AG CARBON SOLUTIONS

CARBON SEQUESTRATION PROJECT LCA

Ag Carbon Solutions LLC 2023 Tax Year
JULY 30, 2024
Lake Pickett Site, 15841 Lake Pickett Rd.
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Prepared by John P. Smith, HSA Golden Inc
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Under penalties of perjury, I declare that I have examined the information contained in this affirmative statement and the documents that substantiate this affirmative statement, and to the best of my knowledge and belief, it is true, correct, and complete. The following testaments are verifiably true:

- The carbon oxide product for which the 45Q credit is being claimed is qualified carbon oxide as defined by §45Q(c);
- The qualified carbon oxide has been captured at a qualified facility as defined by §45Q(d);
- The qualified carbon oxide has been captured at a facility residing in the United States, in the state of Florida.

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List of Exhibits

ACRONYMS AND ABBREVIATIONS

CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOE	Department of Energy
EPA	Environmental Protection Agency
ft	Foot
gal	Gallon
GHG	Greenhouse gas
ISO	International Organization for Standardization
K	Thousand
kg	Kilogram
kJ	Kilojoule
lb	Pound
LCA	Life cycle analysis
m	Meter
M	Thousand
MM	Million
N/A	Not applicable/available
$_2$	Nitrogen
N_2O	Nitrous oxide
NEMS	National Energy Modeling System
NETL	National Energy Technology Laboratory
NG	Natural gas
NGCC	Natural gas combined cycle
NOAK	Nth of a kind
NOx	Oxides of nitrogen
O&M	Operation and maintenance
O_2	Oxygen
PC	Pulverized coal
ppm	Parts per million
PSFM	Power Systems Financial Model
psi	Pounds per square inch
psia	Pound per square inch absolute
psig	Pound per square inch gauge
R&D	Research and development
SC	Supercritical
scf	Standard cubic feet
SO_2	Sulfur dioxide
SOA	State of the art
SOx	Oxides of sulfur
tonne	Metric ton (1,000 kg)
U.S.	United States
°C	Degrees Celsius

Executive Summary

This life cycle analysis (LCA) is required by the United States (U.S.) Internal Revenue Service (IRS) to satisfy the requirements of 26 CFR Part 1, Section 1.45Q-4. The taxpayer completing this study is Ag Carbon Solutions LLC. This LCA report has been prepared in accordance with ISO 14040/14044 requirements and with the NETL CO2U LCA Guidance Document as modified by the 45Q addendum.

This Life Cycle Assessment (LCA) has been commissioned by Ag Carbon Solutions LLC in support of their carbon sequestration project. The report was prepared by HSA Golden, Inc, an independent consultant. The carbon sequestration project is comprised of two main patented processes: The Dry Decay Method and the Agricultural Production Method.

The Dry Decay Method, Patent Number 5,558,694, is utilized to dry incoming clean vegetative, forestry, agricultural, and urban wood residuals to effectively double their offset value. The carbonaceous materials represent an inventory of carbon to be sequestered by the Agricultural Production Method.

Ag Carbon Solutions is licensed to utilize the Agricultural Production Method covered by Patent Number 11,511,325, issued to Ag Carbon Farms LLC. The Agricultural Production System and Method involves dewatering an excavation area of inorganic soil and replacing the void space with the dried wood debris and/or natural organic soils, then allowing the water table to resume. This is an industrial agricultural process that utilizes commonly used heavy equipment in a novel way in accordance with a fully patented process. The method sequesters carbon in a solid state.

The purpose of this LCA is to analyze the quantity of carbon dioxide equivalents (CO_{2e}), in metric tons, that are sequestered by utilization of the Dry Decay Method and Agricultural Production Method. This is a gate-to-grave study to evaluate the volume of wood that enters the facility (input) to the mass of CO_{2e} permanently sequestered, to create carbon offsets (output).

This study is focused solely on carbon sequestration (in metric tonnes) as a result of the Dry Decay Method and Agricultural Production Method.

1 GOAL AND SCOPE

1.1 STUDY GOAL

The specific goals of this life cycle analysis (LCA) are described below:

1. Intended application – to find the metric tons of qualified carbon oxide that the taxpayers demonstrate were captured and permanently isolated from the atmosphere or displaced from being emitted into the atmosphere through use in a carbon sequestration process.
2. Reasons for carrying out the study – to determine the amount of qualified carbon oxide utilized by the taxpayers under paragraph (2)(B)(ii) or (4)(B)(ii) of subsection (a) of 26 CFR Part 1, Section 1.45Q-4.
3. Intended audience – the U.S. Internal Revenue Service (IRS) and Department of Energy (DOE).

1.2 STUDY SCOPE

1.2.1 Functional Unit of the Study

The functions evaluated in this LCA are the stockpiling of green wood for drying (Dry Decay Method) and the burial of wood below the water table (Agricultural Production Method) to create permanent agricultural lands, agricultural carbon offsets, and carbon neutral beef. Additional functions, such as excavation, transport of soil, dewatering, surface drainage and erosion control are omitted from the evaluation since those are construction processes that have little bearing on the long-term sequestration of carbon.

The functional unit is one metric tonne of CO_{2e}. This is conservatively estimated based on published data and scientific studies.

1.2.2 System Boundary

The system boundary is the gate of the facility. Wood, the raw material, enters the gate and is permanently sequestered on the site. The system boundary is shown in the System Environment Flow Chart, Figure 1.

1.2.3 Carbon Oxide Source and Utilization

The source of the wood entering the site is land clearing debris or storm damage; i.e. waste wood. Dry wood is known to have a carbon content of approximately 50% by weight.

1.2.4 Technology Representativeness

Data is based on scientific papers and other published information, specifically:

- One cubic yard of mixed dry wood, when compacted, has an average density of approximately 640 pounds per cubic yard. This is based on *Volume-to-Weight Conversion Factors*, U.S. Environmental Protection Agency, Office of Resource Conservation and Recovery, April 2016.[1]

- One tonne of dry wood contains approximately 0.5 tonnes of carbon. This is based on *Methods for estimating Carbon Within Forests*, Penn State Extension, January, 2023.[2]

- There is negligible decomposition and conversion of wood to carbon dioxide, when the wood is buried beneath the water table. This is based on academic papers:
  - *Carbon Balance and Management, Carbon sequestration via wood burial*, Ning Zeng, January 2008.[3]
  - *Wood Vault: remove atmospheric CO_2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future,* Ning Zeng and Henry Hausmann, Carbon Balance and Management, 2022.[4]

This technology is a novel patented methodology and as such has no comparative process.

1.2.5 Geographical Representativeness

The facility is in the State of Florida, which is suitable for the process due to the prevailing high water table, availability of suitable land, and abundance of waste wood due to storm damage and development activities

1.2.6 Life Cycle Impact Assessment Methods for Results Interpretation

This study utilizes Table A-1 of 40 CFR Part 98 subpart A https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-98 for life cycle impact assessment impact factors for global warming potential (GWP).

1.2.7 Completeness Requirements

The most significant input, other than the raw material, is bio-diesel fuel for the material handling and other miscellaneous equipment used in the process. According to Ag Carbon Solutions, the process uses approximately 2800 gallons of bio-diesel fuel per month for all heavy equipment utilized on the project site. This fuel usage results in burying between 75,000 and 100,000 cubic yards (CY) of wood in the same period. Based on published studies, the carbon footprint of bio-diesel is approximately 21 – 31 grams of CO_{2e} per mega-joule (MJ)[5] and there is approximately 34 MJ of energy potential in one liter of bio-diesel[6]. Therefore:

$$(31\ \text{g}\ CO_{2e}/\text{MJ})(34\ \text{MJ/l})(3.785\ \text{l/gal})(\text{kg}/1000\text{g}) = 4.0\ \text{kg}\ CO_{2e}/\text{gal bio-diesel}$$

$$(4.0\ \text{kg}\ CO_{2e}/\text{gal bio-diesel})(\text{tonne}/1000\text{kg})(2800\ \text{gal}/75{,}000\ \text{CY}) = \underline{0.00015\ \text{tonnes}\ CO_{2e}/\text{CY wood}}$$

The carbon footprint of this energy use is negligible compared to the mass of CO_{2e} sequestered from one CY of wood, and is therefore excluded from the analysis. As shown later, 0.53 tonnes of CO2e are sequestered from 1 CY of wood. Therefore the energy use represents 0.03%.

1.2.8 Sensitivity Analysis

Assumptions used in the calculation are conservative. The density of compacted wood waste is based on EPA data from several studies, and depends on the type of wood, as well as placement and compaction techniques. Any change in compacted density, up or down, will have the same proportional effect on the resulting calculation of tonnes of CO_{2e}. Note that the density reported in the EPA data is for wood that has not undergone the dry decay method, which would have the effect of increasing density of the material by: (1) breaking down smaller sized wood pieces into a soil and (2) when placed and compacted, this soil will fill void spaces between larger buried wood pieces. Based on observations of resultant dry decay material, we believe that the assumed density used in the calculation is conservative.

Data can be validated by periodic testing the CO_2 flux through the ground at random points over a completed carbon sequestration area. Leakage of CO_2 is not expected. However, instruments such as the LI-870 CO_2 Analyzer combined with a Smart Chamber, manufactured by LI-COR, Lincoln, Nebraska, can be used to periodic conformation.

2 LIFE CYCLE INVENTORY ANALYSIS

The Dry Decay Method (Patent No. 5,558,694) involves stockpiling natural wood wastes that result from land clearing or storm debris The materials to be used in this process are clean tree stumps, trunks and limbs, and other clean natural organic material. Other than separation, no additional processing of this material is required. The material is piled in rows approximately 20 feet high and left to dry for a minimum of six months. The smaller fraction wood decomposes into carbon rich organic soil and the larger wood pieces dry-out resulting in an inventory of material that is approximately 50% by weight carbon.

The Agricultural Production System and Method (Patent No. 11,511,325) involves dewatering an excavation area of inorganic soil and replacing the void space with the dried wood debris and organic soils that resulted from the dry decay method. The process is a *beneficial use that is not expected to pose a significant threat to public health or the environment*. The method sequesters carbon, which has been established, in academic papers as well as the Agricultural Improvement Act of 2018 (the Farm Bill), as a significant benefit to the environment. The wood and carbon rich soil to be interned below the water table will exhibit negligible degradation. It is historically recognized that wood below the water table is virtually inert as evidenced by untreated wood piles below the water table that have been used to support structures for hundreds of years. Some structures have been supported by untreated wood piles for more than 1000 years.

This method provides an environmental benefit that increases proportionally with the increase in material accepted. All materials interned below the water table have value sequestering carbon, creating carbon offsets and mitigating climate change.

2.1 CALCULATION PROCEDURE

This calculation is to estimate the mass of CO_{2e} that is sequestered from the wood processed by the Dry Decay Method and buried under the Agricultural Production System Method. Converting the volume of buried wood to the mass of sequestered CO_2 is as follows:

- One cubic yard of mixed dry wood, when compacted, has an average density of approximately 640 pounds per cubic yard.
- 640 pounds = 0.32 tons = 0.29 tonnes (metric tons).
- One tonne of dry wood is approximately 50% carbon.
- One tonne of carbon yields 3.67 tonnes of CO_2.
- Therefore, one cubic yard of mixed wood = 0.5 x .029 x 3.67 = 0.53 tonnes of CO_{2e}.

It should be noted that this process sequesters carbon in its solid state, not as a gas, and the calculation represents CO_2 equivalents. Because the carbon is not converted to a gas, there is negligible chance of leakage or escape of CO_2.

2.2 DATA SOURCES AND QUALITY ASSESSMENT

See Section 1.2.4 for Data Sources.

2.3 ALLOCATION PROCEDURES

This LCA is based on a linear material input and output and therefore allocation principals and procedures have not been addressed in the report.

3 LIFE CYCLE IMPACT ASSESSMENT

The impact category is climate change. The LCI result as it relates to this impact category is the amount of CO_{2e} sequestered (in tonnes). The characterization models and factors; category results and endpoints; and environmental relevance have been established in the creation of carbon credits by the U.S. government.

4 LIFE CYCLE INTERPRETATION

This LCA goal is to estimate the amount of wood waste, in cubic yards, that it takes to create one carbon credit, in tonnes, utilizing the described carbon sequestration system. Significant assumptions included:

- the density of dried compacted wood waste and carbon rich soil;
- the fraction of carbon present in the wood-soil mixture; and
- that wood buried beneath the water table is not converted to carbon dioxide.

The density assumption of 640 pounds/cubic yard for the compacted dried wood / soil mixture is conservative. The density of dried wood ranges from about 22 pounds per cubic foot (pcf) for the lightest pines, to approximately 56 pcf for dense oaks, for an average of 39 pcf. The carbon rich soil resultant from dry decay has a heaver bulk density since it has been size-reduced, so assuming 39 pcf for the carbon soil density is very conservative. When compacted, the carbon soil will occupy most of the void space around the wood. If the void space of the mixture is 30%, the overall compacted density of the matrix works out to be 27.3 pcf, or 737 pounds/cubic yard. Therefore, the assumed 640 pounds/cubic yard is conservative.

The 50% fraction of carbon in the buried material and stability of the wood under water assumptions are based on published data and significant variance from these assumptions are not expected.

5 CRITICAL REVIEW

DOE will serve as the critical review for this study.

6 REFERENCES

1. *Volume-to-Weight Conversion Factors*, U.S. Environmental Protection Agency, Office of Resource Conservation and Recovery, April 2016.

2. *Methods for estimating Carbon Within Forests*, Penn State Extension, January, 2023.

3. *Carbon Balance and Management, Carbon sequestration via wood burial*, Ning Zeng, January 2008.

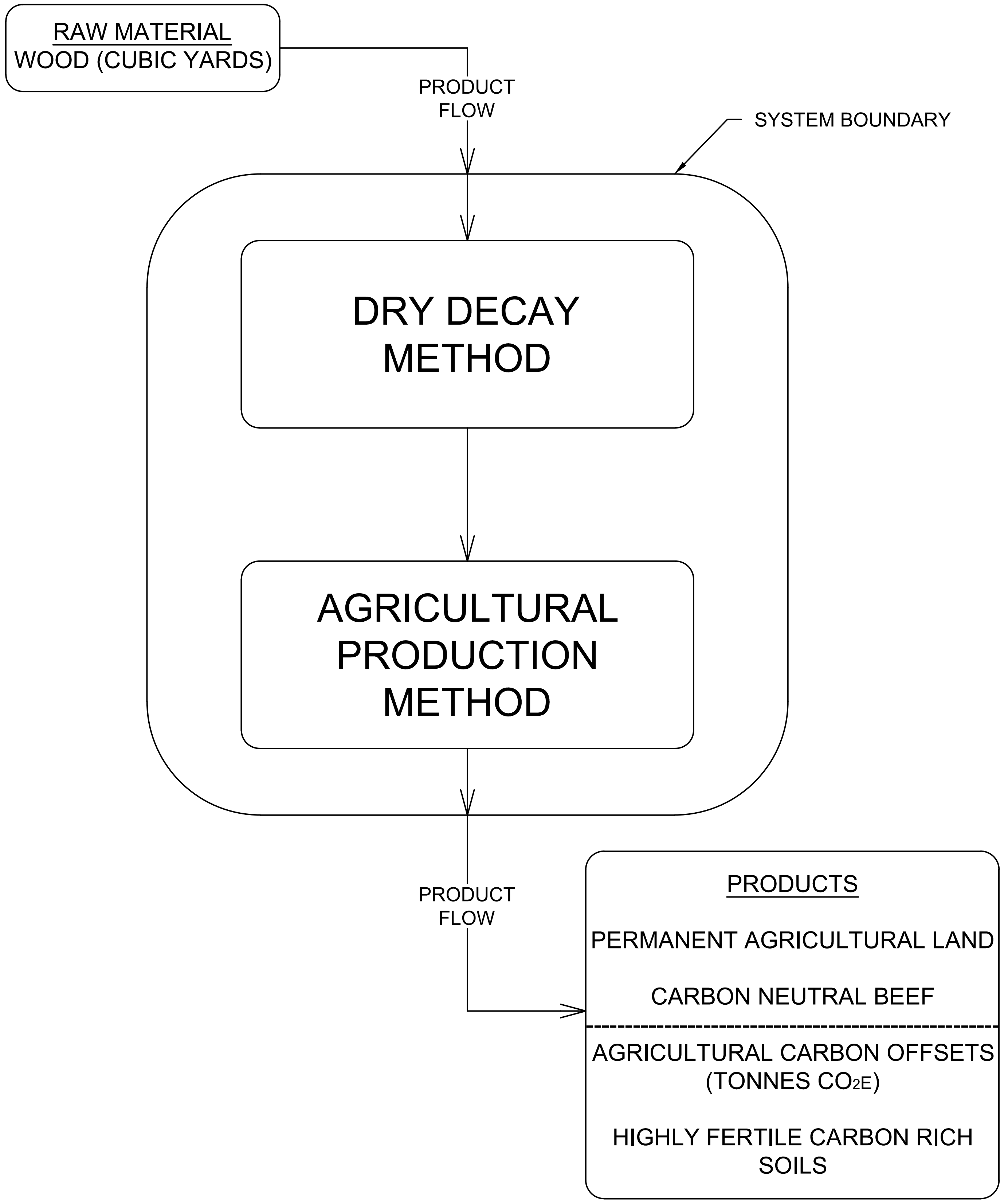
4. *Wood Vault: remove atmospheric CO_2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future,* Ning Zeng and Henry Hausmann, Carbon Balance and Management, 2022.

5. *Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States*, Hui Xu, Longwen Ou, Yuan Li, Troy R. Hawkins, and Michael Wang,, Environmental Science & Technology 56, 7512-7521, 2022.

6. *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels*, Argonne National Laboratory ANL/ESD/08-2, 2008.

FIGURES

01-FIG.dwg



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SYSTEM METHOD FLOW CHART
CARBON SEQUESTRATION SYSTEM
LIFE CYCLE ASSESSMENT

PROJECT #	17-905.007
FIGURE	1

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APPENDIX A: SUPPORTING INFORMATION

Contents

REFERENCE 1

Volume-to-Weight Conversion Factors
U.S. Environmental Protection Agency
Office of Resource Conservation and Recovery
April 2016

EPA's 1997 report, "Measuring Recycling: A Guide for State and Local Governments", was a guide to facilitate standardization of MSW data collection at the local level, which included volume-to-weight conversion factors for comparing recovery efforts between municipalities, regions and states. The factors are also valuable when planners work with the national recovery data presented in EPA's sustainable materials management report series.

This document provides updates to the volume-to-weight conversion factors found in the 1997 report Appendix B.

The goal of this update is to identify more current secondary data measurements of the various products. Of particular interest are products known to have been source reduced through light weighting since the early nineties such as plastic, glass and metal packaging. Some factors included on the original table are excluded from the revised table due to lack of updated data. Primary data collection was not performed.

The original Appendix B table included 12 materials categories; the updated table provides factors for 15 material categories, including the following.

- Appliances
- Automotive
- Carpeting
- Commingled Recyclables
- Electronics
- Food
- Glass
- Metals
- Municipal Solid Waste
- Paper
- Plastic
- Textiles
- Wood
- Yard Trimmings
- Construction & Demolition Debris (C&D)

All of the categories include multiple products and/or density measurements. Four product categories—carpeting, commingled recyclable material, electronics and construction and demolition debris—are new. Previously lead-acid batteries and scrap tires were separate categories but are combined into the single category "Automotive" in the updated table.

Other differences include the removal/addition of products within some of the categories to better reflect the current recycling industry. For example, eliminating "Tab Card" and adding "Mixed Paper" to the paper category reflects the move toward commingled recyclables collection. The addition of "Electronics" reflects the growth in these products since the original table was published.

The updated factors are shown in the table below.

Standard Volume-to-Weight Conversion Factors

Category	Recyclable Materials	Volume	Estimated Weight (lbs)	Source
Appliances	Major Appliances			
	Dishwasher	1 unit	125	1
	Clothes Dryer	1 unit	125	1
	Stove	1 unit	150	1
	Refrigerator	1 unit	250	1
	Clothes Washer	1 unit	150	1
Automotive	Lead-Acid Battery			
	Auto	one	36	3
	Truck	one	47	3
	Scrap Tire			
	Light Duty Tires (passenger, light truck)	one	22.5	5
	Commercial Tires	one	120	5
	Fluids			
	Used Motor Oil	gallon	7.4	2
	Antifreeze	gallon	8.42	2
	Other Automotive			
	Oil Filters not crushed	drum	175	1
	Oil Filters crushed	drum	700	1
	Oil Filters	gallon	5	1
Carpeting	Carpet			
	Carpet	cubic yard	147	6
	Carpet Padding	cubic yard	62	6
Commingled Recyclable Material	Containers (Plastic bottles, Aluminum cans, Steel cans, Glass bottles) and Paper			
	Commingled Recyclables	cubic yard	262	4
	Containers (Plastic bottles, Aluminum cans, Steel cans, Glass bottles), Corrugated Containers and Paper			
	Campus Recyclables	cubic yard	92	7
	Commingled Recyclables	cubic yard	111	4
	Containers (Plastic bottles, Aluminum cans, Steel cans, Glass bottles) – No paper			
	Campus Recyclables	cubic yard	70	7
	Commingled Recyclables	cubic yard	67	4
	Commercial Recyclables	cubic yard	113	8
	Containers (Cans, Plastic) - No glass			
	Campus Recyclables	cubic yard	32	7
	Containers (Cans, Plastic) and Paper - No glass			
	Residential Recyclables	cubic yard	260	2
	Containers (Food/beverage, Glass) Corrugated Containers and Paper			
	Commercial Recyclables	cubic yard	88	2
	Commercial Recyclables	cubic yard	58	21
	Multifamily Recyclables	cubic yard	96	2
	Multifamily Recyclables	cubic yard	51	21

Category	Recyclable Materials	Volume	Estimated Weight (lbs)	Source
Commingled Recyclable Material	*Single family Recyclables*	cubic yard	126	2
	Containers (Food/beverage, Glass) Corrugated Containers and Paper- No glass			
	Campus Recyclables	cubic yard	139	2
	Commercial Recyclables	cubic yard	155	2
Electronics	Computer Equipment			
	Desktop	one	27	24
	Laptop	one	9.8	24
	Monitor			
	CRT	one	40	1
	15"	one	30	2
	17"	one	45	2
	21"	one	60	2
	Flat Panel	one	24	1
	Mixed Monitors	one	29.4	24
	Televisions			
	CRT < 19 inch	one	41	1
	CRT ≥ 19 inch	one	73	1
	Flat Panel	one	29	1
	Mixed TVs	one	67.3	24
	Peripheral Devices			
	Printers	one	16.1	24
	Mice	one	0.2	9
	Keyboards	one	2.9	9
	Mobile Devices			
	Cellular Phone	one	0.22	9
	Mixed Electronics			
	Brown Goods	cubic yard	343	6
	Computer-related Electronics	cubic yard	354	6
	Other Small Consumer Electronics	cubic yard	438	6
Food				
	Fats, Oils, Grease	55-gallon	412	2
	Organics - commercial	cubic yard	135	21
	Source Separated Organics - commercial	cubic yard	1,000	15
	Food Waste - restaurants	cubic yard	396	21
	Food Waste	cubic yard	463	4
	Food Waste	cubic foot	22-45	4
	Food waste - university	gallon	3.8	22
	Food Waste	64 gallon toter	150	4
	Food waste	2 cubic yard full towable	2,736	4
Glass	Bottles			
	Loose	cubic yard	380	4

Category	Recyclable Materials	Volume	Estimated Weight (lbs)	Source
Metals	Aluminum Cans			
	Uncompacted	cubic yard	46	4
	Uncompacted	case = 24 cans	0.7	11
	Baled	cubic yard	250-500	10
	Steel Cans			
	Whole	cubic yard	50-175	10
	Baled	cubic yard	700-1,000	10
	Steel Cans - Institution			
	Whole	can	0.09	7
	Whole	cubic yard	136	7
Paper	Newsprint			
	Loose	cubic yard	360-800	1
	Baled	cubic yard	750-1,000	10
	Books - paperback, loose	cubic yard	428	23
	Old Corrugated Containers			
	Flattened	cubic yard	106	4
	Baled	cubic yard	700-1,100	10
	Old Corrugated Containers and Chip Board			
	Uncompacted	cubic yard	74.54	4
	Office Paper			
	Computer Paper			
	Loose	cubic yard	375-465	1
	Compacted/Baled	cubic yard	755-925	1
	Mixed			
	Loose	cubic yard	110-380	1
	Loose	cubic yard	323	4
	Compacted	cubic yard	610-755	1
	Shredded	cubic yard	128	4
	Mixed Baled	cubic yard	1,000-1,200	10
	Miscellaneous			
	Cartons (milk and juice) uncrushed	cubic yard	50	7
Plastic	PET			
	PET Bottles - baled	30"x42"x 48"	525-630	12
	PET Thermoform - baled	30"x42"x 48"	525-595	12
	HDPE			
	HDPE Dairy - baled	30"x42"x 48"	525-700	12
	HDPE Mixed - baled	30"x42"x 48"	525-700	12
	Mixed PET and HDPE			
	Loose	cubic yard	32	7
	Mixed Bottles/Containers #1 - #7			
	Loose	cubic yard	40.4	4
	Mixed Bottles/Containers #3 - #7			

Category	Recyclable Materials	Volume	Estimated Weight (lbs)	Source
Plastic	*Loose*	cubic yard	25.7	4
	Film			
	LDPE, loose	cubic yard	35	13
	LDPE, compacted	cubic yard	150	13
	LDPE, baled	30" x 42" x 48"	1,100	13
	Miscellaneous			
	Trash Bags	cubic yard	35	6
	Grocery/Merchandise Bags	cubic yard	35	6
	Expanded Polystyrene Packaging/Insulation	cubic yard	32	6
Textiles	Mixed Textiles			
	Loose	cubic yard	125-175	10
	Baled	cubic yard	600-750	10
Wood	Wood			
	Wood Chips, green	cubic yard	473	1
	Wood Chips, dry	cubic yard	243	1
	Saw Dust, wet	cubic yard	530	1
	Saw Dust, dry	cubic yard	275	1
	Pallets	one	25	1
	Pallets and Crates	cubic yard	169	18
	Christmas Trees, loose	cubic yard	30	1
Yard Trimmings	Yard Trimmings			
	Leaves	cubic yard	250-500	1
	Leaves (Minnesota)	cubic yard	300 - 383	15
	Mixed Yard Waste			
	Uncompacted	cubic yard	250	1
	Compacted	cubic yard	640	1
	Prunings & Trimmings	cubic yard	127	6
	Branches & Stumps	cubic yard	127	6
Municipal Solid Waste	MSW - Commercial			
	Commercial - dry waste	cubic yard	56-73	16, 8
	Commercial - all waste, uncompacted	cubic yard	138	21
	Mixed MSW - Residential, Institutional, Commercial			
	Uncompacted	cubic yard	250-300	14
	Compacted	cubic yard	400-700	14
	Mixed MSW - Multifamily uncompacted	cubic yard	95	21
	MSW - Landfill			
	Compacted - MSW Small Landfill with Best Management Practices	cubic yard	1,200-1,700	17
	Compacted - MSW Large Landfill with Best Management Practices	cubic yard	1,700-2,000	17

Category	Recyclable Materials	Volume	Estimated Weight (lbs)	Source
Municipal Solid Waste	*Compacted - MSW Very Large Landfill with Best Management and Cover Practices, Combined MMSW/Industrial/and other solid waste, or/and Leachate Recirculation*	cubic yard	>2,000	17
C &D	Concrete			
	Large Concrete with Re-bar	cubic yard	860	18
	Large Concrete without Re-bar	cubic yard	860	18
	Small Concrete with Re-bar	cubic yard	860	18
	Small Concrete without Re-bar	cubic yard	860	18
	Asphalt Paving			
	Large Asphalt Paving with Re-bar	cubic yard	773	19
	Large Asphalt Paving without Re-bar	cubic yard	773	19
	Small Asphalt Paving with Re-bar	cubic yard	773	19
	Small Asphalt Paving without Re-Bar	cubic yard	773	19
	Roofing			
	Composition Roofing	cubic yard	731	18
	Other Asphalt Roofing	cubic yard	731	18
	Other Aggregates	cubic yard	860	18
	Wood			
	Clean Dimensional Lumber	cubic yard	169	18
	Clean Engineered Wood	cubic yard	268	18
	Other Recyclable Wood	cubic yard	169	18
	Painted/Stained Wood	cubic yard	169	18
	Treated Wood	cubic yard	169	18
	Gypsum Board			
	Clean Gypsum Board	cubic yard	467	18
	Painted/Demolition Gypsum	cubic yard	467	18
	Aggregate			
	Large Rock	cubic yard	999	18
	Small Rock/Gravel	cubic yard	999	18
	Dirt and Sand	cubic yard	929	18
	Remainder/Composite Construction and Demolition	cubic yard	417	18
	Construction & Demolition Bulk	cubic yard	484	20
	Metal			
	Major Appliances	cubic yard	145	18
	Other Ferrous	cubic yard	225	18
	Other Non-Ferrous	cubic yard	225	18
	Remainder/Composite Metal (avg of metals, without used oil filters)	cubic yard	143	18
	HVAC Ducting	cubic yard	47	18

1 Oregon Department of Environmental Quality. 2007 Oregon Material Recovery and Waste Generation Rates Report September 2008 08-LQ-092. Attachment B: Measurement Standards and Reporting Guidelines 07-LQ-134. http://www.deq.state.or.us/lq/pubs/docs/sw/MRAttachmentB.pdf

2 Department of Ecology, State of Washington. Coordinated Prevention Grant Conversion Sheet. March, 2014. www.ecy.wa.gov/pubs/1107016.pdf

3 Factor developed using lead per battery data from Battery Council International. Recycling Rates 2009 to 2013. April 2014. http://c.ymcdn.com/sites/batterycouncil.org/resource/resmgr/BCI_Recycling_Rate_Study_200.pdf applied to battery composition data from Sulllivan, JL and Gaines, L. 2010. A Review of Battery Life Cycle Analysis: State of Knowledge and Critical Needs. October 2010. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory ANL/ESD/10-7.

