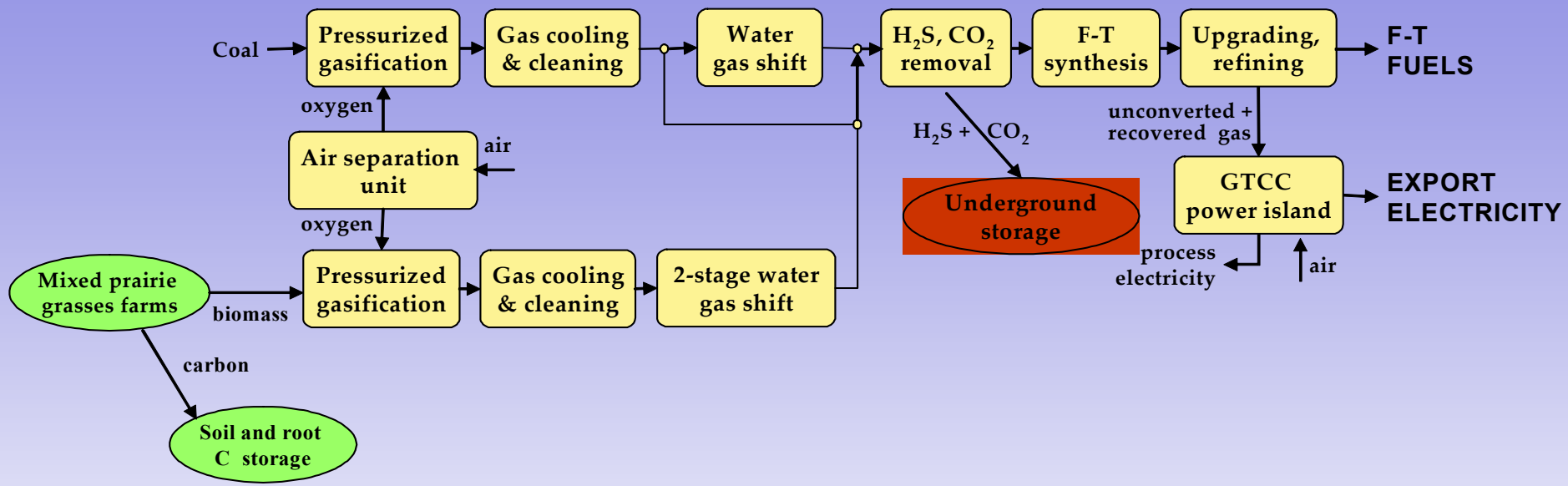

- $CO_2$ can be recovered upstream of the synthesis reactor so as to reduce $CO_2$ emissions associated with both F-T fuels & electricity
- With CCS, the GHG emission rate for:
  - Electricity ~ same as for a coal IGCC with CCS
  - F-T fuels ~ slightly higher than for crude oil-derived hydrocarbon fuels
- No synfuel plant should ever be built w/o CCS—incremental cost of CCS is less than for adding CCS to any coal plant making electricity
- In a climate-constrained world, liquid fuels characterized by near-zero GHG emissions needed➔ must do better than CCS for coal F-T fuels