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5 Rubber Manufacturers Association (RMA). 2013 U.S. Scrap Tire Management Summary. November 2014. http://www.rma.org/download/scrap-tires/market-reports/US_STMarket2013.pdf

6 California Integrated Waste Management Board. Targeted Statewide Waste Characterization Study: Detailed Characterization of Construction and Demolition Waste. June 2006. http://www.calrecycle.ca.gov/publications/Documents/Disposal%5C34106007.pdf

Brown Goods: larger, non-portable electronic goods that have some circuitry. Examples include microwaves, stereos, VCRs, DVD players, radios, audio/visual equipment, and non-CRT televisions (such as LCD televisions).

Computer-related Electronics: electronics with large circuitry that is computer-related. Examples include processors, mice, keyboards, laptops, disk drives, printers, modems, and fax machines.

Other Small Consumer Electronics: portable non-computer-related electronics with large circuitry. Examples include personal digital assistants (PDAs), cell phones, phone systems, phone answering machines, computer games and other electronic toys, portable CD players, camcorders, and digital cameras.

7 Keep America Beautiful, Recycle-Bowl Competition. Accessed February 2015. http://recycle-bowl.org/wp-content/uploads/Recycle-Bowl-Estimating-Data-Fact-Sheet.pdf

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16 Minnesota Department of Administration 2015 hauler records (excludes organics).

17 Minnesota Pollution Control Agency. 2013 MPCA MSW Landfill Annual Report Data.

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19 Tellus scaled down by factor from Florida C&D study -- Converting C&D Debris from Volume to Weight: A Fact Sheet for C&D Debris Facility Operators, University of Florida, 2000.

20 Florida Dept of Environmental Protection http://www.dep.state.fl.us/waste/categories/recycling/cd/canddmain.htm

21 CalRecycle. 2014 Generator-Based Characterization of Commercial Sector Disposal and Diversion in California. September 10, 2015. http://www.calrecycle.ca.gov/Publications/Documents/1543/20151543.pdf

Organics - putrescible material hauled by a contracted third party to a permitted facility mainly engaged in producing compost or mulch, or in anaerobic digestion of organics. Minor mechanical separation of contaminants or recyclable materials may occur at the facility prior to composting or digestion.

22 Goldstein, Nora. "Food Scraps Composting Laboratory". *BioCycle.* January 2013, Vol. 54, No. 1, p. 33. https: //www .biocycle.net/2013/01/22/food-scraps-composting-laboratory/

23 U.S. EPA. Standard Volume-to-Weight Conversion Factors. Last updated: February 28, 2006. https://www.epa.gov/smm/metrics-waste-reduction

24 National Center for Electronics Recycling (NCER). http://www.electronicsrecycling.org/

Mixed monitors and TVs: total pounds collected divided by total units collected.

REFERENCE 2

PennState Extension

Methods for Estimating Carbon Within Forests

A description of the kinds of computation methods used by forestry professionals to estimate amount of carbon in trees and groundcover. Content provided by the Forest Owner Carbon and Climate Education (FOCCE) program.

Updated: January 31, 2023

Forest with some trees marked by blue lines. Photo credit: Dave Jackson

Introduction

Trees contain up to half the carbon in a forest and can be more strategically managed compared to the carbon stored belowground. Estimating how much carbon is in a tree or stand is useful for informing decisions about forests and climate stewardship.

It is unlikely that a private forest owner will be responsible for measuring the carbon in their forest if they want to manage for it or sell the carbon to an offset project developer. However, the information provided here can help owners get a sense of what is typically involved and, if they have forest stand inventory data available, come up with some rough estimates of their own.

Estimating Carbon is a Prediction

Carbon in a forest is not an obvious feature, so it is difficult to measure carbon directly. Instead, carbon amounts are predicted for a tree or stand (a collection of trees managed together as a unit) using simplified mathematical relationships.

Allometric equations are a standard practice in forestry and can be used to estimate the amount of carbon in a tree or stand. It works by determining how the tree variables that are easy to measure (e.g., diameter of a tree) are proportionally related to another tree variable that may be more difficult to measure (e.g., metric tons of carbon).

Changes in the amount of carbon sequestered in a stand over time is done by doing repeated stand inventories. This procedure helps verify how much carbon was likely stored in the same stand between two time periods. "Additional" carbon is produced when there is a change in management activities that lead to more living biomass on the landscape than there would have been otherwise.

Estimating Carbon in a Tree

Estimating carbon in a tree involves two basic steps, (1) determine the dry weight of the wood, and (2) determine how much of that wood is carbon. The following is a simple allometric equation form for predicting the dry weight of a loblolly pine tree growing in the southeastern United States. More specifically, it estimates the dry weight of wood in the above ground part of the tree (i.e., stem) and only requires that you know the tree's diameter (in centimeters) at 4.5 feet above the ground (i.e., diameter at breast height or dbh). This equation is shown here:

$dbh^{2.77}$x 0.021=Stem biomass for loblolly pine (dry weight in kilograms) [1]

Example calculation for a loblolly pine tree:

Step 1: Let's say that you have a loblolly pine tree that is 12 centimeters in dbh. Using equation [1], the dry weight of the above ground wood would be,

$12^{2.77}$x 0.221 = 21.46 kilograms of dry wood

Step 2: Once you have estimated the dry weight of the wood it is typically assumed that the amount of carbon in a tree is approximately half the dry weight. In this example the amount of carbon would be,

21.46 kilograms of dry wood / 2 = 10.73 kilograms of carbon

Most allometric equations are developed for tree species that have a market value. Species-specific equations are generally preferred for their accuracy, but in many cases, a generalized composite equation may be used because it is assumed to be representative of many tree species.

Estimating Carbon in a Stand

In forestry, data describing many individual trees is collected to describe the whole stand. You can use allometric equations, such as the one above, along with other metrics (e.g., number of trees per unit area) to estimate the amount of carbon within a stand.

Initially, an inventory of the trees needs to be conducted of the trees that you want to manage. The inventory can include all the trees, or alternatively, only the trees within designated plots, which are then used to make predictions about the whole stand. Steps 1 and 2 described above in the "Estimating Carbon in a Tree" section can be used to predict the dry weights and amount of carbon in each of the measured trees. The amount of carbon in each of the trees would then be summed to estimate the total amount of carbon in a plot. The plot-level data is then "expanded" or "blown-up" to a per unit area basis, say an acre or hectare. At this point, you would have the information needed to estimate the total amount of carbon in a forest, of a known size, or the average amount of carbon per acre.

Estimating Carbon in a Forest

Within forests, carbon sequestration is not just limited to the merchantable living stems of trees. Carbon is also sequestered in the different parts of the tree (e.g., crown, branches, roots), dead trees and leaves lying on the forest floor, understory vegetation (i.e., groundcover), and forest soils. Managing for these parts of the forest can also provide climate regulation benefits, especially if you plan to harvest and remove some trees from time to time.

In 1987, Baldwin presented an allometric equation that has a slightly different form compared to equation [1]. This equation can be used to estimate the dry weight of the foliage in the crown of a loblolly tree as a function of dbh (inches) and total tree height (feet).

$16.38dbh^{2.91} \times \text{Height}^{-1.47}$ = Dry weight of crown foliage in pounds [2]

Sometimes managers need equations so they can better understand the biological trade-offs between understory and overstory vegetation and the impact to carbon pools. In this case, non-allometric equations may be used, in part because it needs to include non-tree related variables, such as rate of fertilization and precipitation. We can also see how forest management actions such as thinning, impacts the number of trees and site resources to the understory vegetation. The following example is more technical but is a good illustration of how well-designed equations can help make predictions about forest carbon in all types of contexts.

Equation to estimate total understory vegetation dry weight in loblolly pine plantations by VanderSchaaf et al. (2010):

$$\text{lnTotal} = -20.0312 + 0.000177\text{Fert} \times \text{Precip} + 6.656713\text{lnPrecip} - 0.02987\text{lnPrecip} \times \text{SDI}^{1/2}$$
$$-0.00015(\text{SDI}^{1/2} \times \text{Fert} \times \text{lnPrecip}) \quad [3]$$

Explanation of equation 3.
Natural logarithmic transformations, represented by the "ln" term in equation, are often required when estimating various carbon pools. Total refers to what vegetative forms or types are actually being estimated and here it refers to the dry weight biomass of grasses and grass-likes, forbs, woody vines, and shrubs in mid to late August, measured in kilograms on a per hectare basis. As you can see, it is assumed that understory biomass is a function of precipitation amounts and fertilization rates. The positive sign in front of the fertilization and precipitation term (Fert x Precip) represents the synergistic effect of fertilization with greater amounts of precipitation – thus nutrients and precipitation are more available to the understory. Additionally, understory vegetation production is greater as precipitation increases, as shown by the positive sign in front of the precipitation (lnPrecip) term. SDI refers to Reineke's stand density index, a metric that represents the amount of site resources being utilized by the overstory tree component. Generally, a larger SDI results from more trees. Site resources such as of light, moisture, and nutrients at some point become limited to the understory vegetation. The negative sign in front of the terms that contain SDI ($\text{SDI}^{1/2}$ x Fert x lnPrecip and lnPrecip x $\text{SDI}^{1/2}$) represents the negative relationship between overstory trees and understory vegetation, the competition for limited resources. Further, the negative sign in front of the SDI terms implies that fertilization and precipitation not only benefit the understory vegetation, but also the overstory vegetation. Fertilization along with greater precipitation actually deters understory vegetation production at an accelerated rate because of the greater amount of overstory tree production.

Closing Thoughts

- The forest carbon sold on an offset market is not the carbon already in the stand, but the promise that additional carbon will be stored in the future, due to changes in forest management. Learn more about how to manage for additional carbon in the links below.
- To measure the carbon potential in your stand it is best to work with a professional forester and identify which management practices can help enhance carbon storage based on the condition of your forest.

This article was produced by the Forest Owner Carbon and Climate Education Program(https://sites.psu.edu/focce/). What do you think? Please take this short survey.(https://pennstate.qualtrics.com/jfe/form/SV_cvHOeswRkOjkbIA)

Related Articles and Resources

- Carbon Accounting in Forest Management(https://extension.psu.edu/carbon-accounting-in-forest-management)
- Forest Carbon Pools(https://extension.psu.edu/forest-carbon-pools-where-are-they)
- How Much Should I be Paid to Manage Forest Carbon? (https://extension.psu.edu/how-much-should-i-be-paid-to-manage-forest-carbon)
- Long-Term Financial Planning for Timber and Carbon(https://extension.psu.edu/long-term-financial-planning-for-timber-and-carbon)

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REFERENCE 3

Carbon Balance and Management

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Carbon sequestration via wood burial

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Abstract

To mitigate global climate change, a portfolio of strategies will be needed to keep the atmospheric CO_2 concentration below a dangerous level. Here a carbon sequestration strategy is proposed in which certain dead or live trees are harvested via collection or selective cutting, then buried in trenches or stowed away in above-ground shelters. The largely anaerobic condition under a sufficiently thick layer of soil will prevent the decomposition of the buried wood. Because a large flux of CO_2 is constantly being assimilated into the world's forests via photosynthesis, cutting off its return pathway to the atmosphere forms an effective carbon sink.

It is estimated that a sustainable long-term carbon sequestration potential for wood burial is IO ± 5 GtC y^{-1}, and currently about 65 GtC is on the world's forest floors in the form of coarse woody debris suitable for burial. The potential is largest in tropical forests (4.2 GtC y^{-1}), followed by temperate (3.7 GtC y^{-1}) and boreal forests (2.1GtC y^{-1}). Burying wood has other benefits including minimizing CO_2 source from deforestation, extending the lifetime of reforestation carbon sink, and reducing fire danger. There are possible environmental impacts such as nutrient lock-up which nevertheless appears manageable, but other concerns and factors will likely set a limit so that only part of the full potential can be realized.

Based on data from North American logging industry, the cost for wood burial is estimated to be \$14/tCO_2(\$50/tC), lower than the typical cost for power plant CO_2 capture with geological storage. The cost for carbon sequestration with wood burial is low because CO_2 is removed from the atmosphere by the natural process of photosynthesis at little cost. The technique is low tech, distributed, easy to monitor, safe, and reversible, thus an attractive option for large-scale implementation in a world-wide carbon market.

Background

Atmospheric CO_2 concentration has increased from 280 to 380 ppmv (parts per million by volume; a 35% change) since pre-industrial time, largely due to carbon emissions from anthropogenic fossil fuel burning and deforestation 11]. The emission rate of carbon from fossil fuel (oil, coal and gas) consumption is currently about 8 GtC y^{-1} (10^{15} g of carbon per year) 12] while the deforestation rate for the 1990s is estimated to be 1.6 (0.5-2.7) GtC y^{-1}. The cumulative fossil fuel emission since 1800 is 330 GtC, but only about half of that remains in the atmosphere; the remainder absorbed by carbon sinks in the ocean and on land [1].

Fossil fuel emissions are projected to reach 9-20 GtC y^{-1} by 2050 in the absence of climate change policies, according to a range of emissions scenarios (3]. Depending on how the current carbon sinks change in the future, the atmospheric CO_2 concentration for the Special Report on Emissions Scenarios (SRES) A2 emissions scenario is between 450-600 ppmv by 2050, and 700-1000 ppmv by 2100, and global mean surface temperature may increase between l.5-5.5°C [41, with related changes in sea-level, extreme events, and ecosystem shifts. Scientists have argued that severe consequences will occur once atmospheric CO_2 concentrations reach between 450 and 600 ppmv [5-7]. Beyond this point, global climate change would be very difficult and costly to deal with [8].

Keeping the atmospheric CO_2 concentration below 450-600 ppmv poses an unprecedented challenge to humanity. There are two main approaches: (1) to reduce emissions; (2) to capture CO_2 and store it, i.e., sequestration. Since our economy depends heavily on fossil fuel, which comprises more than 80% of primary energy use, to reduce carbon emissions requires drastic changes in energy use efficiency and the use of alternative energy sources that are generally not economically competitive at present [9,10]. Even if advanced technologies such as hydrogen power and nuclear fusion become economical, the infrastructure switch will take many decades. It is thus very likely that at least some carbon sequestration will be needed in the near future to keep CO_2 below a dangerous level.

Carbon sequestration involves two steps: (1) CO_2 capture, either from the atmosphere or at industrial sources; {2) storage. Capture out of the atmosphere is assumed to be much more expensive because of the low CO_2 concentration in the atmosphere relative to N_2 and O_2. For this reason, most current proposals seek to combine capturing CO_2 with power generation, with several pilot power plants planned or underway [11J.The proposals for storing captured CO_2 include pumping it into deep ocean where CO_2 may react with water under the high pressure to form methane hydrates [12) or stays in CO_2 lakes, burying carbon inside deep ocean sediments where conditions are even more stable than ocean bottom [13]. The technique that has been most seriously considered, is to store captured CO_2 in geological formations such as old mines and deep saline aquifers (14]. There is also a spectrum of biospheric carbon sequestration methods, such as enhancing oceanic plankton productivity by iron fertilization, reforestation or altering forestry and agricultural management practices to maximize carbon stored in soil and vegetation, but the potential and permanence of these biospheric techniques have been unclear.

Here I suggest a biospheric carbon sequestration approach in which wood from old or dead trees in the world's forests is harvested and buried in trenches under a layer of soil, where the anaerobic condition slows the decomposition of the buried wood. This can be supplemented by selective cutting of other suitable trees. On the storage side, high-quality wood can also be stored in shelters for future use. In this technique, CO_2 capture is done by the natural process of photosynthesis, and storage is low tech and distributed, thus attractive in two important aspects: cost and safety.

Results

Carbon *sequestration via wood burial: a basic assessment*

The possibility of carbon sequestration via wood burial stems from the observation that natural forest is typically littered with dead trees (Fig. 1). It is hypothesized that large quantities of organic carbon were buried and preserved for over one hundred thousand years under the great Northern Hemisphere icesheets during the Pleistocene glacial-interglacial cycles [15,16]. Other studies have shown that organic matter, especially wood, in municipal landfills decomposes extremely slowly [17). With these, it became clear that wood harvesting and burial could be a viable method for carbon sequestration.

Globally, approximately 60 GtC y^{-1} are temporarily sequestered by land vegetation (Net Primary Productivity or NPP; Fig. 2). This carbon is continuously returned to the atmosphere when vegetation dies and decomposes (heterotrophic respiration, Rh). In a steady state, the death rates of these carbon components equal to their respective decomposition rates and add up to NPP such that the net land-atmosphere carbon flux is near zero (NPP = Rh)- If we can stop or slow down a part of the decomposition

Figure I
Dead trees on forest floor in a natural North American deciduous forest, Belwood, Maryland.

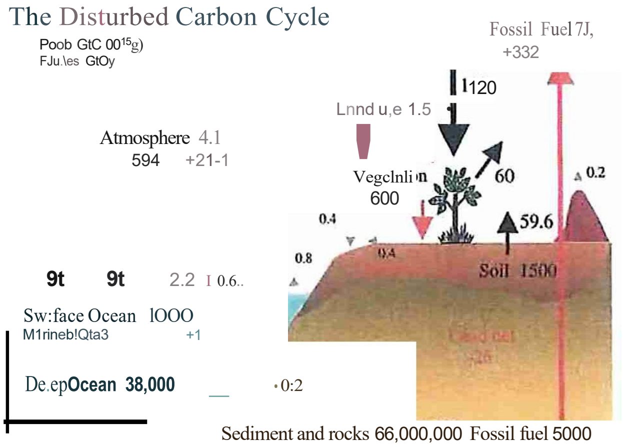

Figure 2

Major pools and fluxes of the global carbon cycle, with red color indicating anthropogenic fluxes for 2000-2006 and cumulative pools for 1800-2006 based on [40,41], with updates from [2]. About 1/3 (20 GtC y^{-1}) of the net terrestrial productivity is wood production, a substantial fraction of which is the target of a sustainable carbon sink via wood burial.

pathway, we have the hope to sequester CO_2 at a rate that may rival the current fossil CO_2 emission of 8 GtC y^{-1}. Since woody material is most resistant to decomposition due to its lignin-cellulose fiber structure which also minimizes nutrient lock-up (below), I will focus on this carbon pool.

Two major questions need to be first answered concerning the potential of this method: what is the production rate of dead wood, and how much is there in the world's forests? Unfortunately, there is a general lack of knowledge of dead wood on the forest floor, and this carbon pool is often neglected in carbon budget accounting. Since death rate is fundamentally limited by growth rate, the dead wood production rate can not exceed the world total NPP of 60 GtC y^{-1}. Then the key question is how NPP is partitioned into the three main carbon pools: leaf, wood, and root. Leaves grow and fall in a deciduous forest each year, but may last a few years in an evergreen forest. Fine woody material such as twigs and small branches may break and fall often, but tree trunks and major branches have a lifespan of decades to centuries and longer. Thus, even though wood biomass is much larger than leaf biomass, its long lifetime suggests a production rate that is much smaller than otherwise. Root biomass can be large and the death rate is also substantial as roots constantly grow to search for nutrient and water. A 'nai've' first guess could be that NPP is partitioned equally into these three pools, leading to a 20 GtC y^{-1} wood growth rate, thus 20 GtC y^{-1} wood death rate at steady state. Since fine woody debris decompose more quickly and more difficult to handle, coarser material such as trunks and major branches are more suitable for burial. Assuming half of the woody material is coarse, then about 10 GtC y^{-1} dead wood may be available for burial, thus leading to a 10 GtC y^{-1} carbon sink. Assuming an average residence time of 10 years for dead trees on the forest floor, about 100 GtC (10 GtC y^{-1} times 10 years) in the form of coarse woody debris would be already on the forest floor. These dead wood materials are under various stages of decay, but even if half of that can be collected and buried, it provides a substantial readily available carbon sink.

The proposal is to (1) collect dead trees on the forest floor and (2) selectively log live trees. Then the tree trunks are either buried in the trenches dug on the forest floor (burial) or suitable landfills, or logs piled up above ground sheltered away from rain (Fig. 3).The buried woody material will have significantly longer residence time, and it effectively transfers carbon from a relatively fast decomposing pool (about 10 years) to a much slower carbon pool (100-1000 years or longer). In the case of (1), it reduces part of the heterotrophic respiration, and is thus an immediate effective carbon sink. In the case of (2), the subsequent regrowth in the 'gaps' left by tree cut is a carbon sink, which would depend on the rate of regrowth. In practice, (1) and (2) probably do not differ a lot, as fallen trees leave gaps for smaller trees to grow in a way very similar to case (2).

Quantifying the carbon sequestration potential

I Sustainable sink of tree removal (limited by growth rate)

To quantify the size of this potential carbon sink, the global dynamic vegetation and terrestrial carbon model VEGAS [15,18,19) was used. While the model simulates the full terrestrial carbon cycle, only the carbon pools and fluxes relevant to the purpose here are discussed. The simulation did not include agricultural land, thus the estimates will be potential rates. The model was driven by modern observed climatology with seasonal cycles of precipitation, temperature, sunshine, wind speed, and vapor pressure. The simulation was run until convergence at a steady state where tree growth is balanced by mortality.

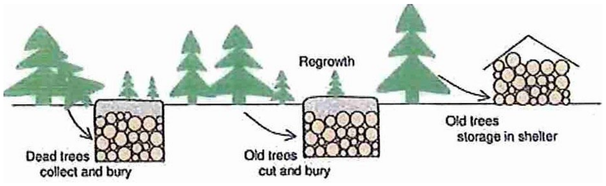

Figure 3

Schematic diagram of forest wood burial and storage.

The modeled global NPP is 57 GtC y-^{1}, of which 19 GtC y-^{1} goes into dead leaf, 17 GtC y-^{1} into dead wood, and 21 GtCy-^{1} to dead root structures. Since fine wood (twigs and small branches) decomposes quickly, is more difficult to handle (more costly to clean up the leaves, etc.), and may occupy more burial space, only coarse wood will be considered as suitable for burial. Forestry literature generally makes a distinction between fine and coarse woody debris, typically using 10 cm stem diameter to separate the two classes. Unfortunately, the relative contribution to the total wood death from fine and coarse wood is difficult to quantify, in part due to the different lifetime (smaller stems generally have shorter life than the whole tree). It is sometimes unclear how these pools and fluxes are defined and what the reported numbers represent in forestry literature. I thus somewhat arbitrarily designate the fine:coarse ratio of death rate to be 7:10 so that the coarse wood death rate is 10 GtC y-^{1}.

The spatial distribution of coarse wood death rate is shown in Fig. 4. The highest rate is found in the tropical rainforest such as the Amazon and the Congo basins, followed by temperate and boreal forests. The fact that the spatial distribution of wood death rate is similar to that of production (NPP) is not surprising because the death rate largely follows growth rate. Any regional deviation from the global mean partitioning ratio among the three pools (leaf:wood:root = 19:17:21) is the result of plant functional type (PIT) and climate dependent carbon allocation strategy. Such deviations are no more than 10-20% in this model.

The carbon sequestration potential of coarse wood for various geographical regions is given in Table 1. The tropical forest has a 4.2 GtC y-^{1} carbon sequestration potential, temperate forest has 3.7 GtC y-^{1}, while the boreal region has 2.1 GtC y-^{1}. Since the model considers only potential vegetation (no agriculture) the temperate regions may have substantially smaller potential.

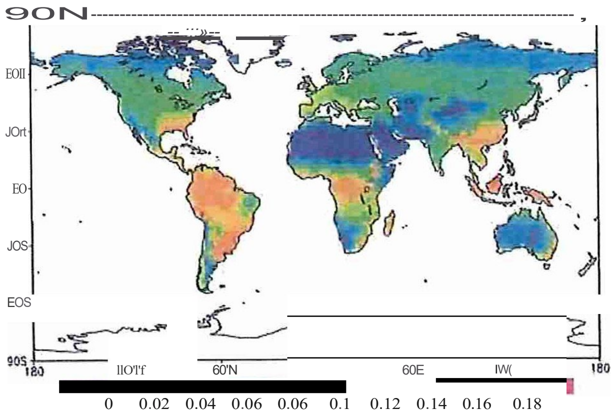

Figure 4
World coarse wood production rate estimated by the model VEGAS in kgC m·2y-l.

Table I: Carbon sequestration potential based on coarse wood production rate (GtC y-^{1}) estimated by **VEGAS** assuming **potential vegetation for the main regions of the world.**

Global	Tropics	Temperate	Boreal
10	**4.2**	3.7	2.1

At a regional scale (Table 2), South America has a carbon sequestration potential of 2.3 GtC y-1, with major contribution from the Amazon rainforest. Africa follows with 1.9 GtC y-^{1}. Russia has a potential of 1.2 GtC y-^{1} due to its vast expanse of boreal forest. The conterminous US has a potential of 0.8 GtC y·^{1} with its extensive broadleaf and mixed forests along the East Coast and the South, and the mountainous West. Canada has a 0.7 GtC y-^{1} potential from its mixed and boreal forests. Of the 0.9 GtC y-^{1} potential for China, probably only a fraction can be realized because much of the country's forests has long been converted into cropland. However, a successful reforestation program could boost the size of this fraction.

The coarse wood death rate estimated by the model is the result of plant functional type and climate dependent carbon allocation strategy that is not well constrained in current generation of global vegetation models [20]. Observations on this carbon pool and its turnover rate have been generally lacking. Nonetheless, some research has emphasized the importance of this carbon pool. Using observed and estimated average tree mortality rates and extrapolating point data using global biomass distribution, Harmon et al. [21] estimated the production rate of coarse woody debris to be 2-11 GtCy·^{1}, with the uncertainty range coming from the tree lifespan estimates. Based on [21], Matthews (22] estimated 6 GtC y-^{1} as the coarse woody debris production rate. A comparison is listed in Table 3. Thus VEGAS model result is within the range of [21 j but on the high side. One of the reasons may be that the equilibrium simulation ofVEGAS implies that the modeled fore ts have reached a steady state, i.e., they are mature forests, while the data used include forests of different ages. Since younger forests tend to have lower mortality than old-growth ones, these young forests will have higher potential in the future as mortality rate increases towards maturity. Given the many unknowns in both methods, I will assign a factor of 2 uncertainty to the 10 GtC y·^{1} model estimate, i.e., a range of 5-15 GtC y-^{1}.

In estimating the 10 GtC y-^{1} potential, l assumed natural vegetation, which by itself would be an overestimate

Table 2: As in Table I, but for some sub-regions (may overlap).

NAm	US	Canada	SAm	Africa	Europe	Russia	Asia	China	SEAsia	AusNZ
1.5	0.8	0.7	2.3	1.9	0.7	1.2	1.8	0.9	0.6	0.4

because some of the potential forest area has been converted to cropland. Since current world forest area is 3 times that of cropland, and a significant part of cropland corresponds to potential grassland and even desert rather than potential forest, the degree of overestimation is modest. On the other hand, the actual potential could be higher due to other factors such as selective cutting (below), planting fast growing tree species, and burying smaller-sized wood. In addition, reforestation, deforestation and climate change in the future will complicate any attempt at a precise estimate including land use. Thus, the choice in using potential vegetation was made here.

2 One time potential from existing coarse woody debris

As a legacy of past tree death, a significant amount of dead wood has accumulated in the world's forests in various stages of decay (Fig. 5). I used the model VEGAS to simulate this dead wood pool and estimated global coarse woody debris to be 130 GtC, somewhat larger than the estimates of 75 GtC of (22], but within the range of 60-232 GtC estimated by (21). These numbers may seem large as relatively little attention has been paid to this carbon pool, but they are not surprisingly large in light of the 390 GtC stored in world's forest vegetation biomass (mostly wood; (23]). Since wood at later stages of decay is not suitable for burial (also less likely to be included in forest inventory studies), even if half of this pool is suitable for burial, that is still 65 GtC available for sequestration. The spatial pattern (Fig. 5) shows a somewhat different distribution from the production rate with higher values in temperate and boreal region mostly due to the slower decomposition rate at lower temperature.

The implication of this large existing carbon pool is that in the initial stage of wood burial, more than the sustainable rate of 10 GtC y^{-1} estimated above will be available.

3 Enhancing the sustainable rate via selective cutting of Jive trees

The 10 GtC y^{-1} dead wood production rate could also be enhanced by active forest management. Instead of waiting for the trees to die, one can also harvest relatively mature trees via techniques such as selective cutting. At first sight, **this** seems to be a carbon source as live trees take up CO_2. However, if trees are selected properly, it may lead to an overall sink because younger forest tends to be more productive, and somewhere in the development stage, productivity significantly exceeds respiration and decomposition loss [24]. Since the less productive trees that do not do well compete for light and other resources, their removal will leave younger trees to grow more vigorously in the gaps, forming a net carbon sink. In an even-aged forest, self-thinning is a major step of the secondary succession in which a major fraction of young trees die to give way to other trees. In this case much younger trees can be selectively cut or collected after death.

Implementation strategy

The implementation of a wood burial scheme will involve three major steps:

(1) Enabling access to the forest if not already in place;

(2) Site selection, trench digging for burial or building a shelter for above ground storage;

(3) Selective tree cutting or the collection of dead wood followed by trimming, shortening and burial or storage, repeated at an appropriate return interval.

I envision a network of roads and paths that will allow machine access, and trenches that are distributed at a more a less uniform spacing. For example, a 1 km x 1 km area (100 hectares) would accumulate about 100 tonne of carbon per year for a typical coarse wood production rate of 0.1 kgC m^{-2} y^{-1} (Fig. 4). At a return interval of 5 years, each trench would bury 500 tonnes of carbon (about 1000 tonne dry wood mass). Assuming a 0.5 tonne dry matter per cubic meter and neglecting some space in between the logs, the volume required would be 2000 m^3. If the pile is buried under 5 meters of soil, the trench can have the dimensions of 10 m x 10 m x 25 m (Fig. 6). The surface area would be 100 m^2, only 0.01% of the wood

Table 3: A comparison of estimates of world total coarse wood production rate (GtC y-1) and coarse woody debris (GtC).

	Harmon et al., 1993	Matthews 1997	VEGAS(this study)
Coarse wood production rate	5 (2-11)	6	10 (5-15)
Coarse woody debris	60-232	75	130

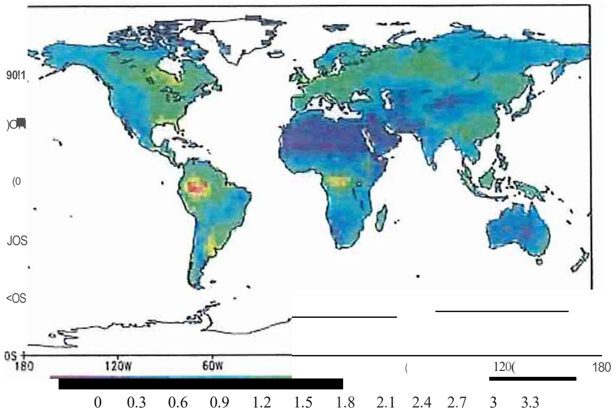

Figure S
World distribution of coarse woody debris, in kgC m·2.

collection area, thus the disturbance would be small. Soil will fill the space in between logs and above and be allowed to settle. Vegetation can be allowed to grow back naturally on the burial sites. Selective sites can be monitored for the decay of the buried wood. Figures 3 and 6 illustrate these procedures.

The actual trench size and distribution need to balance several factors such as cost of digging trench, transporting deadwood, minimizing disturbance to the forest, and selecting the location that most effectively prevents decomposition. Onsite burial is preferred wherever possible to minimize transportation cost. Transportation may be needed where soil is too shallow to dig trenches of sufficient depth. Since soil condition can vary greatly even within a small area such as soil moisture content variation associated with topography, care needs to be taken in site selection.

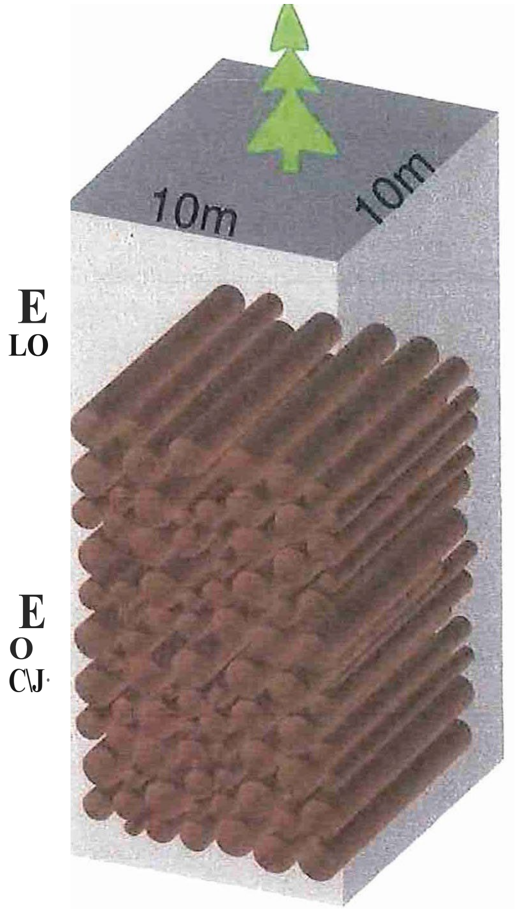

Figure 6
An example trench that could bury 500 tC, the amount of coarse wood carbon from a typical midlatitude forest area of 1 km x 1 km in 5 years.

Depending on the dead wood accumulation and decay rates, this process can be repeated every few (1-10) years, but the burial sites will be different each time. The main criterion for choosing return interval will be a balance between the cost of each operation and the need not to let the dead trees rot away. If selective cutting is the main operation mode so that there is little natural tree death (trees are cut before they die), the dominant factor will be the density of suitable trees to remove. In the case of plantation, it may be a good strategy to clear cut small sections (group cutting) for its low cost, allowing trees to grow back as secondary succession.

Compared to above-ground shelter storage, trench burial is a better choice for fallen trees as they are typically already in the process of decomposition, so they are less useful as lumber wood. On the other hand, shelter storage preserves lumber wood for easy use should future demand increases.

The technology required for collecting or selectively cutting trees is low tech and has been around for thousands of years. Most modern large-scale logging is done by machines in many places such as Europe and North America. The road system for access is already in place in many of these regions such as the US 'Forest Highway' system. Half of the world's forests are already within 10 km, and three quarters are within 40 km of major transportation infrastructure (25]. Since there is no major technological hurdle, such a scheme can be implemented almost immediately in a substantial fraction of these regions. For instance, a common practice in North American forestry is to hire private logging companies with a variety of opera-

Table 4: Comparison of wood burial and power plant CCS. The markets use tCO_2 as carbon unit which can be converted into tC with the conversion factor the molecular weight ratio CO_2:C = 44:12; both units are shown.

Wood Burial	Power plant CO_2 capture with geological storage	Price on Chicago Climate Exchange (CCX) 2006	European carbon trading market price during 2005-2007
\$14/tCO_2 (\$7-27) \$50/tC (\$25-100)	\$20-270/tCO_2 [14] \$73-990/tC	\$3--4/tCO2 \$12-16/tC	Cl-33/tCO_2 C4-120/tC
Storage safe; semi-permanent, reversible; some environmental concern	Possibility of leakage; lower cost storage capacity small		
Potential: 10 ± 5 GtC y•I long-term: thousands of GtC or no practical limit	Potential rate is limited by scale of operation Longterm: > 500 GtC		

tion scales to cut trees on private or public land, allowing the flexibility of handling forests of different sizes and conditions. Although currently intensely managed forests have little dead wood immediately available for burial, their long-term potential still holds.

Such a distributed system can be run with little government intervention except for monitoring, as long as economic incentive is provided through schemes such as carbon trading. In North America, much of the forested land is privately owned. The potential for carbon sequestration will have a positive impact on the logging industry and many land owners and the economy in many regions. The accounting and monitoring of the carbon sinks can be done by certified engineers when logging companies return for each round of harvest. This can be supplemented by larger-scale monitoring systems such as eddy correlation flux measurement (26J, source/sink inversion using atmospheric CO_2 measurements 127] assisted by future satellite CO_2 observations 128]. The vast expanse of boreal forests in Canada and Eurasia are only partly accessible and largely unmanaged at present, but infrastructure such as roads can be built relatively quickly in the relevant countries.

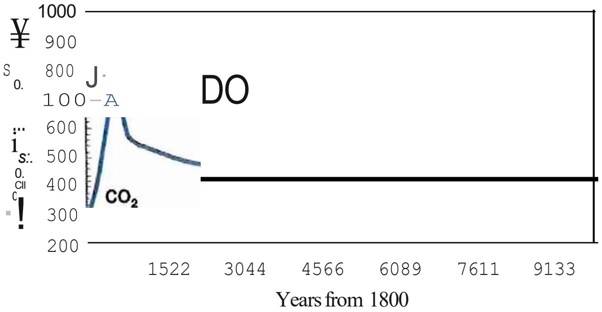

Figure 7
Lifetime of buried wood can be substantially longer than fossil fuel CO_2 residence time in the atmosphere. CO_2 concentration is based on a scenario in which 1000 GtC fossil fuel is burned in the next few hundred years.

If a major portion of the estimated 10 GtC y^{-1} carbon sequestration potential is to be utilized, nearly all the world's forests will need to be managed. Then a main question would be the accessibility to the remote forest regions. Firstly, extremely steep mountainous regions or boggy wetland will be difficult to access. Secondly, there are practically no roads to the deep tropical forests. Moreover, a proposal of building a network of roads in the heart of a rainforest will raise major environmental concerns such as loss of biodiversity. On the other hand, economic incentives will continue to stimulate such road expansion. Even in this case, the issue oflaw enforcement for illegal deforestation, and more broad governance issues need to be first ensured before countries in these regions reach a point-of-no-return. In the near future, a beneficial practice is to bury rather than to burn the trees in the regions with ongoing deforestation.

If the cores of the tropical rainforests are to be left intact which accounts for about 20% of the total carbon sequestration potential (half of the tropical rainforest; Table 1), sequestration in the remaining tropical, temperate and boreal regions still provide a sink of 8 GtC y^{-1}. Difficulty in accessing steep terrains where forests are typically better preserved will further reduce this number. In fact, giving the cost of road construction and environmental concerns, it is desirable to manage more efficiently a smaller fraction of the available forests through methods such as selective cutting or burying part of the finer woody debris, than disturbing a larger fraction at lower per unit area carbon sequestration rate.

Cost

The scale of the climate change problem dictates that any mitigation strategy, whether being alternative energy source, carbon sequestration technique, or geo-engineering approach, has to be cost effective when operated on a large scale. Data from the US logging industry indicate that a typical cost for harvesting 1 tonne of lumber wood is about $20 (29]. Since lumber wood is only part of the coarse woody material that can be buried, which I assume is about 50% more than lumber wood alone (there are substantial amount of smaller branches compared to the trunk). In the other direction, given that lumber wood contains some water and that plant dry mass is approximately 50% carbon, the cost could be $40 per tonne of sequestered carbon. This would be higher if the cost of trench digging, road construction and maintenance is included. I will thus put the cost at $50 for 1 tC (tonne or 10^6 gram of carbon) sequestered, with an uncertainty range of $25-$100/tC.

It is illuminating to compare this with power plant CO_2 capture and geological storage (CCS; Table 4), a strategy that has been under intense study [14}. The $50/tC ($14/tCO_2) cost for wood burial is lower than the $20-270/$tCO_2$ for power plant CCS. The large range in power plant CCS is due to the increasing cost as cheaply available old mines run out. In the case of wood burial, there is no practical storage capacity limitation. A major cost of industrial CCS is the capturing of CO_2 from flu gas, while wood burial is free air capture with near-zero cost because it is done by the natural process of photosynthesis.

It is also interesting to compare this cost with the pioneering European Union Emission Trading System (EUETS) carbon cap-and-trade market price. The EUETS price has fluctuated between Cl-33/tCO_2 during 2005-2007. In comparison, the voluntary Chicago Climate Exchange (CCX) price has been around $3-4/$tCO_2$. Although the wood burial cost is somewhat higher than the current market price, it is expected that future climate mitigation policy will result in higher prices for carbon. When implemented at global scale, many factors will vary from location to location such as technology and labor costs. The cheapest will be the forests that are already under intense management where roads and machinery are in place. The price may increase as the total area of forests utilized this way increases. The operation of machinery will consume some fossil fuel and emit CO_2. These factors need to be evaluated.

Scale of operation

Even if only half of the estimated potential (5 GtC y^{-1}) is carried out in the next few decades, say, by 2050, the scale of such a world-wide operation would be enormous, as illustrated in the scenario below.

If each trench has a 500 tC capacity (example in Fig. 6), then the number of trenches needed for a 5 GtC y^{-1} sequestration rate would be 10 million per year, i.e., one trench every 3 seconds. Assuming it takes a crew of 10 people (with machinery) one week to dig a trench, collect/cut and bury wood over a 100 hectare area, 200,000 crews (2 million workers) and sets of machinery would be needed. This estimate is admittedly simplistic and the task could be quite labor-intensive if it is to be carried out in dense or steep-sloped natural forests.

The scale of such an operation may be difficult to imagine at first sight, but the enormous scale of the CO_2 problem means that any effective mitigation strategy also has to be at a comparable scale. The current rate of 8 GtC y^{-1} fossil fuel carbon emission rate corresponds to 250 tC per second. Since carbon content of wood is roughly the same as in fossil fuel, if wood burial is to counteract the fossil fuel emission (as it could potentially do), the rate (in terms of either mass or volume) at which we bury wood needs to be comparable to the rate we bum fossil fuel. If wood burial is used as part of a portfolio, the operation could be scaled down accordingly.

The plausibility of this operation may be more easily comprehended from an economical point of view. A $50/tC cost for wood burial corresponds to $250 billion per year at a 5 GtC y^{-1}sequestration rate. This is only 0.5% of world total Gross Domestic Product (GDP) of $48 trillion in 2006, compared to the projected 5-20% GDP potential economic damage from climate change [8]. The $250 billion per year cost for 2 million workers means $62,500 per worker, assuming half is for machinery and other costs. Obviously, labor and machine costs can be very different in different countries. The job opportunities provided by the operation and other positive impact on the economy will be attractive in many regions especially the developing countries.

Discussion

Potential issues

I Decomposition of buried wood

Because of the low oxygen condition below soil surface, the decomposition of buried wood is expected to be slow. This is supported by the observation of extremely slow decomposition of woody material such as furniture in landfills where wood products are found to be well preserved after many years of burial by Micales and Skog [17}. Indeed, these authors found that only 0-3% of the carbon from wood are ever emitted as landfill gas after several decades, and considered the remaining fraction locked away 'indefinitely'. Ancient wood can be preserved for thousands of years in undisturbed archeological sites. Indeed, the current proposal can be viewed as creating 'graveyards' for dead trees worldwide. In the boreal forests where the temperature is low, decomposition can be very slow as evidenced by tree trunks hundreds of years old on the boreal forest floor. Since decomposition rate is also function of moisture, the burial sites need to be chosen properly in consideration of local topography and hydrology. If needed, the decomposition could be further slowed by sealing the outer layer with resistant material such as wax. It is also possible to bury dead wood in wetlands or under water, but there will be major transportation cost, availability of suitable sites, and permanence issue in face of human activities and climate change.

The 0-3% range of decomposition rate [17] translates into an e-folding timescale of 1000 years to infinity, assuming a 30 year average age for landfills in their survey. If these burial sites are better protected through, e.g., thicker soil cover, the preservation would last even longer. Thus, we can slow down the decomposition rate of collected wood at least to the timescale of 1000 years (most likely longer) so that the release of this buried carbon pool is negligible compared to forest regrowth uptake in response to collection/cutting that occur on the timescales of decades. If the buried carbon comes out slowly over the timescale of thousands of years, it should have already passed the major peak of atmospheric CO_2 as the anthropogenic CO_2 'pulse' is absorbed into the deep ocean and the carbonate sediments (Fig. *7;* [30]).

Depending on the burial depth, the deep roots of trees regrowing on some burial sites may eventually invade into the trench and facilitate the decomposition of buried wood so that the nutrient and carbon will slowly return to the surface and the atmosphere. Although the vegetation could be made not to re-grow above the trench, or the buried wood could be insulated from the top soil by a layer of resistant material, re-growth might be more desirable than 'permanent' burial (tens of thousands of years or longer). Thus the way wood is buried will determine the decomposition rate, and can be managed to desired effect. Long term monitoring and research of representative sites will be useful for finding optimal burying methods.

2 Nutrient lockup

One potential drawback of wood burial is that nutrient in wood will be locked away. The same drawback also applies to other methods of large-scale vegetation use such as biofuels. This is a serious concern because nutrients may already be a limitation for plant growth in some forest ecosystems. Plants recycle a major part of the nutrient in dead material. This is especially so in the tropical rainforests where the recycling is so efficient that most of the nutrient is locked in live and dead trees rather than in the soil. If a major fraction of the nutrient becomes locked up by buried wood, the forest growth could be severely limited after some decades so that the strategy becomes unsustainable. Here I use nitrogen as an indicator of nutrient for analysis.

Fortunately for our purpose, the nutrient content in wood is much smaller than in leaves and fine roots. For instance, typical carbon to nitrogen ratio (C:N) is 20:1 for leaves, but 200:1 for wood [31,32]. This is fundamentally because the structural components of plants consist mostly of lignin-cellulose complexes which are carbohydrates, i.e., C, O and H, while nutrients are concentrated in the photosynthetic and metabolic components such as chlorophyll and protein.

The magnitude of this potential problem can be viewed in two ways. First, because leaf turnover rate is comparable to wood turnover (above), but the C:N ratio is 10 times larger, so that the nitrogen recycling rate in leaves and fine wood is more than 90% faster than that in the coarse wood, even though the total amount of nitrogen in wood may not be too different from that in leaves. The fact that tropical rainforest is extremely quick at 'grabbing' whatever nutrient is on the forest floor suggests the great ability of forest at utilizing what is on the ground.

The ultimate question is whether internal fixation and external input are fast enough to compensate for the loss rate due to burial lockup. If 10 GtC y^{-1} of carbon is to be buried, a C:N ratio of 200 implies that about 50 MtN y^{-1} (Mega tonnne or 10^{12} gram of nitrogen per year) will be locked up in the buried wood. Although 50 MtN y^{-1} is a nontrivial amount, this is only a fraction of both the global natural nitrogen fixation rate of 110 MtN y^{-1} and the anthropogenic N (mainly from fossil fuel burning and fertilizer use) deposition rate of 140 MtN y^{-1} [33]. In addition, natural fixation rate may increase when nitrogen is in short supply. Thus, globally speaking, the nutrient lockup due to burial does not appear to be a problem big enough to hold back the wood burial proposal. However, it will depend on the spatial distribution and the fraction of the nitrogen deposition that can be utilized [34]. Our current understanding of such issues is limited, and more research in this area is needed. In some regions or localities this may be a more important issue. In these cases, some moderate fertilization could be used to alleviate the problem, or the intensity of the operation could be reduced.

3 Habitat loss

Dead wood, whether standing (snags) or down, plays an important role in forest ecology, acting as habitat for animals such as cavity-nesting birds, plants and microbial lives. To minimize the impact, it may be desirable not to completely clean the forest floor, but leave a fraction to maintain these important ecological functions.

4 Disturbance to forest floor and soil

Although modern forest logging practice has shown that disturbance can be kept at minimum, there is no guarantee it will be the case when practiced world-wide. If not executed properly, it may harm forest regeneration capability, biodiversity and cause significant loss of soil carbon. One method is to have ecological monitoring and carbon accounting conducted together by certified agencies or institutes following carefully crafted international standards.

The soil carbon pool is a dynamic balance between dead vegetation input and decomposition. If the deadwood input to soil is reduced, the soil carbon pool will decrease somewhat. It is difficult to quantify this possible loss at present. Regardless of the extent of this soil carbon loss, equilibrium will be reached after sometime so that the cumulative effect of a sustainable wood burial will eventually exceed the initial loss.

5 *Competition with other wood usage*

Wood has been a major resource for humans ever since our ancestors learned to use fire and sticks. Current world total wood consumption is about 0.9 GtC y^{1} (35). Obviously, priority will be given to these uses such as furniture and building material, but compared to the 10 GtC y^{-1} coarse wood production rate, there will be large additional capacity for carbon sequestration. Indeed, the burial scheme may be carried out most naturally as an expansion of the existing logging capacity. In addition, if old furniture and building lumbers are buried rather than left to decay in open dumps, they will still serve the purpose of carbon sink. This has already been practiced to some extent in landfills.

Research is ongoing in cellulosic biofuel where cellulose in woody material is converted to fuel [36]. Should this become economical with minimum environmental impact in the future, obviously it will have priority over wood burial because of the energy produced. This can also be said for other uses such as co-firing of wood chips and agricultural residue with coal. Nevertheless, the capacity built for wood harvest and burial will lend itself naturally to collecting wood for biofuel use. The 10 GtC y^{-1} wood production rate also provides an (approximate) upper limit on how much biofuel can be produced, and the caveats discussed here such as nutrient lock-up also apply.

6 *Other unintended* consequences

One possibility is that if roads are built into remote forests, it will make it easier for deforestation. What has happened in the Brazilian Amazon over the last 3-4 decades where deforestation (legal and illegal) follows road construction cautions against the implementation of wood harvest and burial in such regions. For this and many other environmental concerns, a considerable fraction should be preserved and left completely natural. A wise strategy would be intense management of suitable land to achieve higher efficiency while preserving as many forests in their natural states as possible.

There may be the concern that wood burial (or any other effective carbon sequestration scheme) will hinder the motivation to reduce emissions and the development of alternative energy. While this is a legitimate and important concern, there is currently a major mismatch between the urgency of the climate problem and the slow pace of the transition toward a carbon-neutral economy due to technological, economical and political hurdles. Carbon sequestration should only be used to 'buy time' so that the society has sufficient lead time to adjust while avoiding dangerous climate change.

Synergy *with other activities*

1 Reforestation and afforestation: making the carbon sink long-lasting

Reforestation is a widely embraced carbon sequestration technique [37,38). However, its capacity in sequestering carbon is limited by competition with other land use purposes such as agriculture. In addition, as forest and underlying soil mature, the carbon sink becomes saturated. If the trees are cut or burned by fire, the stored carbon would be lost back into the atmosphere. Such concerns had led to a disappointingly small role of reforestation in the Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC). Wood harvest and burial comes most naturally to such forests because they are by definition managed. Reforestation followed by wood burial will extend the lifetime of such land carbon sink indefinitely. Because much marginal land suitable for reforestation is currently not utilized, the earlier such activities are undertaken, the earlier is the effect.

2 Deforestation:cutting off the CO_2source

Deforestation currently accounts for a significant fraction of the anthropogenic CO_2 emissions (0.5-2.7 GtC y^{-1}; [1]). While mid-latitude regions such as China, India, Western Europe and North America were mostly deforested in earlier centuries, current deforestation takes place mainly in the tropics, notably the Amazon and Southeast Asia. Deforestation at the southern Amazon is typically done at the end of the dry season. Trees are cut, piled up and burned, often with the help of kerosene. While development pressure makes deforestation difficult to stop at present, burying the downed trees instead of burning will reduce the associated CO_2 emissions at minimum cost. Such a strategy is not in defense of deforestation, but serves to reduce its negative impact.

3 Post-consumer *wood: making waste a carbon sink*

A large fraction of municipal waste is wood, e.g., old furniture and construction lumber, and backyard dead trees. Most of these are burned or buried in landfills where they may already have relatively long lifetime. If these can be collected and buried in landfills with long-storage time ensured, it will serve as a carbon sink of up to 1 GtC y^{-1} assuming the current wood use rate [35J. This is of course part of the estimated 10 GtC y^{-1} world potential. One advantage of burying waste wood is that there will be no additional ecological impact, unlike wood harvest from the forest. Because it already carries significant cost to handle the waste wood, burial for carbon sequestration should be even more economically viable. On the other hand, such wood could also be incinerated to produce energy and their costs and relative merits need to be evaluated, but the wastes do not have to be wasted anymore.

4 Fire suppression: burying the fuel

Fire suppression, such as in the US and Canada over last several decades, has left a large amount of dead vegetation on the forest floor and contributed to an apparent carbon sink in North America. This additional fuel load, combined with recent drought in the America West has led to more frequent and large fires in recent years. The release of this carbon pool through catastrophic fires may become an important source to atmospheric CO_2 in the future. Collecting dead trees and burying them would reduce fire danger while creating a carbon sink.

Conclusion

Coal was formed by the burial of ancient plants in anaerobic conditions such as swamp and peatland. The proposed wood burial method is essentially a first step of a fossil fuel formation process, only drastically *accelerated* by active human management. It is ironic that the whole climate change problem is caused by the human *accelerated* release of the fossil fuel carbon pool. Thus it will not be surprising if this method turns out to be the most 'natural' way to undo fossil fuel CO_2 emission.

The wood burial technique uses natural tree growth to capture CO_2 from the air at nearly no cost, thus making it significantly more economical than other carbon capture methods. For storage, past focus has been on geological formations and in the ocean. Storing carbon by wood burial under soil will not only cut down atmospheric CO_2, but also relieve the CO_2 burden on the ocean where acidification is of major concern [39).111e traditional carbon sequestration techniques tend to be industrial scale, while the present proposal is a distributed approach. This has both advantages and disadvantages that need to be sorted out. It is likely that many of these methods will be practiced to some degree, but the merits of wood burial malce it an attractive option: low tech, low cost, distributed, easy to monitor, safe, reversible, thus a no-regret strategy. On the other hand, forest is a precious resource Mother Nature endowed upon us that serves many critical ecosystern functions and human needs. Care needs to be taken in pursuing such a strategy at large scale.

Competing interests

The author(s) declare that they have no competing interests.

Authors' contributions

This is a single-authored paper.

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Wood Vault: remove atmospheric CO_2 with trees, store wood for carbon sequestration for now and as biomass, bioenergy and carbon reserve for the future

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Abstract

Background: Wood harvesting and storage (WHS) is a hybrid Nature-Engineering combination method to combat climate change by harvesting wood sustainably and storing it semi-permanently for carbon sequestration. To date, the technology has only been purposefully tested in small-scale demonstration projects. This study aims to develop a concrete way to carry out WHS at large-scale.