# F-T FUELS + ELECTRICITY FROM COAL + BIOMASS w/CCS (C/B-FT-CoC)



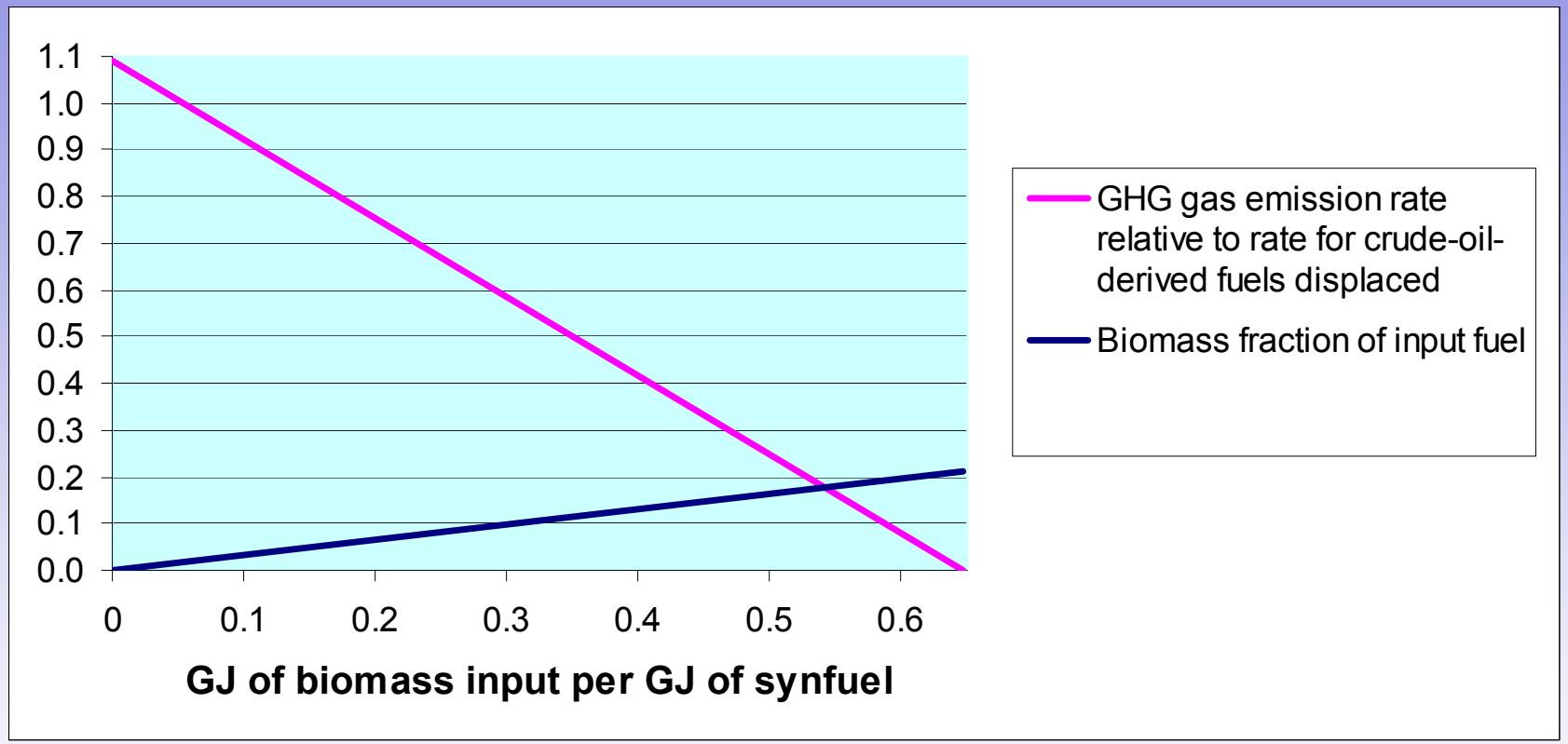

- Adding biomass (*residues or dedicated energy crops*) to system with CCS ➔ can exploit negative $CO_2$ emissions potential of storing photosynthetic $CO_2$ in geological formations to offset coal $CO_2$ emissions from plant and from eventual F-T fuel combustion
- Co-processing coal/biomass ➔ low emissions @ low cost exploiting:
  --scale economies of coal conversion, low cost of coal
  --negative emissions potential of biomass (*highly valued w/C policy*)
- No commercial large-scale biomass gasifier…but such could become commercial in 5-10 years if there were sufficient market interest

# F-T FUELS + ELECTRICITY FROM COAL + PRAIRIE GRASSES WITH TWO C-STORAGE MECHANISMS




- Growing mixed prairie grasses on C-depleted soils ➔ substantial build-up of C in roots/soils
- Exploiting CCS + soil/root C buildup ➔ realization of near-zero GHG emissions for F-T fuels with modest biomass inputs
- Two-C-storage strategy ➔ much larger role for biomass in mitigating climate change than is feasible with any conventional biofuel strategy

# RELATIVE GHG EMISSION RATE & BIOMASS INPUT FRACTION VS (BIOMASS INPUT)/(FTL OUTPUT) FOR COAL/BIOMASS F-T POLYGEN PLANT w/CCS

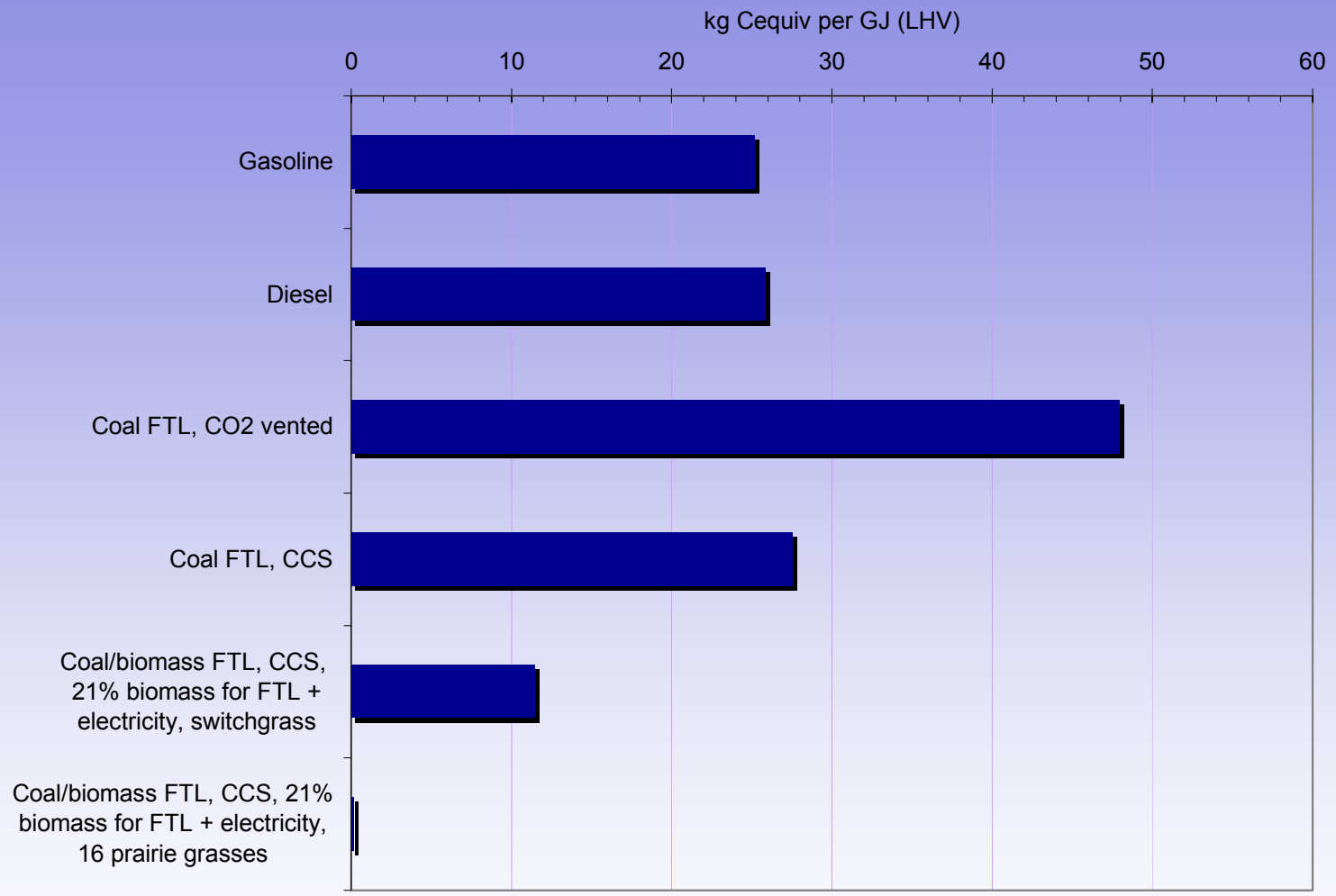



Assumptions:

- biomass = mixed prairie grasses grown on C-depleted soils
- soil/root C storage rate = 60% of C in harvested biomass