Results: We describe a method of constructing a wood storage facility, named Wood Vault, that can bury woody biomass on a mega-tonne scale in specially engineered enclosures to ensure anaerobic environments, thus preventing wood decay. The buried wood enters a quasi-geological reservoir that is expected to stay intact semi-permanently. Storing wood in many environments is possible, leading to seven versions of Wood Vault: (1) Burial Mound (Tumulus or Barrow), (2) Underground (Pit, Quarry, or Mine), (3) Super Vault, (4) Shelter, (5) AquaOpen or AquaVault with wood submerged under water, (6) DesertOpen or DesertVault in dry regions, (7) FreezeVault in cold regions such as Antarctica. Smaller sizes are also possible, named Baby Vault. A prototype Wood Vault Unit (WVU) occupies 1 hectare (ha, 100 m by 100 m) of surface land, 20 m tall, stores up to 100,000 m^3 of wood, sequestering 0.1 $MtCO_2$. A 1 $MtCO_2\ y^{-1}$ sequestration rate can be achieved by collecting currently unused wood residuals (WR) on an area of 25,000 km^2, the size of 10 typical counties in the eastern US, corresponding to an average transportation distance of less than 100 km. After 30 years of operation, such a Wood Vault facility would have sequestered 30 $MtCO_2$, stored in 300 WVUs, occupying a land surface of 300 ha. The cost is estimated at \$10–50/tCO_2 with a mid-point price of \$30/tCO_2. To sequester 1 $GtCO_2\ y^{-1}$, wood can be sourced from currently unexploited wood residuals on an area of 9 Mkm^2 forested land (9 million square kilometers, size of the US), corresponding to a low areal harvesting intensity of 1.1 $tCO_2\ ha^{-1}\ y^{-1}$. Alternatively, giga-tonne scale carbon removal can be achieved by harvesting wood at a medium harvesting intensity of 4 $tCO_2\ ha^{-1}\ y^{-1}$ on 3 Mkm^2 of forest (equivalent to increasing current world wood harvest rate by 25%), or harvest on 0.8 Mkm^2 forest restored from past Amazon deforestation at high harvest intensity, or many combinations of these and other possibilities. It takes 1000 facilities as discussed above to store 1 $GtCO_2\ y^{-1}$, compared to more than 6000 landfills currently in operation in the US. After full closure of a Wood Vault, the land can be utilized for recreation, agriculture, solar farm, or agrivoltaics. A more distributed small operator model (Baby Vault) has somewhat different operation and economic constraints. A 10 giga-tonne sequestration rate siphons off only 5% of total terrestrial net

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primary production, thus possible with WHS, but extreme caution needs to be taken to ensure sustainable wood sourcing.

Conclusions: Our technical and economic analysis shows that Wood Vault can be a powerful tool to sequester carbon reliably, using a variety of wood sources. Most pieces of the technology already exist, but they need to be put together efficiently in practice. Some uncertainties need to be addressed, including how durability of buried wood depends on detailed storage methods and burial environment, but the science and technology are known well enough to believe the practicality of the method. The high durability, verifiability and low-cost makes it already an attractive option in the current global carbon market. Woody biomass stored in Wood Vaults is not only a carbon sink to combat current climate crisis, but also a valuable resource for the future that can be used as biomass/bioenergy and carbon supply. The quantity of this wood utilization can be controlled carefully to maintain a desired amount of CO_2 in the atmosphere to keep the Earth's climate from diving into the next ice age, acting as a climate thermostat. The CO_2 drawdown time is on the order of 100 years while the ramp-up time is a decade. A sense of urgency is warranted because the CO_2 removal rate is limited by biosphere productivity, thus delayed action means a loss of opportunity. In conclusion, WHS provides a tool for managing our Earth system, which will likely remain forever in the Anthropocene.

Background

To achieve the goals of the Paris climate accord and the Glasgow climate pact of keeping global mean temperature increases below 1.5–2 °C, carbon sequestration via negative emissions technology (NET) will be needed to augment emissions reduction [1]. Additionally, it is not enough to simply remove CO_2 from the atmosphere, but also necessary to sequester it reliably for hundreds of years or longer [2].

Wood harvesting and storage (WHS) has been proposed as one such method [3, 4]. In this method, sustainably harvested or collected woody biomass are buried underground in anaerobic condition or stored in other environments designed to prevent decomposition, forming an effective carbon sink.

Compared to many nature-based methods, WHS is a hybrid Nature-Engineering approach, with the key difference of being continual (no-saturation) and semi-permanent storage enabled by engineering methods. On the WHS method, a recent US National Academy of Sciences (NAS) report [2] states that "[WHS]…could be viable approaches to increasing carbon removal… To date, this proposed approach has not been tested though the technology is simple and easily applied". Actually, a limited number of projects have been conducted [5], but are not at the scale or quality needed. Financial and societal challenges remain before the method can be applied at large scale.

Methods

Here we propose a concrete way to carry out WHS. The method envisions centralized facilities to store wood semi-permanently. We name such a facility Wood Vault because it stores wood in a specially engineered enclosure that protects it from decay, with the potential for future use. It is valuable now as sequestered carbon to mitigate climate change, and in the future as a reserve of carbon, biomass and bioenergy. Such large facilities are particularly suitable for collecting and storing wood acquired from diffused sources. Three key aspects of the vision are (Fig. 1):

1) Collect and stockpile wood from surrounding regions, such as natural wood residuals (NWR) or sustainably harvested wood.
2) Construct the facility by digging a trench, filling it with wood, and enclosing the wood in a way that maintains an anaerobic condition.
3) After enclosure of the Wood Vault, use the land for recreation, agriculture, or solar farming.

In the results below, we describe the technical details to carry out these steps. Several versions of Wood Vault are proposed to create anaerobic, dry, or cold environments, conditions ideal for wood preservation. Data from literature are also used to estimate the carbon sequestration rate and economics of operating a Wood Vault facility. Data used are described in the text and the Appendix.

Results

Woody biomass availability and wood sourcing

General types of wood sourcing and their potential for CO_2 removal

We consider two types of wood sources: Type-A or opportunistic sources (Fig. 2) and Type-B or harvested wood from sustainably managed forests (Fig. 3).

In Type-A wood sourcing, woody biomass is collected from opportunistic sources, often with environmental co-benefits such as fire risk reduction and waste utilization.

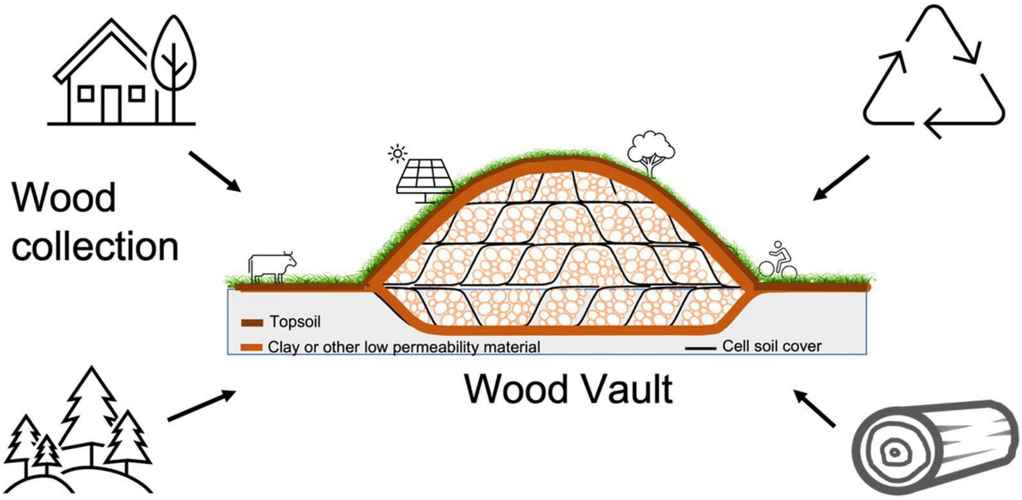

Fig. 1 Wood Vault is a centralized storage facility that collects wood from a variety of sources such as urban natural wood residuals (woody yard trimmings, NWR) , wood from storm damage, wood from forest thinning, construction and demolition debris, wood harvested in sustainably managed forests. The buried biomass is sealed off from oxygen with clay or other low-permeability material and embedded in a subterranean environment that will prevent decomposition semi-permanently. Variations and other versions are discussed later

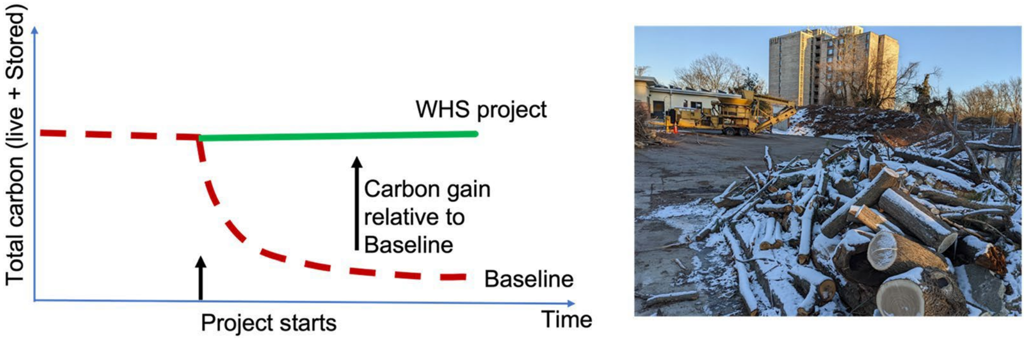

Fig. 2 Type-A wood sourcing for WHS: Opportunistic sources such as urban natural wood residuals (NWR) that would decompose within a short amount of time (Baseline scenario, red-dashed line), whereas a WHS project (Project scenario, green line) stores it semi-permanently. The difference between the two scenarios (Project minus Baseline) is the carbon gain that serves as the basis for carbon accounting. Photo: Urban wood collected at the municipal public works facility, City of Takoma Park, Maryland. Photo by Ning Zeng

They are 'low-hanging fruits,' limited by the availability of 'waste' wood. They are often one-time opportunities such as the utilization of urban 'waste wood.' This method may have a potential of up to 1 $GtCO_2$ per year globally [4].

Opportunistic sources are not reliable individually. However, over a large enough area, there will be a near steady supply for a large facility, with the amount fundamentally controlled by forest productivity in the region, except for regions with large wood imports/exports. Opportunistic sources include urban wood residuals (WR, wood trimmings from backyard tree removal, construction and demolition debris, old furniture and wood pallets etc.), land clearing for development and agriculture, logging residue, thinning for precommercial treatment, thinning for fuel treatment to reduce fire risk, and wood processing residue. In the US, it is estimated that a total of 328 Mt (mega-tonnes) of wet biomass is unexploited annually [6], corresponding to a 1.1 $tCO_2\ ha^{-1}\ y^{-1}$ availability if distributed over 3 Mkm^2 (3 million square kilometers, US forested area) (see details in Appendix). Throughout this paper, we approximate 1 tonne of wet/green biomass as 1 tonne of CO_2

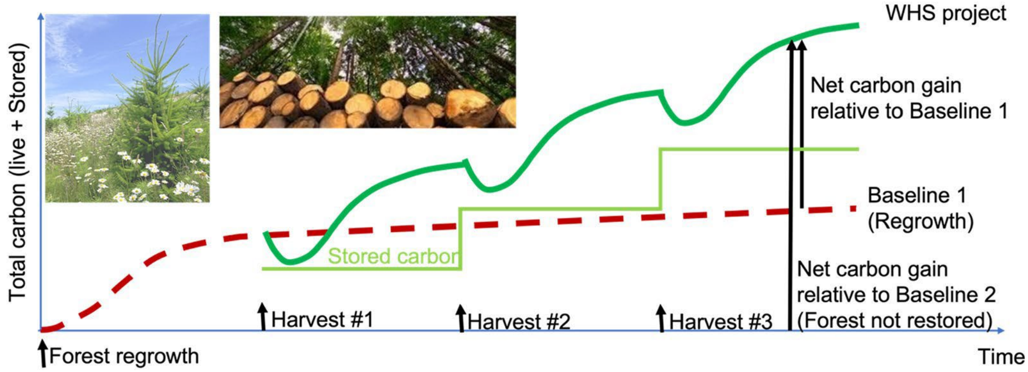

Fig. 3 Type-B wood sourcing from a sustainably managed secondary-growth forest that grows back from disturbance such as fire, storm damage, deforestation. The grow-back can be either natural or facilitated (planted). The total carbon on land (green line) consists of the active forest (live vegetation, litterfall and soil carbon) plus the stored carbon from the WHS Project (lime green). The net carbon gain of the Project (green line) can be counted relative to regrowth without WHS (Baseline 1, red-dashed line, starting from Harvest #1), or no-regrowth (Baseline 2, red-dashed line, starting from forest regrowth at time = 0). Photo insets: forest regrowth after disturbance and harvested wood (source: Wikipedia)

Table 1 Targets of carbon sequestration amount and example scenarios to achieve them using WHS

Target rate of carbon sequestration	Examples to achieve the goal without expansion of current wood harvest (use only unexploited wood residuals)		Examples with expansion or repurposing of forest management and harvest	
			Medium harvest intensity (4 $tCO_2\ ha^{-1}\ y^{-1}$)	High harvest intensity (12 $tCO_2\ ha^{-1}\ y^{-1}$); fast growing species
1 $MtCO_2\ y^{-1}$	Unused urban wood residue on 25,000 km^2 (size of MD, or 1/6 of NC) at 0.4 $tCO_2\ ha^{-1}$	Forest thinning for fuel treatment on 25,000 km^2	On 2500 km^2 of forested land (size of two counties in eastern US)	On 800 km^2 (30 km by 30 km forest, land area of New York City)
1 $GtCO_2\ y^{-1}$	Most unexploited wood residue from 9 Mkm^2 (temperate forested land the size of US; US wood utilization rate) at 1.1 $tCO_2\ ha^{-1}$ intensity	25% of current world wood harvest rate	2.5 Mkm^2 of forest	0.8 Mkm^2 restored Amazon rainforest (area deforested since 1970)
10 $GtCO_2\ y^{-1}$ (27% of 2020 fossil fuel emissions; total NETs needed in IPCC 1.5 °C scenario)			25 Mkm^2 forest land (about half of total world forest)	8 Mkm^2 of productive forest land (slightly less than the size of US/China)

MD: the state of Maryland; NC: the state of North Carolina. Mkm^2: million square kilometers, or 100 million hectares. A targeted rate can be fulfilled with a specific wood sourcing option listed, but in practice more likely by a combination of multiple choices because the best option depends on the local circumstances

sequestered.[1] For estimating waste wood collection area for a large storage facility below, we will use a benchmark value of 0.4 $tCO_2\ ha^{-1}\ y^{-1}$, which we consider immediately available at no or low cost to the facility as it is simply to make a 'waste' valuable.

For Type-B sourcing, wood is harvested from forests managed for carbon sequestration (fully or partially). Here we consider two benchmark values: a medium harvesting intensity of 4 $tCO_2\ ha^{-1}\ y^{-1}$, and a high harvesting intensity of 12 $tCO_2\ ha^{-1}\ y^{-1}$, based on the top-down estimates of Zeng et al. [4] using forest coarse wood productivity. If conducted at the medium harvesting intensity over an area of 3 Mkm^2 (current US forested area), it will lead to 1 $GtCO_2\ y^{-1}$ sequestration (Table 1), compared to 0.5–3 $GtCO_2\ y^{-1}$ needed to offset hard-to-cut fossil fuel emissions in a renewable energy dominated

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[1] A tonne of wet biomass, also known as a green tonne, contains about 0.5 dry tonne biomass. Dry biomass contains about 50% carbon (C), with the rest mostly oxygen (O) and hydrogen (H). Thus, material in 1 green tonne contains about 25% carbon which is oxidized to about 1 tCO_2 (tonne of CO_2). 1 tC = 3.67 tCO_2 (approximately 4 tCO_2) as the molecular weight ratio of CO_2:C = 44:12. We also approximate 1 short ton in US literature with 1 metric tonne for estimates in this paper. In summary, 1 wet/green tonne of wood has approximately a volume of 1 cubic meter while sequestering 1 tCO_2. Such approximation lends simplicity in our high-level assessment and is within the uncertainty range of natural variations in tree species, wood moisture content, and other factors.

Table 2 Wood availability per unit area for large-scale storage facility depending on the method of wood sourcing, based on US forestry data (see Appendix)

Method	Potential wood availability ($tCO_2\ ha^{-1}\ y^{-1}$)	Size of wood collection area for large storage facility	Assumptions in the estimated potential
Urban-suburban wood residuals	0.4	2500 km^2	Utilize 30–50% of unexploited urban wood residuals
Rural (Managed forest)	4	2500 km^2	Utilize most of wood residuals and forestry residue, or sustainably managed forest
Combination	0.4–4	2500–25,000 km^2	Collection over a larger area or high rate

future [7]. At the high intensity of 12 $tCO_2\ ha^{-1}\ y^{-1}$ over an area of 8 Mkm^2 (about the size of the US, or 20% of the world's total forested area), we can sequester 10 $GtCO_2\ y^{-1}$, the total sequestration needed from NETs (assumed to be all BECCS in the IPCC 1.5 °C scenario) [1]. The 10 $GtCO_2\ y^{-1}$ rate corresponds to the high end of the potential of 3–10 $GtCO_2\ y^{-1}$ estimated using a top-down approach with world total forest productivity constrained by land use, topography, conservation and existing wood use [4]. In particular, even this high-end estimate assumed that 50% tropical forests and 20% mid-latitude forests are kept intact. While the high 10 $GtCO_2\ y^{-1}$ rate is indeed possible and can be implemented in a climate emergency, it should be carried out with great caution. On the other hand, the lower values on few gigatonne scale can be achieved quite sustainably.

To give a few examples, to sequester 1 $GtCO_2\ y^{-1}$, a level achievable without dramatic transformation of the industry, wood can be sourced from currently unexploited wood residue on an area of 9 Mkm^2 (9 million square kilometers, size of the US/China) (low intensity), or by increasing current world wood harvest rate by 25% (equivalent to harvesting wood at a medium harvest intensity of 4 $tCO_2\ ha^{-1}\ y^{-1}$ on 3 Mkm^2 of forest), or harvest on 0.8 Mkm^2 of restored Amazon forest at high harvest intensity of 12 $tCO_2\ ha^{-1}\ y^{-1}$, or a combination of multiple possibilities.

Size of wood collection area for a single large facility

Here we only consider wood residuals collected from urban-suburban regions, for example, an area of 2500 km^2 (50 km by 50 km), the size of two typical counties in the eastern United States.

The wood availability of 0.4 tonne $ha^{-1}\ y^{-1}$ over 2500 km^2 yields 100,000 tonne y^{-1}. After 10 years, a total of 1 Mt will be collected. For rural area with harvesting from managed forest, at 10 times higher wood availability, or a larger area of 25,000 km^2, the first year will already collect 1 Mt. Intermediate scenarios are also possible by collecting wood from somewhat larger area (more than a couple of counties for suburban, at added transportation expense), or a combination of these. A summary is given in Table 2.

A Wood Vault facility can have multiple WVUs that are built up over time. We suggest one facility for an area the size of a few counties in the US, constraint by the availability and sustainability of wood sourcing.

Project-level prototypes of wood sourcing

While the 'top-down' assessment above provides a panoramic view of wood sourcing potential, here we list several 'bottom-up' project-level opportunities. Firstly, under Type-A (opportunistic sources) we propose (Fig. 4):

1) Project URBAN: utilize currently unexploited urban wood residuals. Biomass from urban tree removal, construction site tree removal, demolition and old furniture wood. These are often a burden and may be costly to dispose. Collect and bury this biomass for carbon sequestration can completely reverse the cost equation.
2) Project FIRETHIN: Woody biomass from forest thinning for fire risk reduction, precommercial treatment and other purposes is used for sequestration. Fire suppression, such as in the America West over the last century, has left a large amount of dead vegetation on the forest floor. Combined with drought and insect infestation, this has led to more frequent and larger fires in recent years. Additionally, the release of this carbon pool through catastrophic fires may become an important source of atmospheric CO_2 in the future. Collecting dead trees or thinning and burying them would reduce fire danger while creating an effective carbon sink (relative to letting it burn or rot).
3) Project RECOVER: utilize naturally damaged woody biomass caused by natural disasters such as hurricanes, tornados, fire, aging/death, and disease. Recovering trees from storm blowdown and other natural or unnatural disasters and storing the carbon

Fig. 4 Type-A opportunities for sourcing wood for WHS, with co-benefits: (1) Project URBAN: utilize currently unexploited urban wood residuals; (2) Project FIRETHIN: utilize woody biomass from forest thinning for fire risk reduction; (3) Project RECOVER: utilize storm-damaged woody biomass by hurricanes and tornados; (4) Project RESIDUE: forestry residue from timber harvest and other operations

will prevent the release of this carbon into the atmosphere. It's a loss of opportunity if we don't do it.

4) Project RESIDUE: utilize forestry residue from timber harvests and other operations. Residues from forestry operations include slash and woodchips. In many places, they are not utilized due to economic and other constraints. To the degree that nutrient and other ecosystem functions are sufficiently maintained, a portion can be buried for carbon sequestration. Furthermore, careful management enabled by the carbon value has the potential to support better ecosystem functioning. Compared to whole wood logs, the smaller-size woody biomass such as woodchips may not preserve as well, so their permanence after burial needs to be better established before large-scale implementation.

Type-B projects, with wood sourcing by harvesting different types of forest, when implemented globally, have the potential for multi-gigatonne scale annual carbon sequestration (Fig. 5).

1) Project TIMBER: Wood is harvested from a managed forest such as timberland. The forest is often privately owned, and has been used for timber, pulp for paper, biomass or bioenergy for many years. The sustainability and environmental impact of the forest are generally well established. Wood can be sustainably removed via thinning, rotation or other schemes. Carbon sequestration re-purposing adds a new revenue to the original forest management objectives. Other traditional uses of wood such as furniture should have priority, but there is more wood available beyond the traditional market demand.
2) Project RESTORE: utilize wood from forests restored from degraded or marginal land. Carrying out WHS after initial forest establishment will extend indefinitely the carbon sequestration potential of reforestation/afforestation projects whose carbon sink approaches saturation after some decades. This synergistic carbon benefit that accrues over time is seen clearly in Fig. 3. This fundamentally changes the equation of the climate benefit of reforestation, acting as a strong incentive for supporting reforestation/afforestation as soon as possible. Because these restored forests are, by definition, managed, so there is no issue with conservation. Of course, sustainability should be included as part of the WHS project methodology requirement for carbon credits. For example, tropical deforestation leaves land in poor quality after some years of grazing and agriculture. As an idealized scenario, a sequestration rate of 1 $GtCO_2\ y^{-1}$ can be achieved if the 0.8 Mkm^2 restored Amazon rainforest (area deforested since 1970) is fully utilized with WHS at high harvest intensity

Fig. 5 Prototype projects with Type-B wood sourcing: (1) Project TIMBER: utilize partially or fully the wood harvested from existing timberland; (2) Project RESTORE: utilize wood from forest restored from degraded or marginal land; (3) Project Nature-2: utilize wood from forest recovered from natural disturbance/death. Type-B projects, when implemented globally, have the potential for multi-gigatonne scale carbon sequestration. Also shown is Project REMEDIATION, not in terms of wood sourcing, but using abandoned quarry/mine as burial site with co-benefits of carbon sequestration and mine remediation

(Table 1), though in practice we recommend mixed use.

3) Project NATURE-2: utilize wood from forests recovered from natural disturbance/death (secondary regrowth forest). Wood is harvested from a secondary-growth forest, that is, a forest growing back from agricultural abandonment, degradation, fire or other disturbances. Such a forest goes through initial growth, followed by self-thinning, natural death, disease and other processes. Active management can lead to an overall more productive forest and better ecosystem service, while producing a carbon sequestration stream.
4) At this point of time, we warn against using old-growth and other conservation forests for WHS.

Also shown in Fig. 5 is Project REMEDIATION, not in terms of wood sourcing, but using an abandoned quarry/mine as a burial site with the co-benefits of carbon sequestration and mine remediation. In this case, wood needs to be sourced with one or more of the above wood sourcing methods.

In the analysis below, we use urban wood residuals as an example (Project URBAN) because this is an immediately available 'low-hanging fruit', while recognizing that some aspects may differ for other types of wood sourcing. In general, for Type-A wood sourcing, no major policy incentives are needed other than allowing the stored carbon to be eligible in current carbon markets such as EUETS at the recent €50–100/tCO_2, the US IRS 45Q tax credit at \$35–50/tCO_2, and many other national and regional carbon markets [8], or the burgeoning voluntary markets [8, 9]. It is straightforward to extrapolate our estimates to higher wood availability on managed forests which is also quite feasible in rural regions such as the US Southeast. If we include the medium harvest intensity 4 $tCO_2\ ha^{-1}\ y^{-1}$ on managed forest, the facility can be either larger to collect wood from a similar area, or similar size with wood from a smaller area.

Wood Vault as carbon storage facility

Wood Vault: the concept

We propose the term Wood Vault to describe a class of specially engineered structures that keep woody biomass from decomposing or being otherwise damaged, for the purpose of semi-permanent wood storage as carbon sequestration and biomass/bioenergy reserves. The main type of Wood Vault uses soil. Other types of Wood Vaults in water and dry or cold conditions are also possible. The illustration in Fig. 6 shows the essence of the soil category of Wood Vault in relation to a standard soil profile. The key factors of a Wood Vault are:

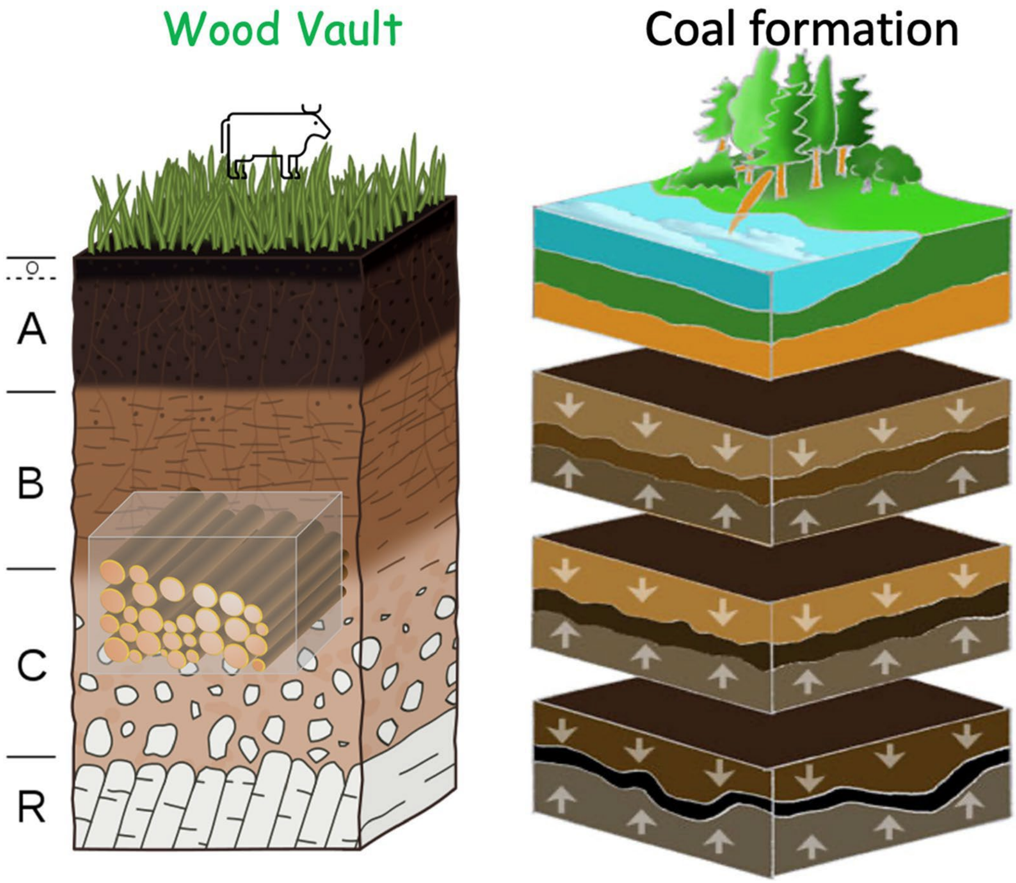


Fig. 6 The essence of Wood Vault in relation to a standard soil profile: Wood is buried in the subsoil (B-horizon) or lower horizon, completely isolated from the biologically active topsoil above. The wood is capped with clay or other low-permeability material to ensure anaerobic condition. If the original subsoil already has sufficiently low permeability, no other material needs to be imported. After enclosure, the top is backfilled with original topsoil and organic layer to allow shallow vegetation cover or other use. The semi-transparent cubic enclosure is only conceptual as the actual material and engineering methods are described in the various versions of Wood Vault. Source of background graphics: Wikipedia

- Woody biomass, raw or minimally processed, is buried deep underground, isolated from the biologically active topsoil above.
- The wood is buried in a way to ensure anaerobic condition or stored in dry or cold conditions in order to prevent decomposition, leading to durable semi-permanent storage.
- The WHS process is akin to the first step of coal formation. Compared to natural coal formation in which plants are buried in fortuitous conditions at slow geological rate, the rate of WHS-style wood burial is accelerated by human intervention via wood harvesting and Wood Vault construction. This is the exact opposite of accelerated oxidation of fossil fuel by dig-and-burn. WHS is a 'near-perfect' reversal of fossil fuel digging and burning, thus a 'natural' way to undo fossil fuel CO_2 emissions.

Wood Vault in practice: prototype Version 1.1 (burial mound: Tumulus)

Our 'poster-child' Wood Vault is a burial mound, nicknamed Tumulus after the semi-underground human burial sites in the pre-historical Mediterranean region. What size of a large burial facility will be needed to accommodate this amount of wood? 100,000 tonnes of green biomass is about 100,000 cubic meters in volume. This volume of wood can be stored in a space of dimension 1 ha (100 m by 100 m; size of two soccer/football fields) with a trench 5 m deep, and a mound 20 m above ground. The air space of the structure is about 150,000 m^3, after accounting for the tapered geometry of the mound. We assumed 1/3 of the volume is filling space occupied by clay sealant, water and soil backfill. The aspect ratio (height:length) of 20:100 gives a moderate slope. It can in principle be made even taller which would provide a nice

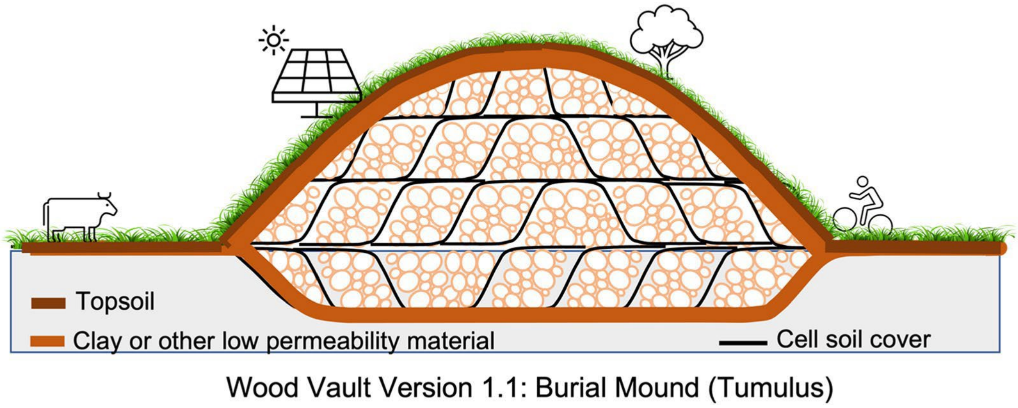


Fig. 7 A basic Wood Vault unit partially aboveground, partially underground (Wood Vault Version 1.1: Burial Mound Tumulus). A prototype unit occupies 1 hectare of land (100 by 100 m, or size of two soccer/football fields), 5 m deep, 20 m tall. The unit is divided into cells. Each cell is sealed as soon as it is filled. After closing of the top at final enclosure, the original topsoil is put back, grass and shallow rooted trees can be allowed to grow, then used as park, grazing land, cropland, solar Farm, or combination of these. Reddish brown represents clay or clay-like low permeability soil or liner to ensure anaerobic condition, while dark brown represents backfilled topsoil

vista point on flat land and recreational space if used as a park after sealing. It can also be made deeper at some additional excavation cost. Both can reduce the requirement of surface land area. Such a Wood Vault is illustrated in Fig. 7. This is Wood Vault Version 1.1 (Burial Mound: Tumulus).

We call this 1-hectare area a basic Wood Vault Unit (WVU, see below for more discussion), which is the size of two football/soccer fields. Obviously, any other practical sizes are also possible. It does not change the analysis below. On the timescale of a few months to a few years, the unit is filled and then enclosed at the top. Within each unit, multiple cells can be partially sealed with excavated soil more frequently, say each month, to further minimize decomposition before a complete seal off. Multiple Wood Vault units can be added over time and are independent of each other. At higher wood availability such as the rural harvesting case, the process can be done at higher frequency. This will be more effective for wood preservation and more cost-efficient.

It is also possible to use a similar size facility to bury wood collected from a larger area at the same wood availability per unit area. In this case, the facility can be filled to capacity earlier. The additional cost of transporting wood material over longer distances but within ~ 100 km may still be quite economical. The optimal size of the wood burial facility needs to strike a balance between size of wood source region and the cost of facility construction and transportation, depending on local circumstances.

Construction of a Wood Vault (Version 1.1 as example)

To accommodate wood material from a variety of sources such as urban wood residuals and forest residues, as well as woody biomass collected from a broader region, large-size Wood Vault can be built to handle the material efficiently. To construct such a facility (Fig. 7):

1) Firstly, estimate the sustainable rate of wood source within the region of interest.
2) Then select a suitable site with size commensurate to the estimated wood source and planned operation time horizon of the facility.
3) The suitability of the site is based on an assessment of site characteristics, including soil type, soil depth, soil profile, topography, hydrology, climate, environment, cost, ownership, and other relevant factors.
4) Collect wood to build up a stockpile for temporary storage before burial.
5) Then excavate soil to form a large trench/pit, with the soil laid on the side. The organic containing topsoil should be excavated first, separately from subsoil, in order to be put back on the surface later to minimize environmental impacts via land use change and provide nutrients and substrate for decomposers, as well as supporting vegetation regrowth on top. Wood is buried in the subsoil (B-horizon) or lower horizon, completely isolated from the biologically active topsoil above (Fig. 7).
6) Then divide the pit into multiple sections (cells). To minimize degradation before the closure of the cell, wood material is trucked over and laid down in the cell before moving on to the next cell. After it is fully filled, the cell is covered with a layer of soil

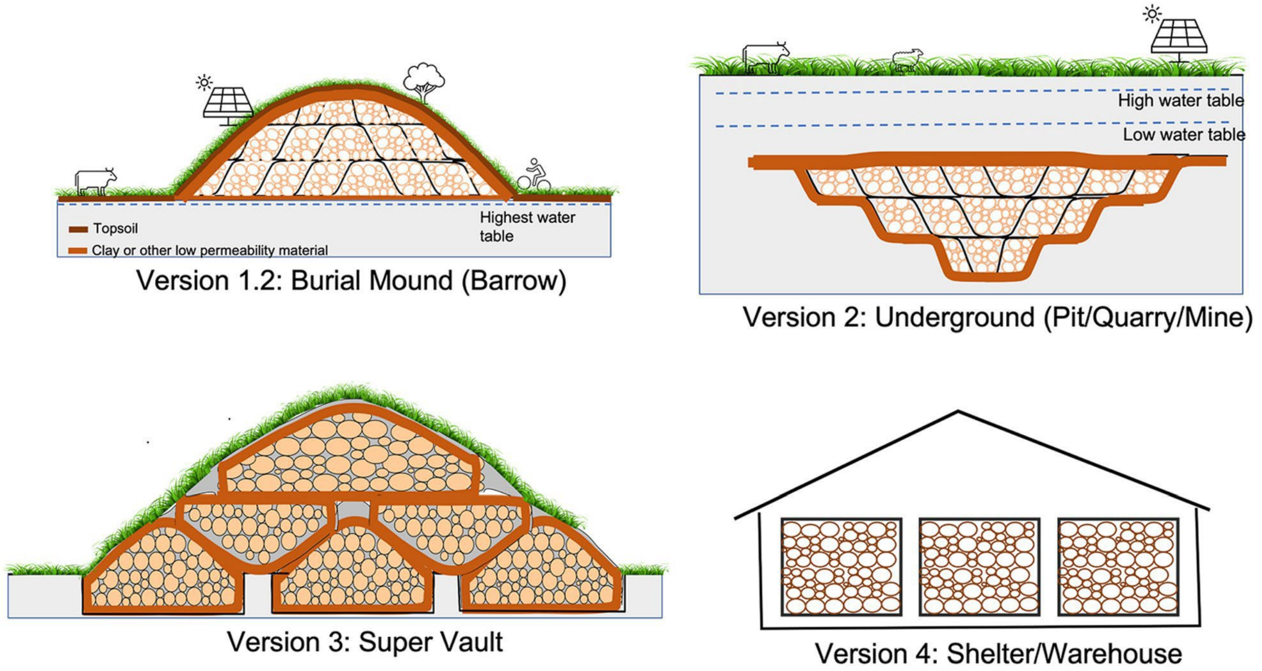
and closed. Soil is compacted and allowed to settle to fill the gaps. The cell size is such that it can be filled, ideally in less than a few months of the first dump, and the shorter the better. The optimal cell size can be determined by balancing wood sourcing rate and engineering cost (larger cell will be more space efficient and cheaper per unit mass of wood stored).

7) It is useful to take into account the seasonal variations (cold vs. warm, or wet vs. dry) in carrying out different steps of operation. For instance, cutting wood at the end of the growing season after leaf fall will minimize nutrient lockdown as trees send their nutrients down to the rooting zone before shedding leaves. Logging/collection operations are best carried out in cold/dry season with frozen ground to minimize soil damage and compaction as well as to allow better machine maneuverability.
8) Wood material can be minimally pre-treated to extend the storage lifetime. For example, the treatment material can be contained inside a pond on site. Wood can be dipped into the pond, packed into easy-to-handle units after or before treatment. Another technique is to spray over the wood as the pile runs through a carwash like tunnel, especially on the cut surfaces. A cheaper option is to spray only the cut-ends of whole logs. Charring of the surface of the cut ends is yet another technique. The recommendation of minimal or no treatment is an economic consideration, not that treatment is not good for preservation.
9) Use the excavated local soil to cover the buried wood if it has low permeability such as clay. The permeability, measured in Darcy velocity, should be lower than 10^{-8} m s^{-1}, and even better less than 10^{-9}-10^{-10} m s^{-1}. If clay is not available on site, source it from somewhere else. Fine silty and muddy soil may be used in case clay is not available, but wood durability may be lessened somewhat.
10) If covering soil is sourced from outside or the soil excavated is not reused for backfilling or covering, wood can be simply piled up without excavation (Version 1.2 below). This may be a preferred approach if the water table is very shallow and fluctuates significantly so that it's difficult to keep the buried wood outside the fluctuating zone.
11) Where the topographic slope is significant, line with clay or possibly synthetic material the upslope-facing side to prevent water from moving laterally through the buried wood, in order to minimize episodic reoxygenation of the burial environment. The best method is, however, to seal the pile completely from all sides with clay.
12) If possible, the base of the pit should be either above the local water table at its highest level or below the lowest level to avoid fluctuating water–air boundary bringing in oxygen.
13) When considering all factors for site selection, if the water-level requirement (either completely above the seasonal highest water level or completely below the lowest seasonal level) cannot be satisfied, and the local soil does not have very low permeability, one can use clay to enclose the pit completely with sufficient thickness on all sides. The degree of anaerobic condition depends on clay thickness. We recommend a ballpark value of 0.3 to 1 m, which obviously depends on the quality/permeability of the clay.
14) After the facility is enclosed, grass or trees with shallow roots can be allowed to grow back, and the land can then be used as pasture for grazing animals, cropland, park, photovoltaic solar farms, or combinations of the above.
15) Some land settling over time may be inevitable. Carefully packing the filling material of wood and soil can minimize but is unlikely to eliminate settling. If wood eventually rots, even just partially, land settling will become significant, in which case the Wood Vault would have failed. Obviously, the purpose of Wood Vault is to ensure no or little decay over a long period of time. From an engineering point of view, the design lifetime is a key criterion, but because Wood Vault as well as its climate goal are novel concepts and we don't have enough engineering data to quantify it, this is an area that needs to be further explored and better defined, in particular, in light of long-term climate goal of WHS as a thermostat (below).

Seven versions of Wood Vault

Other versions of Wood Vault construction are also proposed (Fig. 8):

- Wood Vault Version 1.2: Fully aboveground (Burial Mound: Barrow).
- Wood Vault Version 2: Fully underground (V2.1: Pit, V2.2: Quarry, V2.3: Mine). Filling exhausted quarry or mine with wood provides a co-benefit for mine remediation.
- Wood Vault Version 3: Stacked multiple units (Super Vault). This will be more land use efficient.
- Wood Vault Version 4: Shelter/Warehouse. Woody biomass is stored in shelters built to keep out animals and insects. The shelters can be made of a variety of construction material, including wood itself. The wall can be made with traditional method of straw-mud or mudbrick (known as adobe in Spanish and cob in English; Fig. 9), sheltered from rain on top. Mud



Version 1.2: Burial Mound (Barrow)

Version 2: Underground (Pit/Quarry/Mine)

Version 3: Super Vault

Version 4: Shelter/Warehouse

Fig. 8 More versions of Wood Vault: Version 1.2: fully above-ground (Barrow); Version 2: fully underground (Pit/Quarry/Mine); Version 3: aboveground shelter/warehouse; Version 4: Stacked units (Super Vault): each sub-unit is one of Tumulus or Barrow

Fig. 9 Adobe (Spanish) or cob (English), a traditional construction material/technique that mixes mud with fibrous material such as straw. Adobe can be an excellent choice for aboveground versions Wood Vault, for example, Shelter, DesertVault, or aboveground Baby Vault. Left: adobe wall in Palencia, Spain; Right: Maintenance of historic architecture in Agadez, Niger, by adding a new layer of mud rendering. Photo source: Wikipedia

can usually be locally sourced. It is highly effective at fire prevention as well as acting as an insect/animal barrier. Multiple stockpiles can be further put inside a large warehouse, either open or closed. Slow wind erosion on the order of decades to centuries can be countered with some maintenance. Each sub-unit is a Baby Vault. Each sub-unit can be sealed airtight with adobe. Another option is not to seal off the wood piles, but have it ventilated naturally or with an engineered system. In this case, many more issues need to be resolved because it's not anaerobic.

We use Tumulus and Barrow to distinguish Version 1.1 from Version 1.2 according to whether the Vault is partially belowground. In Archaeology, the term Tumulus, with its Latin origin, is commonly used to describe burial mounds in the Mediterranean region where they are typically built partially below ground, such as the Etruscan tombs in central Italy. In contrast, the term Barrow can be traced to a southern English dialect. The English tombs as well as northern European burial mounds tend to be built fully above ground. We hypothesize that this is due to the wet climate and high water table in these regions, while the drier Mediterranean climate allows underground burial. This distinction is more than just terminology. Indeed, it has important engineering implications for the construction of Wood Vault for wood preservation. A fluctuating water table leads to aeration and oxygenation, thus not conducive for maintaining anaerobic condition in a Wood Vault. Thus, in wet regions, the fully above ground version (Barrow) is better than Tumulus, though sufficient clay sealing can still make Tumulus version work. This is a critical factor in our design of several versions of Wood Vault.

The construction of these other versions may differ somewhat from Version 1.1 (Tumulus). For instance, the underground version (Version 2) would work well on low-lying area with high water table, where the wood can be buried completely underground below the lowest level of fluctuating water table.

1) Such places are typically low-lying land with little lateral transport, so sealing requirement may not need to be as stringent but care needs to be taken as we are talking about a very long time scale. These places also tend to have silty soil as they are often formed by alluvial/fluvial sedimentation which already has low permeability.
2) In the case of a valley or other sloping topography, there may be strong one directional underground water flow. In this case, the upslope direction should be lined with clay or synthetic liner to minimize water flow in the burial chambers.
3) Similar methods can be applied to bury wood in abandoned mines or quarries which involves little digging.

Burying the wood completely below ground will require more excavation, thus somewhat higher costs. The excavated soil may be sold to compensate for the excavation cost, depending on the market. In the case of utilizing an exhausted mine or quarry, there is little cost of excavation, and additionally contains many environmental and social co-benefits.

Compared to the underground versions, aboveground Wood Vaults would require more maintenance. For Vaults with an open woodpile, a key factor would be fire prevention. Traditional construction material such as adobe/cob (mud-straw brick wall) is an excellent choice because it is locally sourced and low-cost. An adobe enclosure of woody biomass can last for decades or longer without major maintenance (Fig. 9). Synthetic material can also be used. In wetter climate, a roof will be needed for rain sheltering. Another concern is animal burrowing or wind erosion, both can be repaired in time with low-cost.

It is also possible to store wood in perpetually wet (submerged under water) or dry (desert) conditions [3] (Fig. 10), which leads to our Versions 5 and 6:

- Version 5.1: AquaOpen. Wood logs are barged over to water bodies with low-oxygen bottom water such as the Black Sea or the Great Lakes and dropped to the bottom. Ballasts (weights) may be needed to sink the logs, but eventually the logs will remain sunk after saturation with water. It is possible that some dried logs may be resin-sealed so that water cannot penetrate the wood so some research is needed here. A good technique is pre-soaking the logs. Not all water bodies are suitable because bottom organisms such as marine borers and bacteria can attack wood. These waters are not completely devoid of oxygen due to mixing, no matter how weak it is, but the biological activities may be slow enough such that sediments can cover the logs before significant wood decay occurs. Once trapped in the silty sediments, the wood should stay semi-permanently. Examples of wood preservation include the well-preserved Roman and Greek wooden ships at the bottom of the Black Sea, the Swedish Vasa warship at the bottom of Stockholm harbor, and the Neolithic village wooden artifacts at the bottom of Lago di Bracciano in Central Italy, as well as the newly discovered Endurance ship of Ernest Shackleton preserved in near-perfect condition 107 years after sank to the bottom of the Weddell Sea, Antarctica.
- Version 5.2: AquaVault. Bundles of wood logs are wrapped inside a lining material, for example plastic or rubber, that is resistant to attack from bottom water dwelling organisms, then are sunk to the bottom. The wrap does not need to be completely waterproof. Similarly to a diving wetsuit, as long as the wrap maintains integrity, the water inside the wrap and between the wood logs will be stagnant enough to maintain low enough oxygen concentrations to prevent bacteria and the wrap itself will deter marine borers. Burying logs in bogs and wetland can also

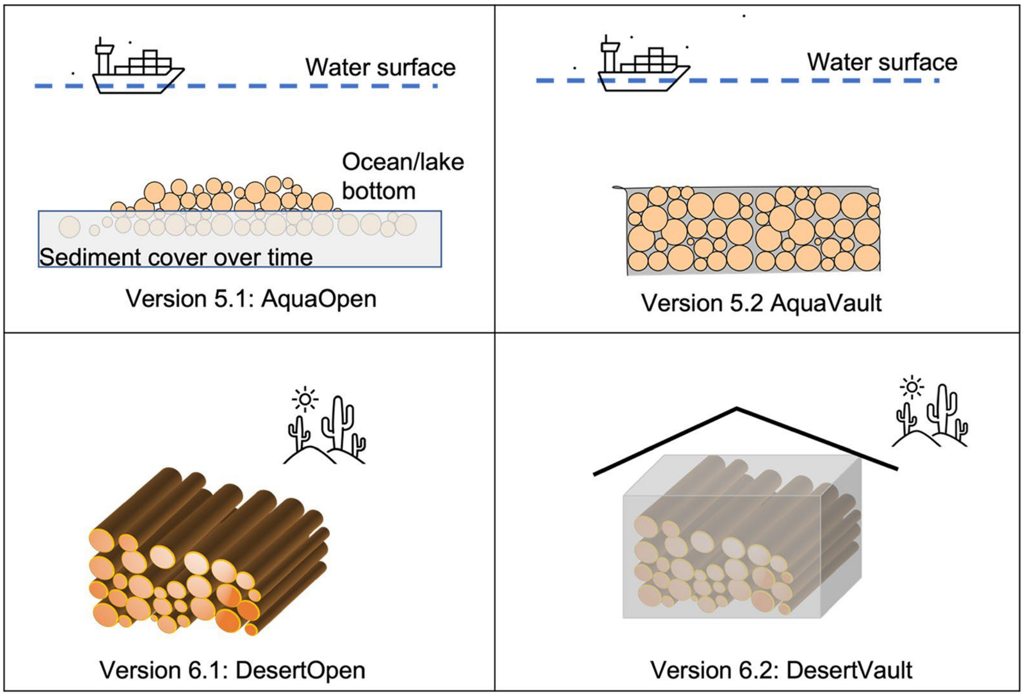


Fig. 10 More Wood Vault versions. Version 5.1 AquaOpen: submerged underwater, open without protection. Version 5.2 AquaVault: submerged underwater with protection. Version 6.1 DesertOpen: stockpiled in dry condition (desert) without protection. Version 6.2 DesertVault: stockpiled in dry condition with protection

be classified in this category, though it can equally fit in underground burial category.

- Version 6.1: DesertOpen. Piles of wood logs are left open in the desert. Dry air and wind minimize decay. Fire is a potential hazard. Having relatively small wood piles separated from each other can minimize loss in the event of fire. Piling the logs in a way such that it is naturally ventilated can significantly extend the life of preservation.
- Version 6.2: DesertVault. Wood piles are protected with synthetic material, or the traditional methods of straw-mud walls or mudbrick (adobe), sheltered from occasional rain on top. Mud can usually be locally sourced. It is highly effective at fire prevention as well as acting as an insect/animal barrier. Slow wind erosion on the order of decades to centuries can be reinforced with some maintenance. In desert regions, wood sourcing is more of a limitation as forests are mostly in the mountains with modest productivity and many other desired uses. Thinning for fire risk reduction may be a major opportunistic source. Transportation cost is another limiting factor, but there should still be good opportunities for relatively in-situ storage. DesertVault bears similarity with Version 4 (Shelter/Warehouse), but it can be much simpler because the dry desert climate poses significantly lower risk to wood preservation. There are two options of airtight sealing vs non-airtight, whose pros and cons need to be further evaluated though our current inclination is for airtight because we think climate goal needs a guaranteed lifetime much longer than 100 years, which is a commonly stated goal in the current Carbon Dioxide Removal and Carbon Sequestration communities (See below discussion

Fig. 11 Wood Vault Version 7: FreezeVault. Wood piles are stored in cold regions such as Antarctica. Illustration is conceptual, and it does not necessarily imply actual site or wood storage details. Background photo: US McMurdo Station, Antarctica (source: Wikipedia)

on WHS as climate thermostat). Same consideration applies to Shelter (above) and Baby Vault (below).

Finally, we propose Version 7, named FreezeVault, where wood piles are stored in cold regions such as Antarctica (Fig. 11), ideally in locations perpetually below freezing, but occasional short-term warmth should not be a problem. For safety, we should also take into account possible future warming. The wood piles are open in a natural freezer-like environment, which we still call conceptually a Vault because even though there is no physical protection to construct, it is a natural place we move the wood to. The transportation, placement etc. still consist of engineering effort. Transportation cost dictates that it needs to be in the coastal region, perhaps 1–2 m above sea-level in case of future sea-level rise, though moving the piles upland by 1–2 m are totally feasible should it become necessary in the future. The wood piles should not be placed on fast moving glaciers.

Transportation cost for some versions above may be a concern, such as water bodies and Antarctica as wood source may be far away from the storage site. However, wood logs can be rafted down water ways, and barges or bulkers can be used for long-distance transportation of bundled wood piles. The cost should be quite manageable given the state of modern shipping technology.

Even though we have focused on local wood sourcing here, we do not exclude possibilities of transporting wood long-distance via waterway or railway that may be sufficiently economical and carbon efficient.

Land use after enclosure and ensuring the longevity of Wood Vault

Another attractive aspect of Wood Vault is the value for later land use. Unlike a landfill for municipal waste disposal, where leachate, odor and methane gas from chemical and biological activities are of major environmental concern, a Wood Vault is clean, stable and safe.

After the topsoil from excavation is backfilled after enclosure, grass and certain types of trees can be allowed to regrow. It can be used as pastureland or other agricultural use, or recreational use such as parks (Fig. 4). Yet another attractive possibility is to use it to install solar panels to generate electricity, or agrivoltaics (combination of above). We expect good safety after post-burial soil settlement for low-weight buildings such as warehouses and animal barns, but as a precaution, it may not be ideal for constructing houses and some other building types. This is a precaution for the rare case where the burial was not done properly or unforeseen geological activities occur because a well-constructed Wood Vault should be as solid as normal ground after a period of soil settlement.

Another key step is ensuring the legal permanence of the Wood Vault. Some legal framework must be set up to ensure that the buried wood isn't disturbed on a century timescale or longer, even if the surface is utilized for other purposes or even sold to a new owner. There are several potential methods to ensure this. The first is to set up a legal entity to take control of the land containing the Wood Vault and be in charge of its maintenance and upkeep, possibly making use of the surface but with a primary objective of ensuring sequestered wood permanence. While this may seem simple, it can add other costs and ensuring the century long survival of such an entity is a significant challenge.

Another option is to set up a conservation easement on the land. A conservation easement restricts what land can and can't be used for, with common limits being natural land, agriculture, or sustainable forestry, none of which should interfere with the permanence of sequestered wood. Easements are usually set up on a case-by-case basis, so the preservation of wood could be made an explicit tenet of the easement. Thus, even if the property is eventually sold, the permanence of sequestered wood is legally guaranteed. This approach is much more likely to survive the century scale required for sequestration projects. The easement also has the effect of lowering land values and property tax burdens, reducing expenses if the sequestration entity decides to actively run or manage the Wood Vault after the final burial and capping of sequestered wood. Additionally, buying insurance for possible loss of the stored wood due to unforeseen circumstances would also be useful, but this is an after-fact measure, not a design objective.

The economics of Wood Vault

Wood Vault with wood residuals as source

The cost of a Wood Vault facility includes land purchase, construction, and operation. Suitable land in the suburban US East, such as Maryland, ranges in value from $10,000 to $40,000 per acre, or $25,000–$100,000 per hectare, but can be as low as $2000 per acre in more remote regions. Construction cost will be dominated by excavation and sourcing of clay (should local soil not suitable), estimated at a unit cost of $4/m^3 and $15/m^3, respectively [10]. Work and quality control (QC) will also be a large budget item. Transportation of wood from source to the facility is assumed at a rate of $5/ton for a 25-mile haul [6]. This cost would be zero, or even negative if the facility acts as a waste disposal station which typically is paid for a tipping fee to accept urban solid waste.