➔ low net GHG emission rate with modest biomass input fractions

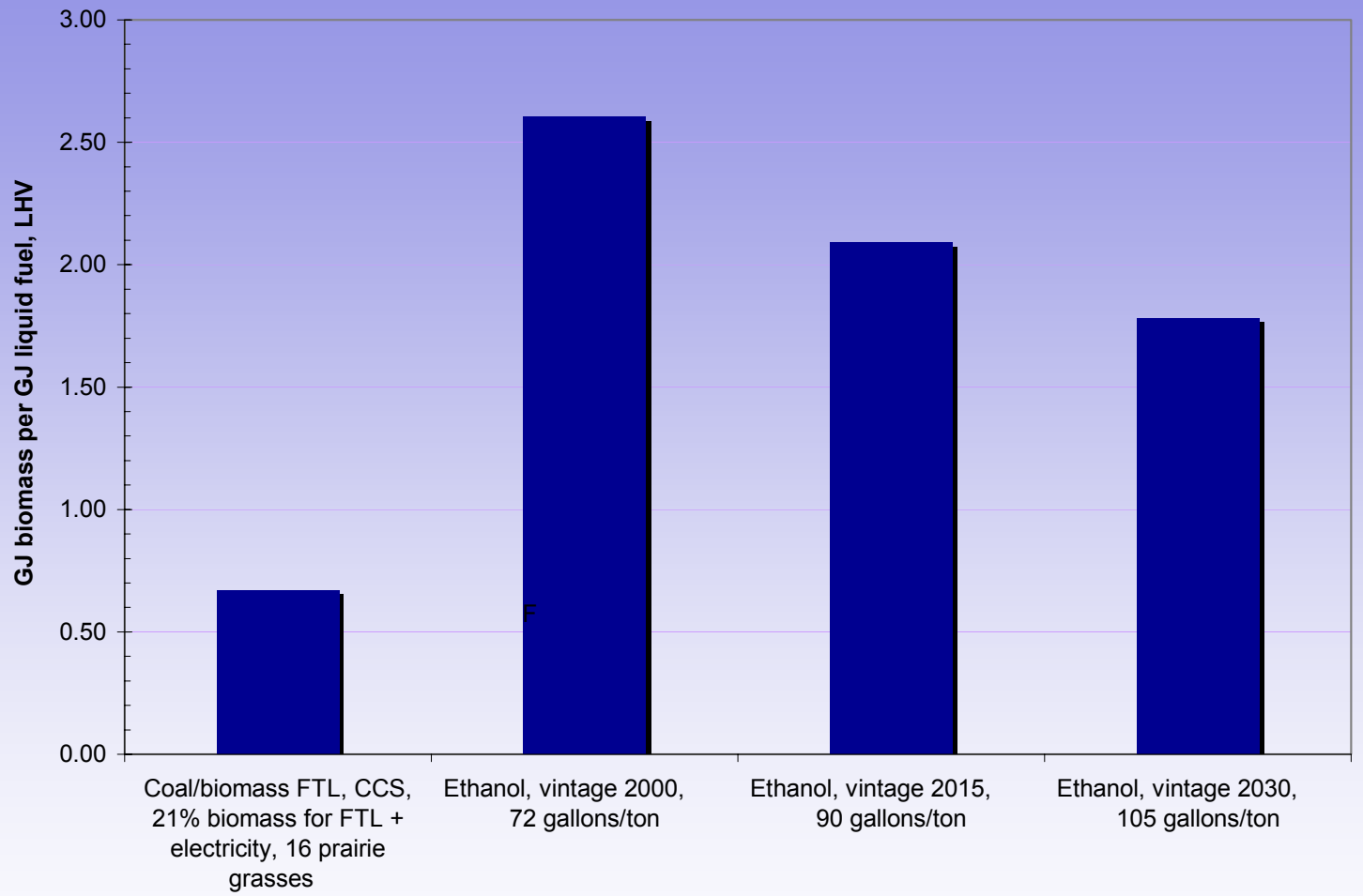
# GHG Emission Rates for Fuel Production and Use




Penultimate case based on switchgrass (45*% of emission rate for gasoline*) exploits negative $CO_2$ emissions potential of photosynthetic $CO_2$ storage in geological reservoirs

**Final case shows what can be realized by exploiting both $CO_2$ storage and soil/root C storage by growing mixed grasses on C-depleted (*formerly cultivated*) soils**