Table 3 Recurrent cost each year for a Wood Vault unit

Carbon stored per year	total cost per unit cell per year	Land purchase	Construction	Operation (staff, management, monitoring)	Transportation	Size of a unit cell
100,000 tCO_2+	$1.2–1.8 million	$25–100K	$700K++	$500K	$0–500K+++ ($5/ton-25mi)	1 ha (2.5 acre) 20 m high 5 m deep

+ Collected from wood residuals in a surrounding region of 50 km by 50 km

++ Excavation = $200K ($4/m^3 × 50,000m^3); material/clay = $300K ($15/m^3 × 10,000m^3); work/QC = $200K

+++ Transportation would be at no cost to the facility if accepting wood

Table 4 Economics of the facility after filling 10 Wood Vault units (assuming urban wood residual collection as the only source)

Total carbon sequestered	Market value at an assumed price $50/$tCO_2$	Total cost	Recurrent cost	One-time cost (Equipment, building)	Land purchase
1 $MtCO_2$	$50M	$13-22M ($13–22/tCO_2)	$12–18M	$1M	$1–4M (40 ha) +

It also applies to collecting wood at higher rate but in shorter time. Cost in millions of USD

+ Land is purchased up front and is larger than Wood Vault area: 40 ha (100 acre) area is assumed at a cost of $1-4M ($10-40K/acre, and cost less in remote region), with 10 ha used for Wood Vault, and extra 30 ha for operation or future use

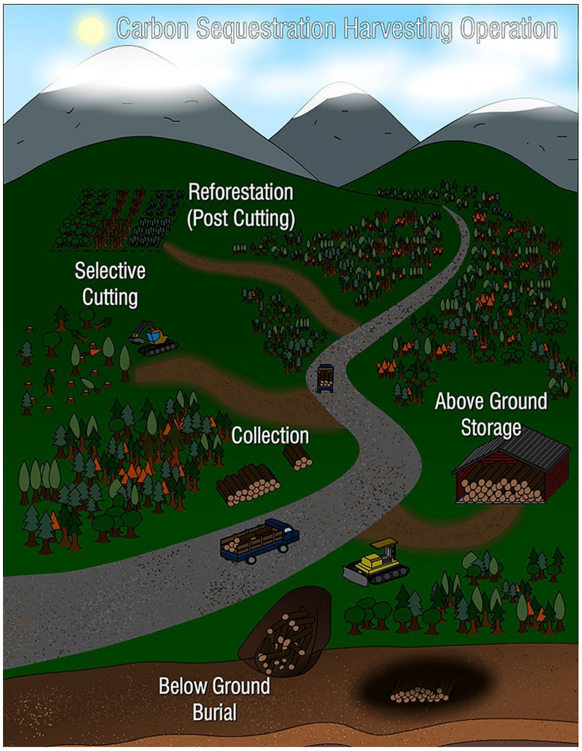


Fig. 12 A vision of Wood Harvesting and Storage operation, showing how an operator can move crew and machinery around a large region from one plot to the next. The burial can be done in-situ or the wood can be transported outside the region to a large facility. Illustration by Wesley Tse of the Gemstone Carbon Sinks Team

Altogether, the estimated cost for the 1 ha Wood Vault unit will be $1.2–1.8 million for storing 100,000 tCO_2 in 1 year, at a price of $12–18/$tCO_2$ sequestered (Table 3).

10 such Wood Vault units, as in the urban wood residual collection case after 10 years, or over a larger area in one year, would sequester 1 $MtCO_2$. The total cost, now including up-front and other one-time costs will be $13–22 million (Table 4). The cost of sequestered carbon is $13–22/$tCO_2$.

If the wood is sourced from residues from fuel treatment, logging, or forest clearing from commercial development, all incurring little extra cost, the total wood availability will be much higher. Similarly, if wood is sourced from larger area than 2500 km^2, a larger source will be available at somewhat higher transportation cost. In such cases, the facility can achieve higher carbon sequestration rate in shorter amount of time.

Wood Vault with harvested wood source and transportation

The above example assumes a central facility that collects only urban wood residuals. The cost estimate can serve as a basis for other types of storage and wood collection methods. For example, should wood be sourced from managed forests in the surrounding region, additional cost of raw material, harvest, and transportation should be included. Assuming a stumpage price of $5/tonne, harvest and transportation of $15/ton [3, 11], this adds $20 to the basic scenario above ($13–22/tonne) whose high range includes transportation. Also importantly, land and operation cost would be significantly lower if co-siting with an existing landfill, but this scenario is not used in our estimates here.

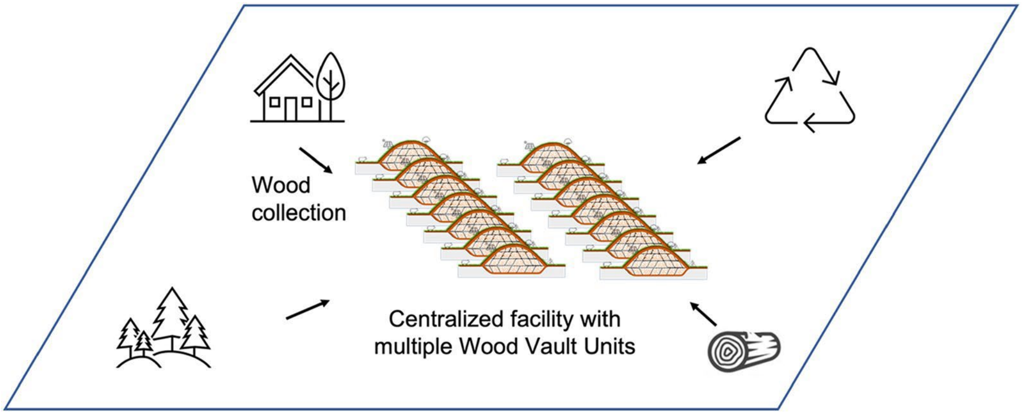


Fig. 13 A centralized facility that hosts multiple Wood Vault Units (WVUs)

Altogether, we give a cost range of \$10–50/tCO$_2$ with a mid-value of \$30/tCO$_2$ for carbon sequestration in large Wood Vault storage facilities. The large range arises mostly from the following factors: (1) whether the wood source is 'waste' (at little or no cost) or harvested (higher cost), (2) transportation distance, (3) local soil and environmental condition and (4) land cost of the storage facility. Our estimate does not include transaction cost in a carbon market.

Put it all together: operational considerations

Operation

To summarize, we illustrate in Fig. 12 an envisioned operation. The operator, say a 'WHS company' crew with machinery goes around, harvesting/collecting wood, then bring the wood to burial sites or stockpile before burial operation. A variety of specific operation styles can be envisioned based on wood availability (Type-A vs Type-B), burial site (large facility further away, or small facility mostly in-situ).

A unit for Wood Vault: implication for the scale of operation

To facilitate macro-scale planning, bookkeeping and carbon accounting, we propose a unit for Wood Vault, simply named Wood Vault Unit (WVU). One WVU is defined as a semi-permanent carbon storage containing 100,000 tCO$_2$ equivalent of wood.

This simple definition provides an intuitive linkage between carbon accounting and the physical size of a Wood Vault, among other potential usages. It has the following attributes:

- A Wood Vault of 1 WVU stores 100,000 tCO$_2$ equivalent of wood, by definition.
- A Wood Vault of 1 WVU contains an effective wood volume of 100,000 m^3, occupying 1 hectare (100 m by 100 m, the size of two soccer/football fields) surface area, with an effective height/depth of 10 m, but actual height/depth of 20–30 m to account for the space in between the woody biomass occupied by backfill material, water/air and the geometry of the burial mound. These numbers are only approximate, and a design can be wider and lower where land availability is not a tight constraint.

For an application example, a target of 1 MtCO$_2$ y^{-1} sequestration rate needs to construct 10 WVUs per year (1,000,000/100,000 = 10), thus requires 10 ha of land surface. Up to 2–3 times more storage capacity is possible if the units are stacked vertically (Super Vault). Because a 1 MtCO$_2$ y^{-1} rate can be satisfied with a wood sourcing scenario of medium harvest intensity from 2 counties in the eastern US (Table 1), which we assume to be a likely scenario in the next few decades, a 300 ha facility will store 30 MtCO$_2$ in 300 WVUs, after 30 years of operation with wood sustainably sourced from the surrounding 2 counties (Fig. 13). We note that 300 ha is the size of a medium-size landfill. For example, the Brown Station Landfill at Prince George's County, Maryland occupies 850 acre (340 hectare).

The implication of the above analysis is that a Wood Vault facility can be deployed sustainably at a scale an order of magnitude smaller than current landfill operations. Should the local government be the sole operator of all the Wood Vaults, simply co-siting with current landfills and sharing existing machinery and workforce will be enough to utilize its sustainable wood source, with the great benefit of minimum additional infrastructure, and high cost-efficiency. Should private entities such as individual farmers, forest owners, or corporations develop and operate the facility, the overall cost may be

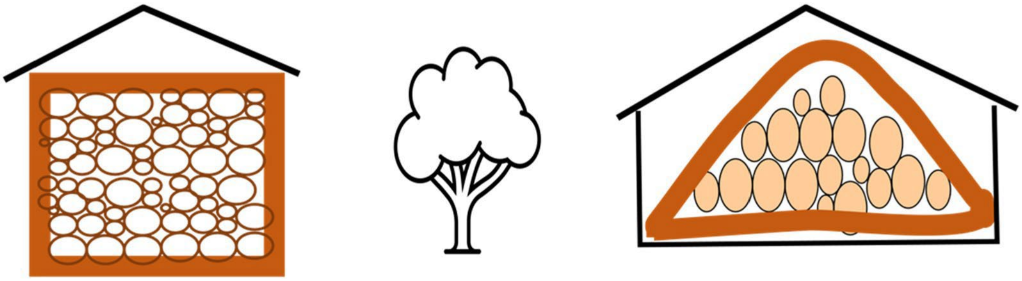


Fig. 14 Baby Vault is a small shelter that can be built manually or with light machinery, using wood sourced from the immediate vicinity. The enclosure can be constructed with traditional adobe technique using local material of mud and straw. An underground version is also possible. Version Baby1 (Left) constitutes vertical walls that may be constructed before filling in logs, while Version Baby2 (Right) piles up logs naturally first before covering with mud or clay

higher, but it should still be viable even with the current carbon market price.

For a target of 1 $GtCO_2$ y^{-1} sequestration, we need 1000 such Wood Vault facilities, compared to more than 6000 operational landfills in the US. Since the above assumed medium harvest scenario that provides 1 $MtCO_2$ y^{-1} available woody biomass is suitable for typical forested area and US forest area 3 Mkm^2 is about 1/3 of the country, we estimate that the US alone can contribute 1 $GtCO_2$ y^{-1} sequestration rate by operating a network of Wood Vault facilities on a scale 10–20% of current operating landfill facilities.

Baby Vault: the small operator model and an opportunity for technology innovation

Our analysis so far has assumed a 'developed country model' in a 'big operator mode' for its efficiency and economy of scale. In particular, we assumed the availability of machinery needed for logging, transportation, excavation, and burial on a large facility, supported by a corporate-style business operation. However, in many developing countries such as in Africa, the southern Amazon, or Southeast Asia where there are great opportunities for wood sourcing, including areas with potential for reforestation, this is simply not possible, at least not in the near term.

We propose a 'small operator model', as envisioned originally by Zeng [3]. In this operation mode, wood is sourced and stored in-situ. The relatively small wood collection area means that the stream of wood availability is also small. With manual and animal power, wood transportation quickly becomes prohibitive at longer distance. This offers the opportunity for innovative technologies such as solar-powered all-terrain robots that can haul logs, replacing traditional labor done by horses and mules. Rechargeable small chainsaw is already widely available (NZ has one at home). Similarly, small and low-cost rechargeable excavator/backhoe can also play an important role. In general, a potential WHS carbon sequestration market can provide the impetus to bring down the cost of existing technology or stimulate new technology in forestry operation from cutting, delimbing, forwarding, as well as various aspects of Wood Vault construction.

Because wood stockpile permits only temporary storage before significant degradation occurs and now with wood collection from immediate vicinity, wood is best buried/stored in a relatively small Wood Vault, which we will call 'Baby Vault'. Baby Vault is not necessarily a new type of Wood Vault, but just a smaller version of, for example, Tumulus (Version 1.1), Barrow (Version 1.2) or Shelter (Version 4). The Shelter-style Wood Vault (Version 4 or Version 6.2 DesertVault) seems ideal as Baby Vault for developing countries, run by individual farmers, co-operatives or other small operators (Fig. 14). It does not require digging which is labor intensive without machine. Piling the logs above ground is much more practical, though the height may be limited, thus using somewhat more land-surface area compared to a large burial mound.

For Shelter-style Baby Vault, an adobe/cob enclosure is particularly attractive because of the easily sourced local material and the practical experience of building/maintaining such structures across many human cultures. A straw-mud walled structure can be built, wood can be placed in it over a suitable period of time, then finally enclosed on the open side and on top which is sheltered with a thatched roof in wet climate (Fig. 14). The walls need to be sufficiently thick to be both structurally sound and prevent erosion and animal intrusion. Vines may grow which can be cut back or left alone, though trees should not be allowed on top. Long-term maintenance is needed but is expected to be minimal if the Baby Vault is constructed properly. We also note that, Baby Vault is not

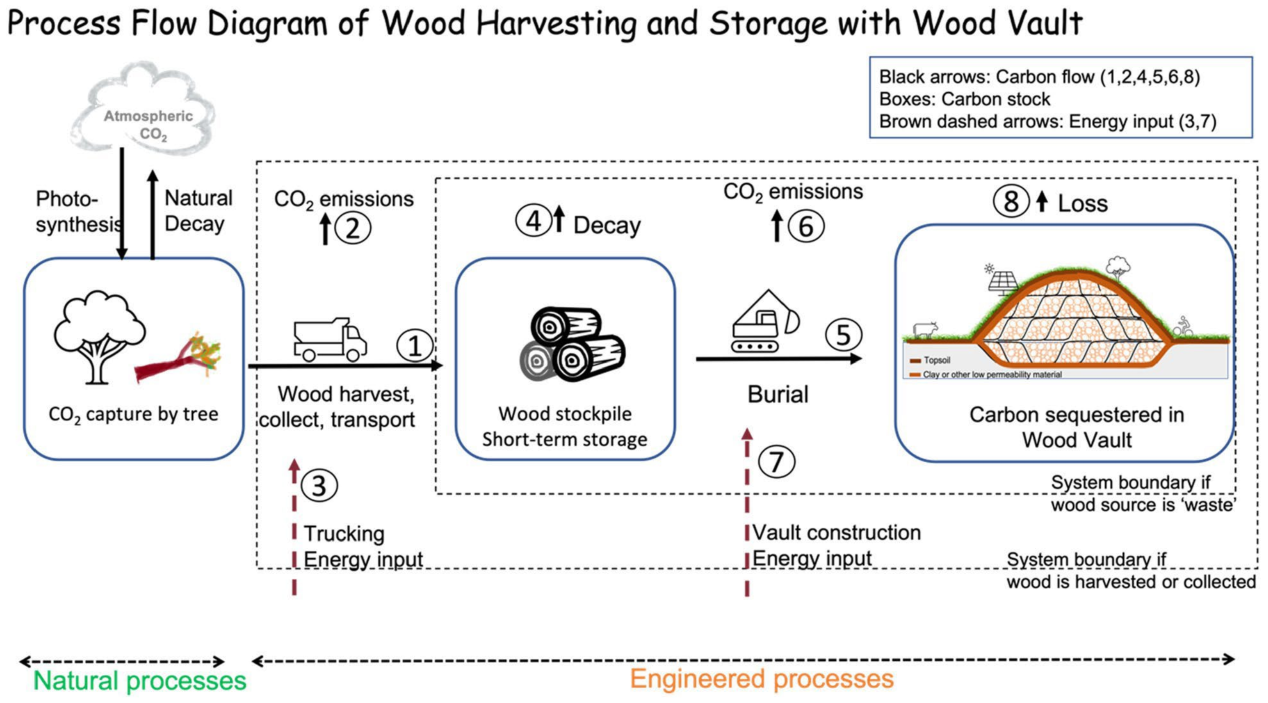


Fig. 15 Process flow diagram (PFD) of Wood Harvesting and Storage with Wood Vault. The Natural Processes and the Engineered processes are clearly separated, defining the engineering system boundary. The two types of wood sourcing (wood residual reception or Type-A vs. harvesting or Type-B) correspond to somewhat different system boundaries. WHS takes advantage of 'free' photosynthesis and a simple engineering process to minimize wood decay, thus offering an effective, efficient, and low-cost Nature-Engineering combo solution for semi-permanent carbon sequestration

limited to developing countries, and indeed we see great potential in developed countries as well where an individual land owner can carry it out independently.

In-situ storage on the forest floor, near the logging landing site, or on the roadside where wood is harvested has the advantage of minimizing transportation cost and other benefits [3]. Indeed, Zeng [3] estimated a cost of \$14/tCO_2 for such in-situ operation. A disadvantage is the cost of moving machinery to the site and other overhead costs of each operation. It may be most efficiently carried out by an operator who continually goes around a certain large area consisting of many smaller sites with multiple ownerships, moving from one plot to the next on the time scales of days to weeks to minimize cost of transporting machine. The crew can return to the same site after some years for another harvest (Fig. 13). Materials and machinery can be planned out and used most efficiently this way. In practice, there is likely going to be a continuous spectrum of possibilities between small-scale in-situ burial and large-scale facilities.

Process flow diagram: a Nature-Engineering combo method

To close the loop of a full-scale operation from wood sourcing to burial, we show the process flow diagram (PFD) of WHS with a central storage facility Wood Vault (Fig. 15). The system boundary depends on whether the wood sourcing is 'waste' reception (Type-A) or harvested/transported (Type-B). It is also possible to have an operation somewhere in between Type-A and Type-B, for example, harvesting is already done, but the Wood Vault operator needs to collect wood from a remote site. Also, a wood stockpile for short-term temporary storage is often needed to strike the balance of efficiency/cost and minimizing decay before burial. The diagram lends itself naturally to full life cycle analysis (LCA) should the project-specific data input be provided for carbon and energy flows 1–8.

The fact that CO_2 capture via natural photosynthesis is 'free', an evolutionary wonder from an ecological perspective, puts this process outside the engineering system boundary. This is a great advantage of WHS relative to purely engineered methods such as Direct Air Capture (DAC) where CO_2 capture accounts for the lion's share of cost and energy input. Of course, this advantage is shared by all nature-based methods, thus their popularity. However, the main shortcoming of most nature-based methods is that the permanence of such carbon sinks is generally too short compared to the climate change time scale of hundreds of years. This shortcoming is overcome in WHS by burying wood underground or other means to ensure semi-permanent preservation. This requires dedicated facility carefully engineered to prevent decomposition and an operational process flow that is practical, efficient, and low cost. In summary, WHS is a unique hybrid Nature-Engineering method that combines the advantages of Nature and human intervention, each of which is inadequate for solving the climate problem if acting alone.

How to do it right: Hit the road with model projects

The best method to ensure the durability and semi-permanence of stored wood is to make sure the project is done right at the early stages of Wood Vault construction. If a Wood Vault is found faulty later, reinforcement is possible if the cost is low enough. This 'reinforcibility' should be an important criterion in determining the Wood Vault type of choice. For instance, a Wood Vault constructed in an adobe mud enclosure can be easily repaired should it crack. On the other hand, wood logs sunken to remote ocean depths are left completely to forces of nature as it would be too expensive to intervene at scale. Thus, knowing the processes that determine the timescale of a particular Wood Vault construction with our best knowledge, we can make the decision based on our climate goal (which is not necessarily clearly known on long timescales; see Sect. 5) will be critically important before we implement a specific type of Wood Vault at large scales. In this respect, the terrestrial based methods generally appear to be safer in the sense that they give us the opportunity to reinforce and modify in the future. To put it another way, higher standards will be needed for Wood Vaults that cannot be maintained and reinforced cost-efficiently.

We therefore wish to see the community to start as soon as possible a suite of 'model projects' that encompass the proposed Wood Vault types in representative environments, plus any other possible types we have not discussed here. In planning and conducting these model projects, we will gather interdisciplinary teams of experts and practitioners to figure out the best practical way of Vault construction that ensures durability for the specific environment at low-cost. These projects can serve as the 'blueprints' for world-wide implementation of WHS. Our current knowledge can already inform reasonable decision because there is no truly unknown science or technology in the WHS method, although the interdisciplinary knowledge base needs to be put together to tackle this problem effectively. Iterations will be needed to refine these blueprints. This is also where governments, academics and the scientific community can and should play a key role.

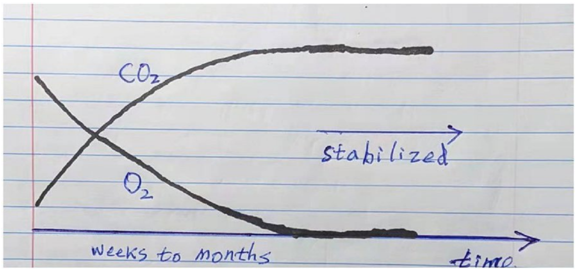


Fig. 16 The expected changes over time of O_2 and CO_2 after the enclosure of a Wood Vault designed to produce anaerobic condition. The gas concentration levels stabilize after a few weeks to months as the Wood Vault enters a quasi-geological semi-permanent state of preservation

Monitoring and verification

After the construction of a Wood Vault, monitoring and verification may be needed for getting carbon credits that can be traded in a carbon market, among other reasons. We propose the following steps:

- Use low-cost sensors to monitor the environment inside the burial chamber, including CO_2, O_2, CH_4, pH, temperature, humidity, and water table. For anaerobic type of Wood Vaults, after Vault enclosure, we expect the initial oxygen level to drop to zero on the timescale of weeks to months, and CO_2 to rise to a high level as a small amount of organic matter is consumed by fungi/bacteria/insects that are ubiquitously attached to or embedded in the original woody biomass (Fig. 16). For a well-constructed Wood Vault, we don't expect CH_4 release (see discussion in Sect. 5) so it should remain zero. Such low-cost sensor capability has been developed in recent years, including at our lab [12, 13].
- These sensors can be built using an Internet of Things (IoT) approach that transmits data to a remote server. Software can be designed to pick up anomalies in various data indicators, for example a rise in oxygen or methane, and action can be taken if practical. The information on the status of the burial chamber also provides data input to the carbon accounting system useful for calculating carbon credit discount (below).
- A powerful analog method can be used to predict future preservation by conducting 'controlled' experiments, similar to the unintended 'natural' experiments from archaeological and geological evidence (Sect. 5 below) that provide real-world evidence of long-term wood preservation. For selected sample projects, periodically collect samples directly from the Vault, observe and analyze the status of wood preservation. The corner or cell of the Vault can be enclosed again, leading to a slight modifica-

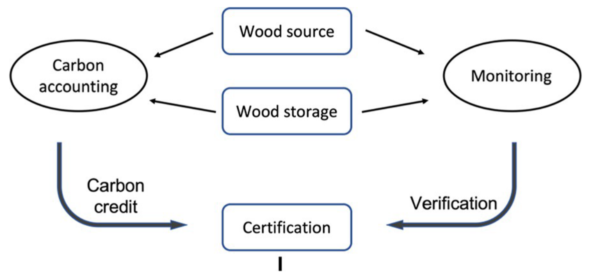


Fig. 17 Monitoring and verification, carbon accounting, certification, carbon market for WHS

tion to future preservation. We can then build predictive mechanistic models that include process understanding, validated by these 'controlled' experimental data as well as the data from the 'natural' experiments. This is akin to how we build predictive climate models that are validated by paleo and modern climate data. By the simple logic of 'analog', similarly constructed Vaults in similar environment will have similar degree of preservation as in a 'control' experiment. In this respect, a failed Wood Vault provides equally valuable information on how Not to construct a Wood Vault that way. The 'model projects' proposed above can best serve this analog purpose.

Full carbon accounting: sustainability and a role for data science

It is critical to conduct a full carbon accounting for the purpose of carbon credits. In the case of residual wood utilization, the stored carbon should be relative to a baseline that corresponds to waste wood decomposition over shorter time spans than the semi-permanent storage (Fig. 2). When wood is sourced directly from live forests, the accounting is more complex. Initially there is a loss of carbon after harvest. It is only after forest regrowth that the combined regrowth and stored carbon exceeds the baseline (Fig. 3). Ensuring the sustainability of wood sourcing, in light of many other current and possible uses of woody biomass, is a key to success for WHS.

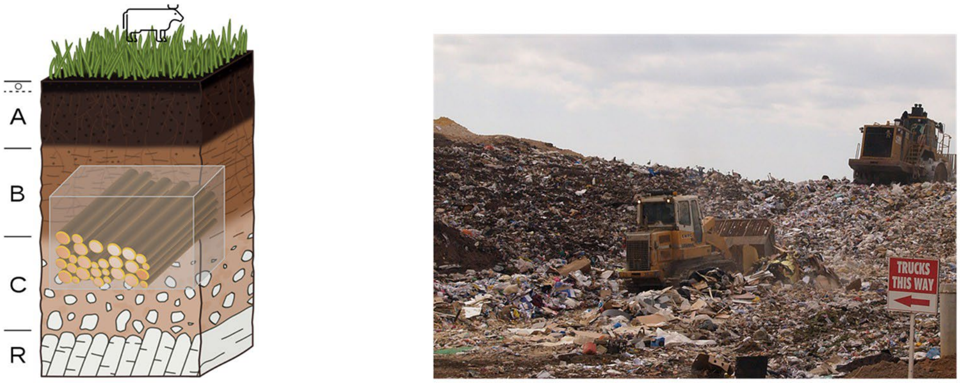
In a world where WHS is fully implemented, millions of Wood Vaults may be created. They need to be carefully monitored and maintained. Databases need to be built to track these Wood Vaults and their attributes, including: quantity (tCO_2), quality (durability), sustainability (wood source, Vault construction environmental impact, etc.), location, ownership, and other details. Such information not only provides the foundation for carbon credit trading in carbon markets, but also the necessary information for monitoring and verification, ensuring sustainability, maintenance, insurance, unforeseen events, and potential future use. The information size will be small compared to the data we typically handle these days, but the quality, fairness and content matrix need to be worked out. The full process of monitoring and verification, carbon accounting, certification, carbon market for WHS is illustrated in Fig. 17.

Durability and permanence of stored wood

Wood Vault is not landfill: biological, physical and chemical factors impacting wood degradation in a Wood Vault

On the engineering side, the construction of a Wood Vault bears some similarity to a modern sanitary landfill as both involve digging and capping, so that we can use landfill data for estimating the economics of a Wood Vault. However, there are fundamental differences between a Wood Vault and a landfill, as illustrated in Fig. 18, including:

- The job of a landfill is to dispose of waste, including highly decomposable food scraps, reactive toxic chemicals, heavy metals that need to be carefully controlled and regulated. In contrast, a Wood Vault buries only clean natural vegetation which is valuable (for carbon sequestration now, with the option for biomass and bioenergy reserve in the future)
- The main objectives are the opposite of each other: a landfill is built to encourage fast decomposition and gas collection, while a Wood Vault is built to prevent decomposition altogether. This requires different design principles and different ways of material use.
- Methane (CH_4), a potent greenhouse gas, is often generated in a landfill as methanogenic bacteria digest organic waste under partially anaerobic conditions. Such concern has been raised against the wood burial concept by citing what happens in a landfill [14]. However, this aspect of landfills does not apply to a Wood Vault. Furthermore, even in landfills, wood, unlike food, is often known to be well preserved, as shown by excavated wood samples from old landfills and modeling [15–17], even inside lab bio-reactors designed to encourage optimal bacterial activities [18, 19]. Thanks to such meticulous research, the IPCC has recently drastically lowered the emission factor of wood in landfills [20]. A precondition for CH_4 generation in landfills is that there is sufficient concentration of nutrient such as food scrap to supply the substrate for anaerobic bacteria to thrive. This is not the case in a Wood Vault.
- Moreover, our standard Wood Vault design calls for total anaerobic condition in the sub-terranean burial



Wood Vault
Anaerobic
Clean wood, little nutrient
'Cold'; CH_4 negligible
Stabilize after weeks-months
of minor decomposition

Landfill
Aerobic to partially anaerobic at depth
Food scraps: high nutrient; chemical reactants
'Hot': bioreactor; CH_4 substantial
Stabilize after years-decades
of bio/chemical activities

Fig. 18 Wood Vault is fundamentally different from landfill. Photo credit: Ashley Felton

chamber (with other designs having similar mechanisms to inhibit organism growth), reasoning that the lack of oxygen (O_2) excludes activities of the main 'wood-eating' organisms such as fungi and insects. Then the main remaining risk to buried wood is anaerobic bacteria. Fortunately for our purpose, they are known to be unable to digest lignin, the glue-like layer that protects the cellulose structure [18], as evidenced by the difficulty of making cellulosic ethanol for biofuel where the challenge is the opposite: to get rid of lignin protection [21]. This explains why wood decomposition is slow in landfills. In a carefully designed and maintained Wood Vault, we expect the decomposition to drop to essentially zero after a short initial period during which any oxygen mixed into the wood-soil matrix initially is quickly consumed (Fig. 16).