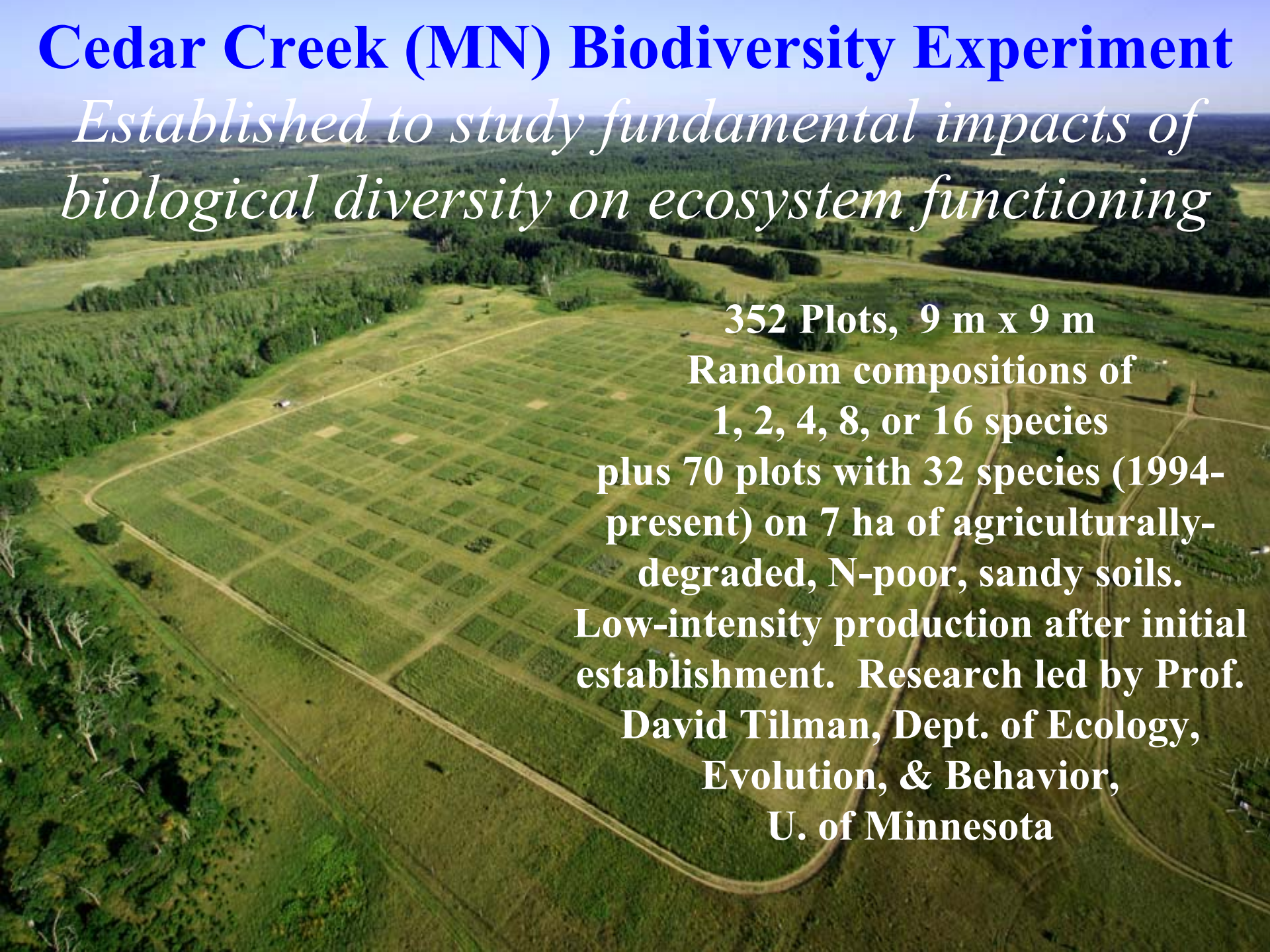
# Biomass Required to Make 1 GJ of Liquid Fuel




The ethanol options involve alternative levels of technology for cellulosic ethanol—present technology (*vintage 2000*), near-term technology (*vintage 2015*) and hoped-for long-term (*vintage 2030*) technology)

# Cedar Creek (MN) Biodiversity Experiment

*Established to study fundamental impacts of biological diversity on ecosystem functioning*