- Decomposition of organic waste as well as chemical reactions by aluminum and other reactive materials in a landfill can lead to a 'hot' interior that typically reaches 40–50 °C (X. Wang, personal communication). The interior of such a landfill is essentially a 'slow cooker' that accelerates biological degradation and chemical reaction. Even in such 'worst' condition, wood is still often found to be reasonably well preserved (above). In contrast, in a Wood Vault, only 'clean' vegetation is buried, and there is little nutrient and substrate for bacteria to establish colonies at first place. A Wood Vault provides a 'cold' and fully capped environment without oxygen. This realization should be sufficient to relieve the concern of 'smoldering wood' or 'smoldering garbage' sometimes seen in open dump or poorly covered landfills. The key is to 'do it right'.
- Whole wood logs are expected to have much higher durability than smaller pieces such as woodchips, as evidenced by multi-year to multi-decadal time scales (depending on the climate condition) needed to degrade whole dead trees on a forest floor, while smaller pieces such as twigs degrade much faster. The reasons are:

  - In both anaerobic or aerobic conditions, the degradation starts from surface and spreads inward very slowly. For a tree log, the spreading of fungal hyphae and bacteria is generally fastest along the cambium layer and inner bark where phloem contains highest concentration of nutrients. Secondly, they can spread along the vessels in the longitudinal direction or rays in the transverse direction from the cut ends or wounds. Certain tree species have high concentration of sap that prevents vessel penetration, thus minimizing this pathway of degradation.
  - In anaerobic condition, because the lignin layer covers the cellulose structure which is what anaerobic bacteria can attack, reduction in the wholeness of wood, leaves vulnerable entry points for bacteria to enter. Keeping the physical integrity thus enhances its durability.

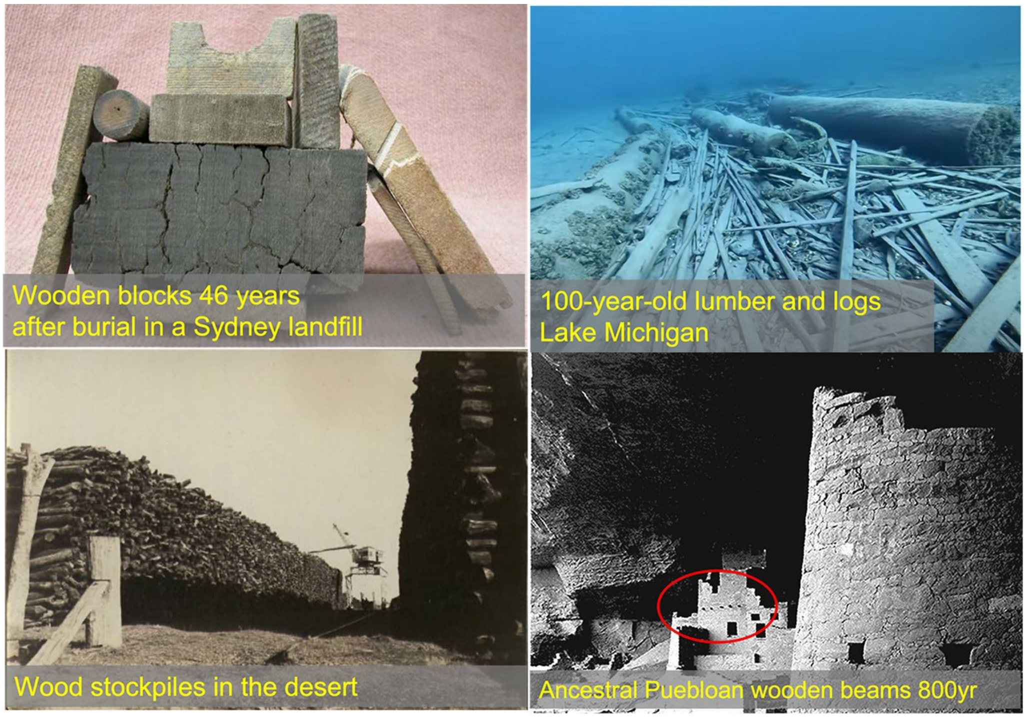


Fig. 19 Preserved wood of human origin: decades to centuries. Photo credits: F. Ximenes, Chris Roxburgh, unknown via Matt Pearson, Ansel Adams via National Archives and Records Administration

Physical transformation of buried wood in a Wood Vault is unlikely due to the lack of light whose UV spectrum is known to degrade exposed exterior of wood structures. As for temperature, it is 'cold' (in comparison with an active landfill), same or slightly higher than ambient, and so is pressure. Should the wood preserve on geological timescales, it may be transformed (carbonized), but the carbon will still largely remain in place. Geological movement such as seismic activities could also potentially bring wood to surface or bring in oxygen. Such occurrence can be mitigated, but in practice, it is unlikely to be a major concern because of the rarity of such occurrence on the human-induced climate change timescale and the distributed nature of the WHS method.

A less clear aspect is potential chemical transformation. For example, a highly alkaline or highly acidic environment is known to damage wood (and many other things!). However, most natural soil environments do not deviate significantly from pH neutral. It is also possible that organic compounds such as terpenes in sapwood can be more easily modified by chemical or biological processes, especially in wet burial environments for tree species with less resin where water can infiltrate into wood vessels and leach out organic compounds inside. However, modification doesn't necessarily convert the organic matter into CO_2 which would subsequently escape back into the atmosphere. If conversion to CO_2 indeed happens, albeit likely slowly, this fraction of carbon would be lost, but the main wood structural ligno-cellulose carbon should remain. In mineral-laden subterranean wet/aquatic environments, minerals would slowly infiltrate wood to seal off the vessels, likely leading to better preservation. While research will be needed to clarify these complexities, carbon accounting for credit can conservatively exclude carbon stored in such organic compounds which only accounts for a small fraction of wood carbon. Thus, the goal of preservation is not necessarily to keep the wood like fresh wood, but can permit transformation to a stable state that maintains wood integrity and keeps most of the carbon in place semi-permanently.

Durability: lessons from archaeological and geological evidence

In our view, the most compelling evidence of the potential for long-term whole wood preservation comes from 'natural' experiments where ancient wood of archeological or geological origin, was found in good condition after hundreds, thousands, tens of thousands, hundreds of thousands, or even millions of years. A few examples are listed below (Figs. 19, 20, 21):

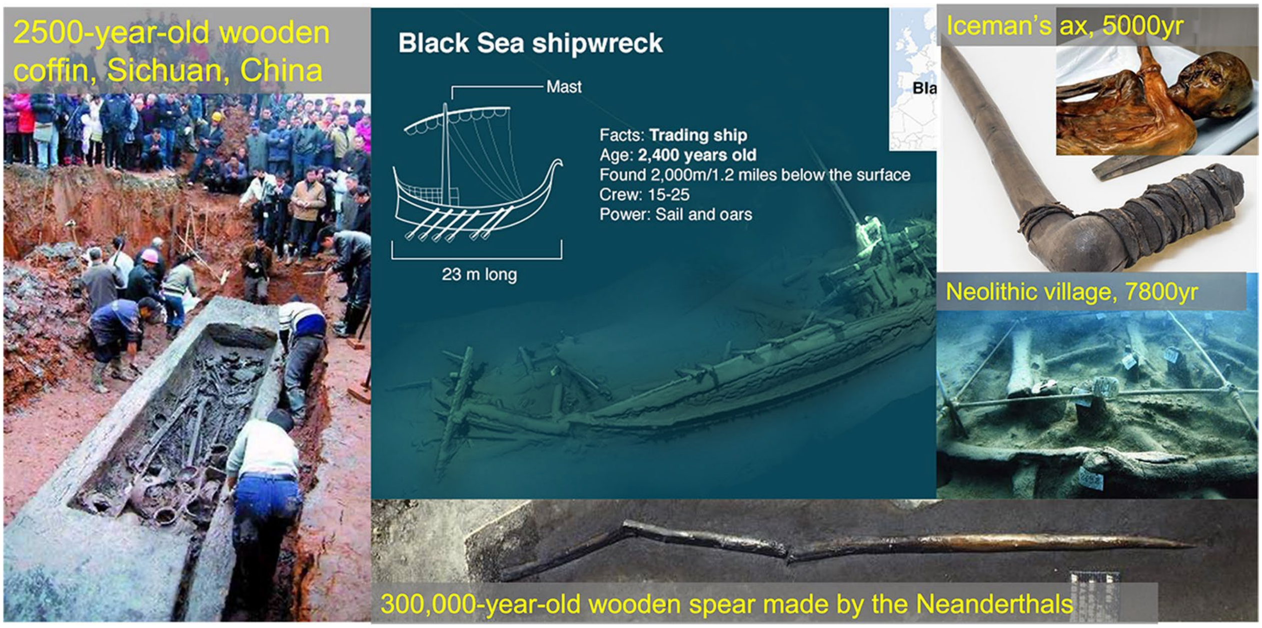


Fig. 20 Ancient wood of human origin, thousands to hundreds of thousands of years. Photo credits: china.org.cn, BBC, Museo Archeologico dell'Alto Adige, Maria Antonietta Fugazzola Delpino, P. Pfarr

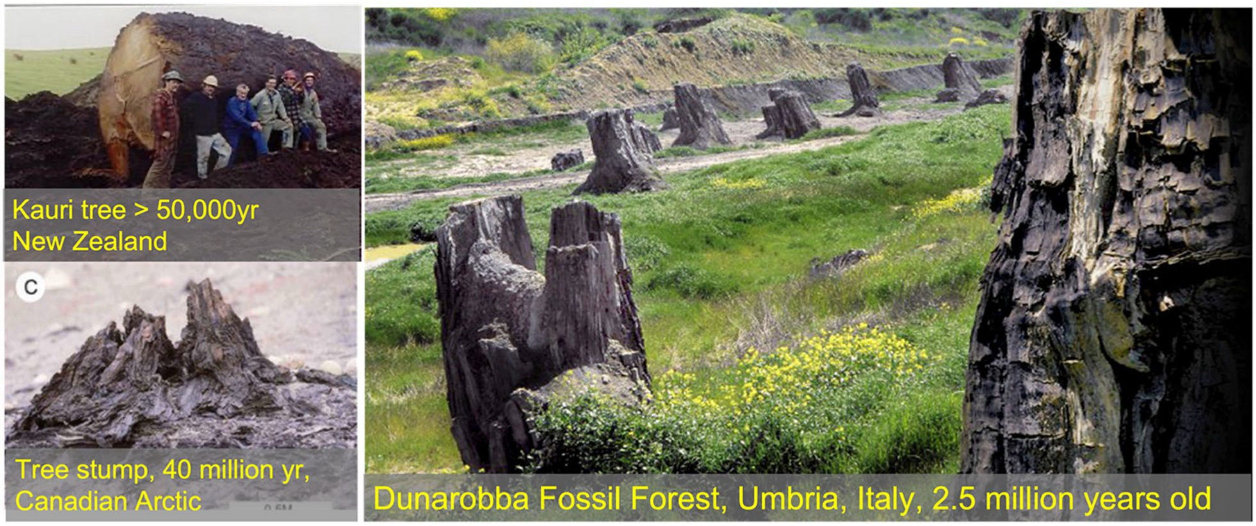


Fig. 21 Ancient wood of geological origin. Photo credits: unknown, William Hagopian via G. Mustoe, umbriatourism.it

1) Wooden blocks in an Australian landfill after 46 years of burial [15]. (Low oxygen)
2) 100-year or older logs found at the bottom in many rivers/lakes around the world. (Anaerobic due to water logging)
3) Stockpiles of wood in the semi-arid region of America West. (Dry)
4) 800-year-old Wooden poles in Anasazi (Ancestral Puebloan) structure, embedded in stone-mud adobe, Cliff Palace, Mesa Verde National Park, Colorado. (Dry)
5) 2500-year-old wooden coffin from the Warring States Period (475–221 BC) found 1.5 m below the surface in red clay in Sichuan, China. (Anaerobic due to clay sealing)
6) 2400-year-old Greek Merchant ship sunken at the bottom of the Black Sea. (Low-oxygen bottom water)

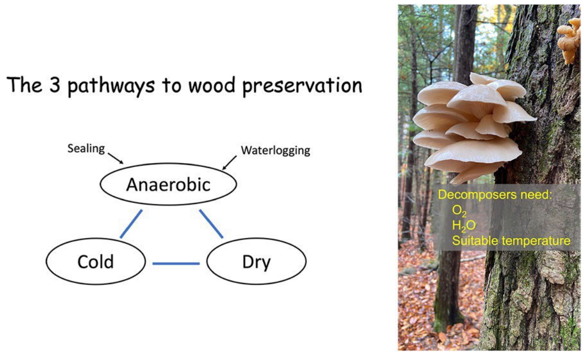


Fig. 22 Three major pathways to prevent wood decomposition: (1) Anaerobic condition that can be created by sealing with low permeability material such as clay or waterlogging; (2) Cold; (3) Dry. Any one of these 3 conditions, if ensured in high fidelity, will be sufficient to preserve wood. This is fundamentally because the main wood decomposers such as fungi and insects need all three ingredients to survive and thrive: oxygen, suitable temperature, and moisture. The 7 versions of Wood Vaults are designed to realize one or more of these 3 pathways. Photo credit: Susan Pike

7) 5000-year-old human body, Ötzi the iceman, together with his wooden tools and undigested food in his stomach, found in an Alpine glacier, Italy-Austria Border. (Cold)
8) 7800-year-old Neolithic settlement submerged under Lake Bracciano, Lazio, Italy. (Anaerobic due to waterlogging and silt)
9) The 300,000-year-old wooden spears used by the Neanderthals, Schöningen, Germany. (peat/lignite)
10) Ancient Kauri trees older than 50,000 years (beyond carbon dating) excavated from wetland 1–2 m below surface in New Zealand. (Anaerobic)
11) 2.5 million-years-old wood stumps found in a clay quarry in Umbria, Central Italy (anaerobic due to clay sealing)
12) 40 million years old wood stumps freely standing on a beach at Axel Heiberg Island, Canadian Arctic. (Currently cold, likely preceded by past waterlogging condition during warm periods)

Pathways to semi-permanent wood preservation

The examples listed above are mostly associated with clay-enclosed or water-logged anaerobic burial environment and the rest with cold or dry conditions. This is consistent with the basic biology of decomposition because the main decomposers such as fungi and insects need all of the following environmental conditions to survive and thrive: (1) oxygen, (2) suitable temperature, (3) moisture. This piece of fundamental biology leads to 3 major pathways to prevent wood decomposition (Fig. 22): (1) Anaerobic, (2) Cold, (3) Dry.

Any one of these 3 pathways, if ensured in high fidelity, will be sufficient to preserve wood semi-permanently. The goal of Wood Vault design is to realize one or more of these 3 pathways. Thus, our 7 versions of Wood Vaults can be classified based on these 3 environmental factors:

1) *Anaerobic* Version 1 (burial mounds), Version 2 (Underground), Version 3 (Super Vault), Version 4 (Shelter, if sealed), Version 5 (AquaOpen and AquaVault), Version 6.2 (DesertVault),
2) *Dry* Version 4 (Shelter, if non-sealed/ventilated), Version 6, Version 7 FreezeVault (freezing condition is simultaneously dry in absolute humidity)
3) *Cold* Version 7 FreezeVault

We note that the best waterlogging conditions are generally accompanied by silty environments such as bogs, wetland and peatland. In contrast, environments with free water movement such as at the bottom of the Black Sea, the Baltic Sea and the Great Lakes is likely to have low enough oxygen levels to enables wood preservation to some degree, but may or may not be anaerobic enough to ensure the long-term preservation needed for climate purpose. The relatively anaerobic bottom water of the Black Sea is caused by vertical stratification, but free-flowing water will inevitably have some amount of mixing, no matter how small it is. An exception is where the sedimentation rate is high so the wood logs can be buried before decay, as illustrated in Wood Vault Version 5.1 (AquaOpen, Fig. 10). Our AquaVault design calls for an artificial wrapping which may be able to circumvent the limitation of AquaOpen. Another caution is the lack of reinforcibility in the future discussed above. Thus, more caution is needed before large-scale implementation in aquatic environments. With our current understanding, terrestrial or wet + silty stagnant environments are more reliable at ensuring anaerobic condition.

In summary, for a Wood Vault enclosed in low-permeability soil, the anaerobic, stagnant sub-terranean environment ensures the durability of buried wood by minimizing biological, physical and chemical activities, ultimately leading to a preservation state of quasi-geological nature. We emphasize the critical importance of air-tight sealing, which leads to ultimate anaerobic condition. The initial oxygen at fresh burial is not a problem, because it would take the decomposition of only a tiny amount of organic matter to consume it.

Research with lab experiments and real-world projects will be needed to establish the best practice and define what is 'sufficiently-good' burial condition that balances cost and preservation under various soil and hydrological

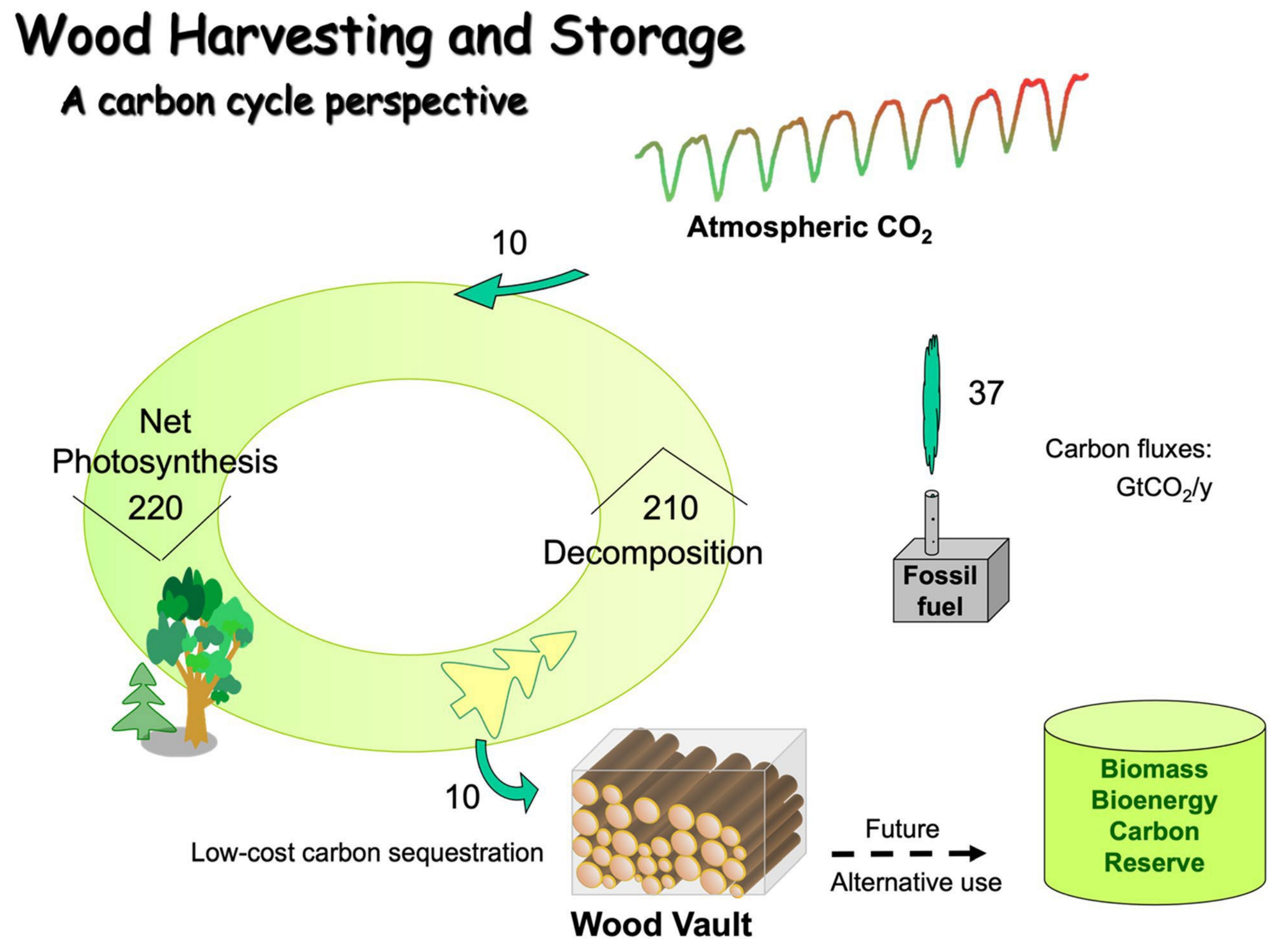


Fig. 23 Wood Harvesting and Storage (WHS) siphons off a sustainable fraction of the biosphere production in the form of harvested wood and stores it in engineered Wood Vaults to prevent decomposition, forming an effective carbon sink. WHS is a 'near-perfect' reversal of fossil fuel emissions by accelerating the slow natural biomass burial process of fossil fuel formation. The stored woody biomass is not only a carbon sink to mitigate current climate change, but also a valuable resource for the future that can be used as biomass, bioenergy, and carbon supply. A WHS carbon sequestration rate of 10 $GtCO_2$ y^{-1} is less than 5% of terrestrial net primary productivity (NPP: net photosynthesis)

settings. In this vein, we emphasize the paramount importance of the practicality of any proposed solution, including low-cost, wide availability of the material such as clay/mud, ease of operation, suitability for local people and stakeholders, and environmental and social impact.

Implication for the future: a thermostat to manage the climate system?

On longer time horizons, the stored wood is also a reserve of biomass, bioenergy and carbon, should future needs arise (Fig. 23). For example, intentionally preserved wood logs in mill ponds or lakes, or naturally buried logs in riverbeds and muddy soil are a priced raw material for making high quality furniture. In another example, the current bioenergy/wood pellet industry is hampered by issues of reliability and sustainability of wood supply, and WHS stored wood would provide a buffer, i.e., more predictable wood source on which a sustainable bioenergy industry can be based. A main practical constraint is of course the cost of this additional buffer step.

On even longer time horizon of thousands of years or longer, after current climate warming trend gets under control as the society transitions successfully to renewable energy, should the natural rhythm of ice-age cycles kick the Earth's climate into a glaciation period [22] (Fig. 24), that is, the opposite problem of current global warming, the buried wood can be taken out, used for energy while releasing CO_2 to keep the Earth's climate from diving into an ice age, particularly effective in light of the dominant role of CO_2-climate feedback on ice age cycles [23–25].

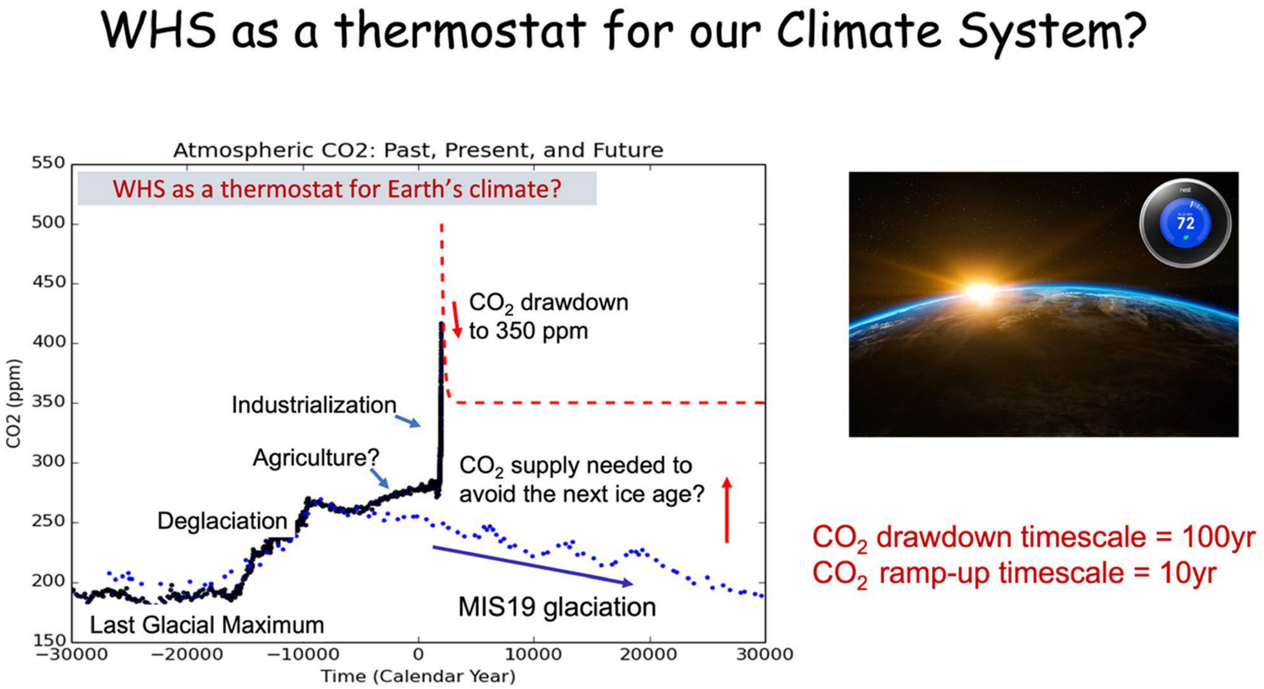


Fig. 24 WHS as a thermostat for managing the Earth's climate. Sustainable Wood Harvesting and Storage helps to remove CO_2 and locks it away semi-permanently as a biomass/bioenergy/carbon reserve, which can be used as a CO_2 supply should astronomical forcings drive the climate into an ice age in the future. CO_2 data from Antarctica ice cores [29] (800,000 years ago to 1999) and Mauna Loa Observatory (1959–2021) [30] plotted in black dots, while red dots indicate a future scenario of an exponential decrease from 500 to 350 ppm [31], starting from 2050 with an e-folding timescale of 200 years. Blue dots are CO_2 during the Marine Isotope Stage 19 (MIS19), shifted by 777,000 years as an analog of orbitally driven climate indicator, known as the Milankovitch Theory [22]. Identified periods in the CO_2 data include the Last Glacial Maximum (LGM), the penultimate deglaciation, a Holocene CO_2 rise of 20 ppm over the last 8000 years that has been hypothesized as consequence of agriculture (the Early Anthropogenic Hypothesis [25, 26]), and industrialization

This leads to a philosophical comment from the perspective of Earth system history. The current climate crisis has been caused by fossil fuel burning since the Industrial Revolution, on top of the disturbance to the global carbon cycle by agriculture that may have already delayed the inception of the next ice age [26]. These and other human activities are leading to a distinct geological epoch named the Anthropocene [27].

Wood Vault stores wood for carbon sequestration for now, while providing a biomass/bioenergy/carbon reserve for the future. The carbon reserve functionality alone allows WHS to be a useful management tool to adjust Earth's temperature, acting as a thermostat. The extent and speed at which this thermostat can work is not totally clear, but should be significant given the basic fact that the Net Primary Productivity (NPP) of the terrestrial biosphere is 220 $GtCO_2\ y^{-1}$ (60 $GtC\ y^{-1}$), of which woody biomass NPP is 70 $GtCO_2\ y^{-1}$ (one third of total) [3], and a sustainable harvesting potential for WHS up to 10 $GtCO_2\ y^{-1}$ [4] (less than 5% of NPP), compared to current fossil fuel emission rate of 37 $GtC\ y^{-1}$. The 10 GtC y^{-1} 'practical' potential has taken into account current land use and conservation needs. The time scale of CO_2 "drawdown time" is dictated by sustainable wood harvest rate and is on the order of 100 years (1000 $GtCO_2$ divided by 10 $GtCO_2\ y^{-1}$, assuming the target is to remove 1000 $GtCO_2$, or 130 ppm CO_2 concentration, approximately fossil fuel carbon accumulated in the atmosphere since Industrialization, excluding the carbon sinks [28]).

This CO_2 "drawdown time" is rather quick on geological time scale, suitable for removing CO_2 for the current climate crisis. In the opposite direction when the stored wood is used to increase atmospheric CO_2, the "ramp-up time" is probably on decadal time scale as we can burn the stored wood quickly if needed. Our discussion here only concerns a 'thermostat' for CO_2, not temperature which would involve additional slow processes such as glacial melting and rebuilding, with very long timescales, but inclusion of these factors is beyond the scope of this paper.