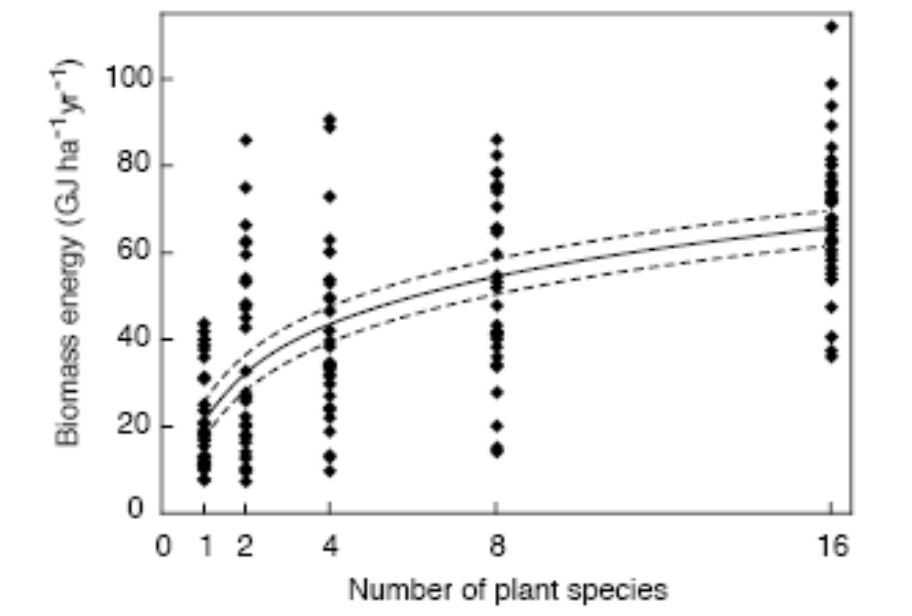
**352 Plots, 9 m x 9 m**
**Random compositions of**
**1, 2, 4, 8, or 16 species**
**plus 70 plots with 32 species (1994-present) on 7 ha of agriculturally-degraded, N-poor, sandy soils.**
**Low-intensity production after initial establishment. Research led by Prof. David Tilman, Dept. of Ecology, Evolution, & Behavior, U. of Minnesota**

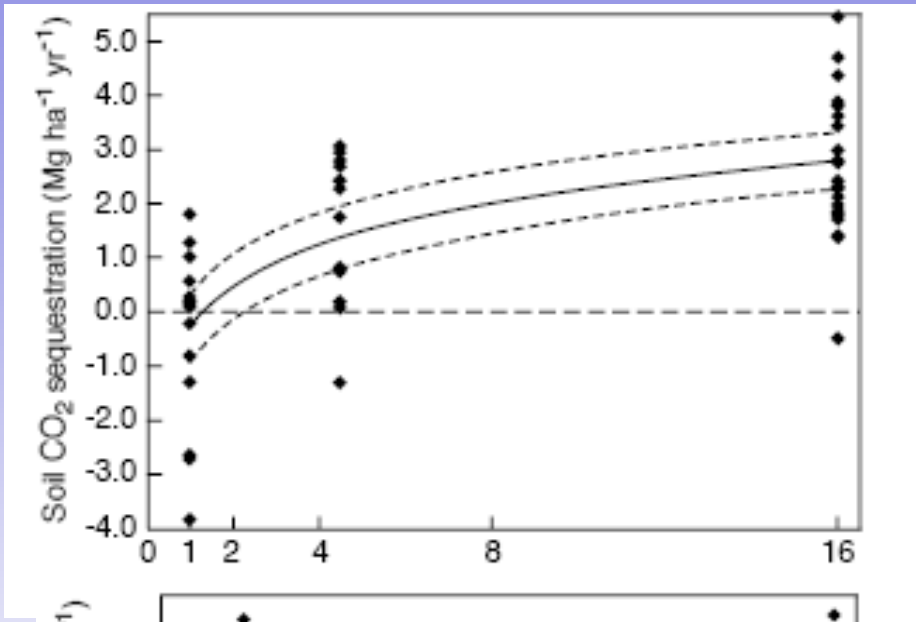
# Major Findings of Research by Tilman's Group

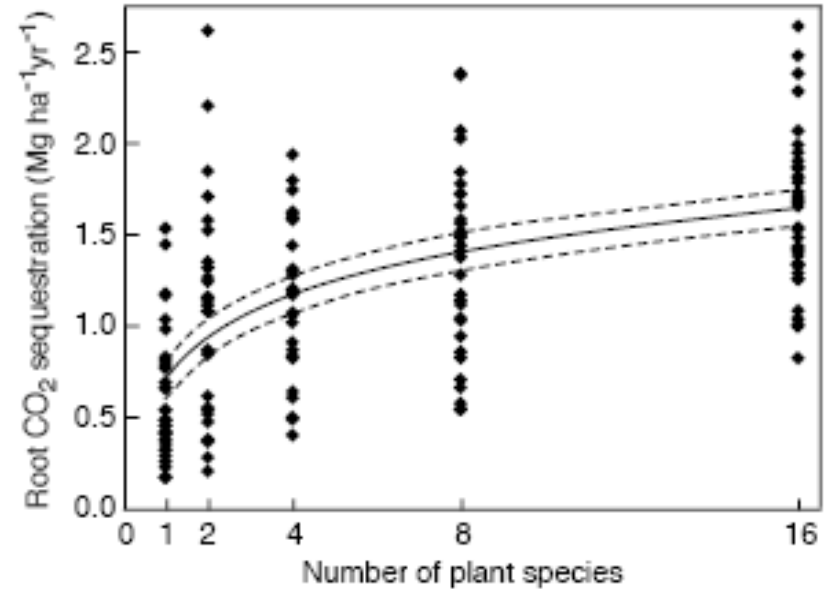
- Higher yields than with monocultures for same level of inputs
- Steady build-up of soil fertility vs little or no change for monocultures
- Much higher ecosystem stability than for monocultures
- Less leaching loss of nitrate/nitrite than for monocultures
- Lower incidence of foliar fungal diseases
- Greater soil microbial diversity
- Lower weed invasion
- High (energy output)/(energy input) for low-intensity production
- High sustained rate of soil C + root C buildup
  ➔ huge climate change mitigation benefit
- Local biodiversity gain vs. net biodiversity loss for monocultures

Source: D. Tilman et al., *Science,* **314**: 1598-1600, 8 December 2006

# Low-Intensity Growing of Prairie Grasses: Biomass Energy, Soil C, & Root C vs. # of Species




Results of research growing prairie grasses on degraded lands at the Cedar Creek Natural History Area, Minnesota, carried out by Tilman and collaborators

Source: D. Tilman et al., *Science,* **314**: 1598-1600, 8 December 2006

# IMPLICATIONS OF "POLYCULTURE MANDATE" TO ADDRESS BIODIVERSITY LOSS CONCERNS

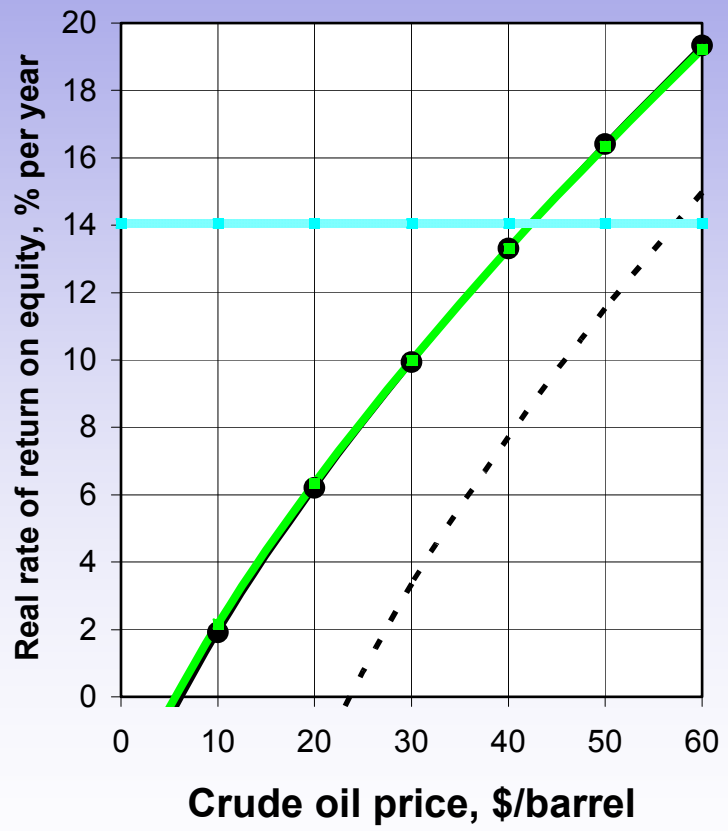
- Not only would cellulosic ethanol be able to provide much less low GHG-emitting liquid fuel than would proposed coal/biomass FTL strategy, but also its potential might be constrained by biodiversity loss concerns
- Although converting into useful fuel heterogeneous feedstock like biodiversity-enhancing mixed prairie grasses is always more challenging than for homogenous feedstock, challenge is far less daunting for thermochemical conversion (*e.g., gasification*) than for biochemical converson (*e.g., fermentation to ethanol*)
- Gasification conversion route might prove to be key in addressing effectively biodiversity loss challenge posed by conventional biofuels such as ethanol, which are likely to be based on monoculture feedstocks

# FINANCIAL/COST PARAMETERS FOR IRR ANALYSES

| | |
|---|---|
| Construction period (y) | 4 |
| Inflation rate (%/y) | 2 |
| Book/tax life (y) | 30/20 |
| Depreciation (for tax purposes) | MACRS |
| Corporate income tax rate (%) | 38 |
| Property taxes & insurance (%/y) | 2 |
| Nominal (real) return on equity (%/y) | Determined by market prices of products via IRR analysis |
| Nominal (real) return on debt (%/y) | 6.5 (4.4) |
| Equity/Debt ratio | 45/55 |

Coal (*prairie grasses*) price = \$0.63 *(\$4.87)* per million BTU—Montana conditions
GHG emissions price = \$100/tC—assumes climate change mitigation policy is in place
$CO_2$ storage in saline formations 100 miles from plant
Oil prices ranging from \$0 to \$60 a barrel

# At $100/tC, making ultra-low GHG emitting synthetic fuels + electricity from $0.63/MBTU coal + $4.87/MBTU mixed prairie grasses would be as profitable as making same products from low-cost coal only




Electricity price = $58/MWh, least-costly coal option with CCS, Aq-S

- Coal FTL + electricity, CO2-AqS, $0.63/MBTU coal
- Coal/grasses FTL + electricity, CO2-AqS, $4.87/MBTU biomass
- Coal FTL + electricity, CO2 vented, $0.63/MBTU coal
- Coal IGCC, CO2-AqS, $58/MWh electricity, $0.63/MBTU coal

21% of fuel input is mixed prairie grasses to coal/grasses plant making 14,000 B/D gasoline-equivalent FTL + 450 $MW_e$ of electricity

Plant-gate synfuel price = $1.4 per gallon gasoline equivalent when crude oil price = $40/barrel

# COMPARING MARKET & EFFECTIVE PRICES FOR COAL & PRAIRIE GRASSES WHEN GHG EMISSIONS PRICE = $100/tC

*FOR SYNFUEL PLANTS WITH $CO_2$ CAPTURE/STORAGE*

(*$ PER MILLION BTU*)

| | payment to farmers | harvesting, storage, and transport | plant-gate market price | upstream GHG emissions | Net $CO_2$ emissions from plant + FTL use | soil and root C storage | effective price |
|---|---|---|---|---|---|---|---|
| coal | - | - | **0.63** | 0.11 | 1.13 | - | **1.87** |
| prairie grasses | 2.36 (*$38/ton*) | 2.50 (*$40/ton*) | **4.87** (***$78/ton***) | 0.14 | -2.41 | -1.70 | **0.90** |

More than 70% of payment to farmer would be for C storage in soil and roots

# SUGGESTED ACTIONS

- Incentives for commercializing biomass gasification technologies
- R&D initiative for biomass production on C-depleted soils—state programs + supplemental federal support…2007 Farm Bill
- Policy to encourage coal/biomass coprocessing with CCS as major activity in Great Plains (GP) states, beginning with residues
- Policy to facilitate development of infrastructure for biomass harvesting, storage, and transport for energy
- Policy to promote improved fuel economy for motor vehicles
- Climate change mitigation policy for transportation fuels, including:
  - *Requirement that no coal synfuel plant be built without CCS*
  - *Low C obligation for fuels*
- Global initiative for low-intensity biomass production on C-depleted lands involving, *inter alia*, China—where there are huge amounts of degraded grasslands and pressing need to make China's emerging coal syfuels program climate-friendly

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