Conclusions

Wood Vault can be an efficient tool to lock down and sequester carbon reliably, using a variety of wood sources. Many sizes and versions of Wood Vault are possible. Most pieces of the technology already exist, but they need to be put together efficiently in practice. Some uncertainties need to be addressed, including how the durability and permanence of buried wood depends on detailed burial methods and burial environment, but the science and technology are known well enough to believe the practicality of the method. The high durability, verifiability and relatively low-cost makes it an attractive option in the current global carbon market.

Because WHS relies on trees to capture CO_2 from the atmosphere, but the rate of photosynthesis and land availability are limited, there is an opportunity loss if wood storage is not carried out as soon as the wood is available because it would otherwise decompose into CO_2. On the ground, this loss of opportunity manifests itself as waste wood rots in a landfill, hurricane damaged trees are collected and burned in a Florida neighborhood, trees are burned in a California forest, and so on. This leads to a SENSE of URGENCY. Assuming we can sustainably sequester 10 $GtCO_2\ y^{-1}$, but we delay action for 10 years, we would have lost the opportunity to sequester 100 $GtCO_2$.

Woody biomass stored in Wood Vaults is not only a carbon sink to combat the current climate crisis, but also a valuable resource for the future that can be used as biomass/bioenergy. The quantity of this wood utilization can be controlled carefully to maintain a desired amount of CO_2 in the atmosphere to keep the Earth's climate from diving into the next ice age. The CO_2 drawdown time is on the order of 100 years while the ramp-up time of this WHS thermostat is a decade.

In conclusion, WHS provides a powerful tool for managing our Earth system, which will likely remain forever in the Anthropocene.

Appendix

Wood availability: regional to global estimates

We consider two types of wood sources: (1) opportunistic sources; (2) harvest from sustainably managed forests. For opportunistic wood, Perlack et al. (2005) analyzed data from US Forest Inventory Analysis (FIA) in the context of biomass for energy use. We extracted information on unexploited wood sources from the current forestry wood use, summarized in Table 5. Not included are other possibilities such as damaged wood from storm-blowdown and insect outbreaks for which there are no comprehensive estimates.

Table 5 Unexploited wood sources in the US (Perlack et al. [6]; dry ton converted to wet tonne or tCO_2 using a conversion factor of two)

Source		Availability per area $tCO_2\ ha^{-1}$	State MD (25,000 km^2) $MtCO_2\ y^{-1}$	US (unexploited/total) $MtCO_2\ y^{-1}$	Permanence and durability after WHS storage	Current use
Urban wood residue (56 out of 124Mt total)	Woody yard trimmings (natural wood) MSW	0.2	0.5	4/20 (4 out of total of 20)	1000+ years	Partially used for mulch, energy
	Construction residue			17/23	100+ years	
	Demolition debris			23/55		
	Wood MSW (Furnitures +)			12/26	100+ years	
Forest thinning (128 Mt)	Thinning for fire prevention (fuel treatment)	0.4	1	120	1000+ years (large pieces) 100 years (smaller pieces)	Not common (needs policy and investment)
Logging residue		0.3	0.75	93	100+ years	Partially used for mulch, energy
Other removals (land clearing precommercial treatment)		0.12	0.3	35		
Forest products industry wastes (Mill residues)		0.05	0.125	16/321		
Total		1.1	2.8	328		

Available = Generated-(Recovered + Combusted + unusable). Unusable sources such as contaminated wood were already excluded. Potential availability per unit area is assumed to be distributed over US forested land of 3 Mkm^2

The total US unexploited wood in green megatonnes is: 56 (urban) + 35 (other removal) + 128 (thinning) + 93 (logging) + 16 (mill) = 328 Mt y^{-1}. If we distribute this over the US forested area of approximately 3 Mkm^2, the wood availability is: 0.2 (urban) + 0.12 (other removal) + 0.43 (thinning) + 0.3 (logging) + 0.05 (mill) = 1.1 t ha^{-1}. This leads to potential availability per unit area of 328/300 = 1.1 tCO$_2$ ha^{-1}.

The unexploited urban and other removal are immediately available, which add to 0.32 t ha^{-1}. Because carbon value will likely divert some more wood from some other current uses such as making mulch which currently utilizes most urban tree removal (tree yard trimmings: 16 of 20 Mt), we assume a 0.4 tCO$_2$ ha^{-1} to be practically available immediately.

It is interesting to compare these bottom-up estimates with the top-down estimates based on forest productivity of Zeng et al. [4]. In the high 11 GtCO$_2$ y^{-1} (3 GtC y^{-1}) global top-down scenario, Zeng et al. [4] found that the US can contribute 500 MtCO$_2$ y^{-1} (0.14 GtC y^{-1}) for the US, slightly higher than the inventory-based estimate above. Distributed over 3 Mkm^2 of forest land, this leads to an areal harvesting intensity of 1.7 tCO$_2$ ha^{-1}. In their low 3.7 GtCO$_2$ y^{-1} (1 GtC y^{-1}) global scenario, the US can contribute 170 MtCO$_2$ y^{-1} at a harvesting intensity of 0.6 tCO$_2$ ha^{-1} over its 3 Mkm^2 forested land.

Globally, for their lower 3.7 GtCO$_2$ y^{-1} scenario, Zeng et al. [4] stated that 4.4 tCO$_2$ ha^{-1} (1.2 tC ha^{-1}) on 8 Mkm^2 leads to 1 GtC y^{-1}. The feasibility of such wood collection rate can be viewed from forest productivity. The 4 tCO$_2$ ha^{-1} rate is about 10% of the NPP of a typical temperate forest [4]. Collecting wood at the 4 tCO$_2$ ha^{-1} on an area of 9 million km^2 (about the area of the US) would sequester 3.7 GtCO$_2$ y^{-1} (1 GtC y^{-1}, 1 wedge of of Pacala and Socolow [32], or 10% of global total fossil fuel emissions in 2020). The urban wood residual availability of 0.4 tCO$_2$ ha^{-1} is only 1% of the NPP of a typical temperate forest. The sustainability of these relatively low intensity harvest is thus likely to be highly feasible, though caution is still needed in overall resource planning, especially from government and regulatory agency perspective.

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Authors' contributions
NZ conceived the idea, did the analysis and drawing. NZ and HH wrote the paper. Both authors read and approved the final manuscript.

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Availability of data and materials
No new data was produced in this work. All derived data are included in the tables and text.

Declarations

Competing interests
The authors declare no conflict of interest. NZ declares that he is in the process of starting a Public Benefit Corporation to implement WHS and support other entities to put WHS in practice.

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Publisher's Note

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Policy Analysis

Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States

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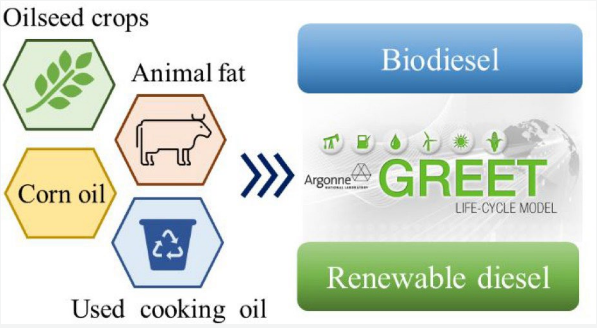
ABSTRACT: This study presents a life-cycle analysis of greenhouse gas (GHG) emissions of biodiesel (fatty acid methyl ester) and renewable diesel (RD, or hydroprocessed easters and fatty acids) production from oilseed crops, distillers corn oil, used cooking oil, and tallow. Updated data for biofuel production and waste fat rendering were collected through industry surveys. Life-cycle GHG emissions reductions for producing biodiesel and RD from soybean, canola, and carinata oils range from 40% to 69% after considering land-use change estimations, compared with petroleum diesel. Converting tallow, used cooking oil, and distillers corn oil to biodiesel and RD could achieve higher GHG reductions of 79% to 86% lower than petroleum diesel. The biodiesel route has lower GHG emissions for oilseed-based pathways than the RD route because transesterification is less energy-intensive than hydro-processing. In contrast, processing feedstocks with high free fatty acid such as tallow via the biodiesel route results in slightly higher GHG emissions than the RD route, mainly due to higher energy use for pretreatment. Besides land-use change and allocation methods, key factors driving biodiesel and RD life-cycle GHG emissions include fertilizer use and nitrous oxide emissions for crop farming, energy use for grease rendering, and energy and chemicals input for biofuel conversion.



KEYWORDS: *biodiesel, renewable diesel, greenhouse gas emissions, carbon intensity, life cycle analysis*

INTRODUCTION

Transportation is critical to enabling commerce, trade, and travel. However, it currently contributes about 29% of United States (U.S.) greenhouse gas (GHG) emissions,[1] because fossil fuels are the dominant transportation energy sources. Globally, the demand for liquid fuels is projected to increase by 32% between 2020 and 2050.[2] To stabilize the global climate within safe bounds, a transition from fossil fuels to sustainable energy resources is needed. To this end, sustainably produced biofuels can play a critical role in decarbonizing various transportation sectors.[3−5]

Biofuels are particularly important for hard-to-electrify transportation sectors with few other mature low-carbon technology options, such as long-haul trucks for freight, shipping, and aviation.[6−8] For road freight, blending biomass-derived diesel with petroleum diesel is one of the GHG mitigation strategies identified in earlier studies.[8−11] Currently, two major types of biomass-derived diesel are available in the market, including biodiesel (BD), or fatty acid methyl ester and hydrogenation-derived renewable diesel (RD), or hydro-processed esters and fatty acids. BD is produced via transesterification, whereas commercial RD production uses the catalytic hydro-processing method.

Recognizing the GHG mitigation potential, the production and consumption of biomass-derived diesel in the United States have been expanding steadily in the past decade. For instance, U.S. biodiesel production has increased 4-fold over the past decade from 0.34 billion gallons (1.30 billion L) per year in 2010 to more than 1.81 billion gallons (6.87 billion L) per year in 2020,[12] driven mainly by biofuel policies such as the federal Renewable Fuel Standard and California Low-Carbon Fuel Standard (LCFS). In recent years, the production and consumption of RD has also been expanding rapidly. RD is a drop-in biofuel in petroleum diesel without blending limitations. BD blending with petroleum diesel is limited in certain applications to an upper threshold (e.g., up to 20% by volume) without vehicle engine modifications. Since 2011, RD consumption has increased 300-fold in California[13] due to favorable policy incentives provided by LCFS.

Over the past decade, feedstocks used for BD and RD production in the U.S. have been more diversified. In addition to soybean oil and animal fats, low-value feedstocks such as used cooking oil (UCO) and distillers corn oil (DCO) are

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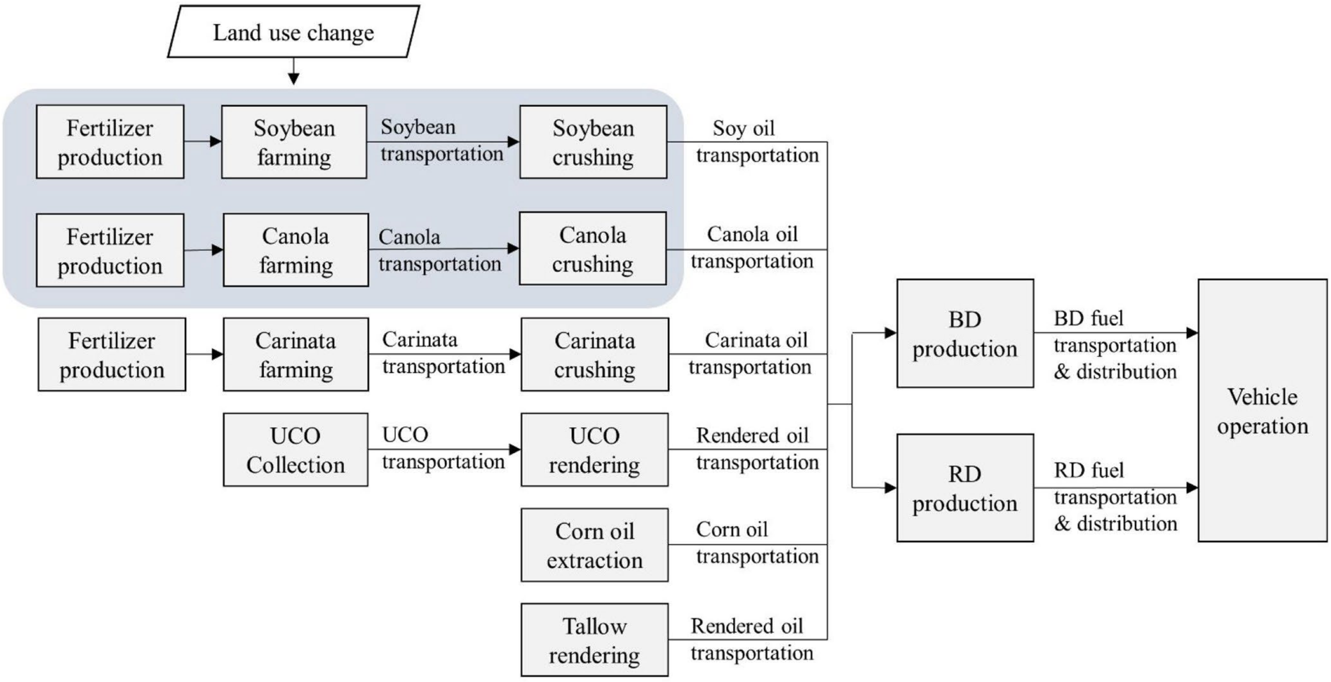

Figure 1. System boundaries for biodiesel (BD) and renewable diesel (RD) pathways. LUC-induced emissions are estimated for soybean- and canola-based pathways.

becoming prevalent. For instance, UCO and DCO share in U.S. biodiesel feedstock inputs increased from 11% in 2011 to 25% in 2019.[14] If all planned projects to expand U.S. RD production come online as intended, total U.S. RD production capacity will increase over 700% from 0.6 billion gallons (2.3 billion L) per year in 2020 to 5.1 billion gallons (19.3 billion L) by 2024.[15]

While domestic biomass-based diesel capacity is expanding rapidly and waste feedstocks are becoming prevalent, life-cycle analysis (LCA) based on real-world, commercial-scale BD and RD production data is lagging. Compared to the current assessment of BD and RD GHG emissions,[9,11,16−18] the novelty and contribution of this study lies in the following aspects. First, we developed detailed LCA models for several biomass to renewable diesel (RD) pathways with proprietary data collected from major biofuel producers. Biofuel LCA results are driven by data inputs, besides methodologies such as system boundaries and allocation methods. A common challenge for biomass to RD LCA is getting real-world data from commercial producers. As a workaround, studies had to use lab-scale data or process-based simulations,[11,19−21] with a few exceptions.[16,22] However, assumptions made in simulations can vary significantly from current industrial practices.[16] To inform evidence-based decision making, biofuel LCAs representing current industrial practices are needed. This study improves current LCAs of BD and RD GHG emissions by analyzing and synthesizing update-to-date proprietary data from major BD and RD producers in the United States. Second, our study models the real-world supply chain of waste feedstocks such as UCO. Residue and waste feedstock such as UCO is increasingly used for biofuel production, but current LCAs of UCO to BD and RD production in the United States do not sufficiently address GHG emissions arising from the UCO supply chain activities. This is mainly because data on UCO collection and processing is only sparsely available, partly because oil/fat rendering is a distributed business that involves many operators and facilities.

Considering the rapid pace of technology development for biomass-based diesel production and that biomass-based diesel will likely continue its fast-growing trend in connection with policies directed toward mitigating GHG emissions, an objective and updated life-cycle analysis (LCA) is needed to assess the carbon intensity of the U.S. biomass-based diesel industry and to inform sustainable expansion of the industry. This study aims to fill these gaps and investigate life-cycle GHG emissions of BD and RD production in the United States, incorporating the latest industry survey data sets covering the U.S. biomass-based diesel and fat rendering industries.

DATA AND METHODS

The Goal, Scope, and System Boundaries. The goal of this study is to provide updated life-cycle GHG emissions for BD and RD from the major feedstocks currently used in the United States. Biomass feedstocks considered in this study include virgin vegetable oils from soybeans (*Glycine max*), canola (*Brassica napus*), and carinata (*Brassica carinata*), as well as waste or byproduct feedstocks tallow, DCO, and UCO. Carinata is not currently used for commercial-scale BD and RD production in the United States. It is included here as a potential low-carbon, inedible feedstock. The functional unit is one megajoule (MJ) of BD and RD produced and used in vehicles.

The LCA is conducted using the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model developed at Argonne National Laboratory.[23] For both BD and RD pathways, well-to-wheels (WTW) GHG emissions are presented as grams of carbon dioxide equivalent per MJ (g CO_2e/MJ) of fuel consumed in a vehicle, which accounts for all energy and emissions associated with biofuel production and vehicle operation. We use the 100-year global warming potentials (GWP) from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)[24] to calculate carbon dioxide equivalents.

The system boundaries of BD and RD pathways (Figure 1) vary based on feedstock types. Key stages for oilseed crops to BD and RD pathways include biomass production (i.e., farming), oilseed crushing and oil extraction, biofuel conversion, and fuel distribution and consumption. Key stages for tallow and UCO pathways include grease/oil rendering, biofuel conversion, and fuel distribution and consumption. In the U.S., beef tallow and white grease (rendered pork fat) contributed 57% and 31%, respectively, of the animal fats used for biofuel production.[25] Industrial data included in this study represent the beef tallow pathway. Tallow is a byproduct recovered from meat production processes and thus does not share upstream emissions (e.g., livestock cultivation). We further assume tallow is processed on-site because it is mainly sourced from meat processors, and an industrial survey by Argonne and North American Renderers Association (NARA) suggests that meat processors render tallow on-site. Survey results are summarized in the Life Cycle Inventory Data section. Still, third-party renderers can purchase meat byproducts from meat processors for off-site rendering. However, data on transportation from meat plants to off-site rendering facilities are not available. For UCO, we also included collection and transportation activities because operators typically have to travel to multiple locations to fill up containers. The system boundary for DCO consists of separating DCO from distillers' grains and solubles (DGS) in corn ethanol plants. DCO is different from food-grade corn oil because it has high free fatty acids (FFA) content (9−16%) and is not suitable for human consumption. Edible corn oil is extracted from corn germs or whole kernels directly, and its FFA content is less than 0.5%.[26] In this study, DCO is considered a byproduct of corn ethanol production, and it does not share upstream emissions (e.g., corn farming) with corn ethanol. Feedstock classification (e.g., coproduct versus byproduct) determines which life-cycle stages would be included in the system boundary. While there is no universally accepted classification method, key criteria used in common classification methods include (1) the intention of the production of feedstock, (2) the economic value, and (3) the supply elasticity.[16] More information on feedstock classification methods can be found in Xu et al.[16] Here, we treat DCO as a byproduct by default because the main purpose of the ethanol refining process is to produce fuel ethanol. Also, DCO is a residual oil recovered from DGS, and its mass or revenue share is less than 5% in a typical dry mill ethanol plant (see SI: DCO share calculation). If DCO is not extracted, it will stay in DGS, which is typically used as animal feed. In the LCA of corn ethanol, this animal feed coproduct is typically treated with system expansions such that it provides a GHG credit to the ethanol equivalent to the impacts of producing the animal feed which would otherwise be required. In the GREET model, the credits are calculated based on the amount of corn and soybean meal that can be displaced by DGS. When DCO is recovered, it lowers DGS yield. Since less corn and soybean meal can be replaced by DGS, we reduced the GHG credits available to ethanol to reflect the consequences of DCO recovery.

During the vehicle operation stage, this study assumes carbon neutrality, which means CO_2 emissions from combustion of biomass-derived diesel are offset by CO_2 uptake from the atmosphere by plants. However, the CO_2 emissions from the combustion of the fossil carbon in the methanol used in BD production are included in BD combustion emissions. The GHG emissions associated with the construction of infrastructure for BD and RD facilities and other aspects of the supply chain are outside the scope of this analysis

Life Cycle Inventory Data. Life-cycle inventory (LCI) data sets used in this study include existing databases in GREET and additional data sets compiled from industrial surveys, government databases, and the literature. With support from National Biodiesel Board (NBB) and North American Renderers Association (NARA), Argonne conducted two industrial surveys to collect data sets from major BD and RD producers and oil/fat renderers in the United States. Due to the nondisclosure agreement, survey results from individual companies are not publicly available, but aggregated data are provided in the following sections.

Biomass to Vegetable Oil. Key parameters for crop cultivation include on-farm energy use, fertilizer inputs, and N_2O emissions from different sources (Table 1). We compiled data on soybean yield and fertilizer inputs from USDA databases.[27] Additional data on soybean farming energy inputs for 2018, which were not published, were shared by the USDA Economic Research Service upon request.[27] Since canola is mainly cultivated in Canada, we use farming data for Canadian canola production in this study.[28] Data on carinata farming inputs were collected from the literature,[29,30] representing typical farming practices in the northern United States. More details on biomass feedstock cultivation LCI, including N_2O emissions, are provided in the GREET 2021 release technical report.[27]

Table 1. Crop Yield, Farming Energy and Fertilizer Inputs, and N_2O Emissions (All in Dry Weight)

	soybean	canola	carinata
crop yield (kg oilseeds/hectare)	2961	1756	1871
energy input (MJ/kg oilseeds)			
diesel	0.42	0.59	1.73
gasoline	0.09		
natural gas	0.01	0.01	
liquefied petroleum gas (LPG)	0.03		
electricity	0.07	0.003	
fertilizer input			
nitrogen (g N/kg oilseeds)	1.85	56.45	26.08
phosphorus (g P_2O_5/kg oilseeds)	8.78	17.40	3.58
potassium (g K_2O/kg oilseeds)	13.92	4.55	0.51
herbicides (g/kg oilseeds)	0.82	0.46	2.66
insecticides (g/kg oilseeds)	0.01	0.04	0.35
N_2O emissions			
from N fixation: (g N_2O/kg oilseeds)[b]	0.23	-	-
N content in residue biomass (g N/kg oilseeds)	23.52	26.45	22.80
percentage of N in fertilizer released as N_2O	1.37%	1.04%	1.37%
percentage of N in biomass[a] released as N_2O	1.26%	0.94%	1.26%

[a]Including both above ground and below ground residue biomass. [b]N fixation is only relevant for soybeans, as canola and carinata are not legumes.

We use the existing LCI database in GREET for the oilseed crushing stage. Energy and material balances for soybean crushing were extracted from a 2010 United Soybean Board report,[31] which was based on a 2008 industry survey conducted by the National Oilseed Processors Association (NOPA).[9] While NOPA is planning to conduct another industry survey, the 2010 report is still the latest database available to the public. Data on canola[32] and carinata oil[33] extraction were collected from the literature. In addition to crushing, energy use related to oilseeds and vegetable oil transportation is also included in this study, using existing transportation data in GREET.

Collection and Processing of Recycled and Low-Value Feedstocks (Tallow, UCO, and Corn Oil). We collected tallow and UCO rendering data (Table 2) with NARA support by surveying primary fat and grease renderers in the United States. The compiled LCI data sets represent industry average practices, covering 46 plants with tallow rendering operations and 61 UCO rendering facilities. The rendering plants included in this study either process beef byproducts only or predominantly use beef byproducts as raw material. Companies typically own several facilities, and most companies provide aggregate-level data instead of facility-level data to protect business-sensitive information. The tallow rendering process yields both rendered tallow and meat and bone meal (MBM), sold separately as animal feed ingredients.

Table 2. Inventory Data for Tallow and Used Cooking Oil (UCO) Rendering

	tallow	UCO, traditional	UCO, settling
feedstock input (kg/kg finished oil)	2.26	1.35	1.35
energy input (MJ/kg finished oil)	7.43	2.36	0.85
natural gas	4.99	2.11	0.76
animal fat	0.98	-	-
electricity	1.46	0.25	0.09
outputs (kg/kg finished oil)			
rendered fat/oil	1.00	1.00	1.00
meat bone meal (MBM)	1.04	-	-

There are no marketable coproducts from the UCO rendering process. The purpose of UCO rendering is to separate impurities and water from oil. In addition to the traditional UCO rendering method consisting of high-temperature cooking and tricanting, some renderers also use the so-called "settling" method to reduce energy demand. Instead of evaporating water in raw UCO via high-temperature cooking, raw UCO in settling plants is heated and then left to settle. Once settled, water is withdrawn from the tank, and UCO is subsequently recovered. NARA survey data show 25% of UCO renderers, representing 39% of facilities covered by the NARA survey, use settling as the primary method. Most companies use high-temperature cooking and tricanting.

We also collected transportation data (e.g., distance, mode, payload) for UCO (Table S1). Responses from companies indicate two primary UCO collection methods: direct route and bulk transfer. For the direct route method, trucks visit multiple locations along planned routes to fill up oil containers. On average, trucks need to travel 6.8 km to collect one ton of UCO. Once complete, they will return to the rendering facility directly. The total distance for a round trip is about 186 km on average. With the bulk transfer method, UCO collected from multiple individual trips/routes is aggregated at a bulk tank and then shipped to the rendering facility using heavy-duty trucks. The average distance from the bulk tank to rendering facilities is 124 km. Companies can use one or a mix of both collection methods. On the basis of survey responses, about 77% of UCO is collected via the direct route method, whereas bulk transfer contributes 23%.

For DCO, electricity use associated with separating corn oil (0.43 MJ/kg oil)[23] from distiller's grains and solubles, using a centrifuge, is assigned exclusively to DCO. In addition, transportation of DCO from ethanol plants to biodiesel plants is included in the analysis, using existing transportation data in GREET.

Biodiesel and Renewable Diesel Production. We summarized responses from the 2021 NBB industry survey to build LCI databases for BD production via transesterification and RD production via hydro-processing (Table 3). The NBB surveyed their membership for the purposes of this research. Thirty-eight producers were sampled, equaling 60 plants. The respondents include 27 plants, representing 45% of surveyed NBB plants. The data sets cover the production years 2018, 2019, and 2020. We processed inputs from the 27 plants (Table 3) to model typical commercial biodiesel production practices in the United States. The total BD production for the 27 plants which responded to the survey represents 60% of U.S. total biodiesel production.[34] Out of the 27 biodiesel plants, 13 processed vegetable oil (89.4 wt % soybean oil and 10.6 wt % canola oil) only, and the other 14 plants processed both vegetable oil and feedstocks with high FFA contents, including DCO, animal fat such as tallow, and UCO. On average, high FFA oils represent most (61 wt %) of the feedstock inputs in the 14 plants with mixed feedstock supply. This study uses data from the 13 vegetable oil processing plants to model soybean, canola, and carinata to BD pathways.

Table 3. Inventory Data for Biodiesel (BD) Production via Transesterification and Renewable Diesel (RD) Production via Hydro-Processing (per kg BD or RD)

	biodiesel		renewable diesel
	vegetable oil	high ffa oil	all pathways
feedstock input (kg/kg BD or RD)	1.00	1.05	1.26
energy use (MJ/kg BD or RD)			
natural gas	1.07	2.78	0.82
electricity	0.13	0.36	0.43
material inputs			
hydrogen (MJ/kg)	-	-	4.81
methanol (g/kg)	109	109	-
sodium hydroxide (g/kg)	1.07	-	-
sodium methoxide (g/kg)	3.62	-	-
hydrochloric acid (g/kg)	1.68	2.61	-
phosphoric acid (g/kg)	0.44	2.17	-
sulfuric acid (g/kg)	1.10	-	-
citric acid (g/kg)	0.003	-	-
sodium methylate (g/kg)	0.35	-	-
water consumption (L/kg)	0.15	0.99	-
outputs			
fuel (BD or RD, kg)	1.00	1.00	1.00
coproducts (fuel gas, LPG, and naphtha) (MJ/kg RD)	-	-	1.93
glycerin (100% pure, kg/kg BD)	0.10	0.07	-
FFA and distillation bottoms coproducts (kg/kg BD)	0.01	0.07	-

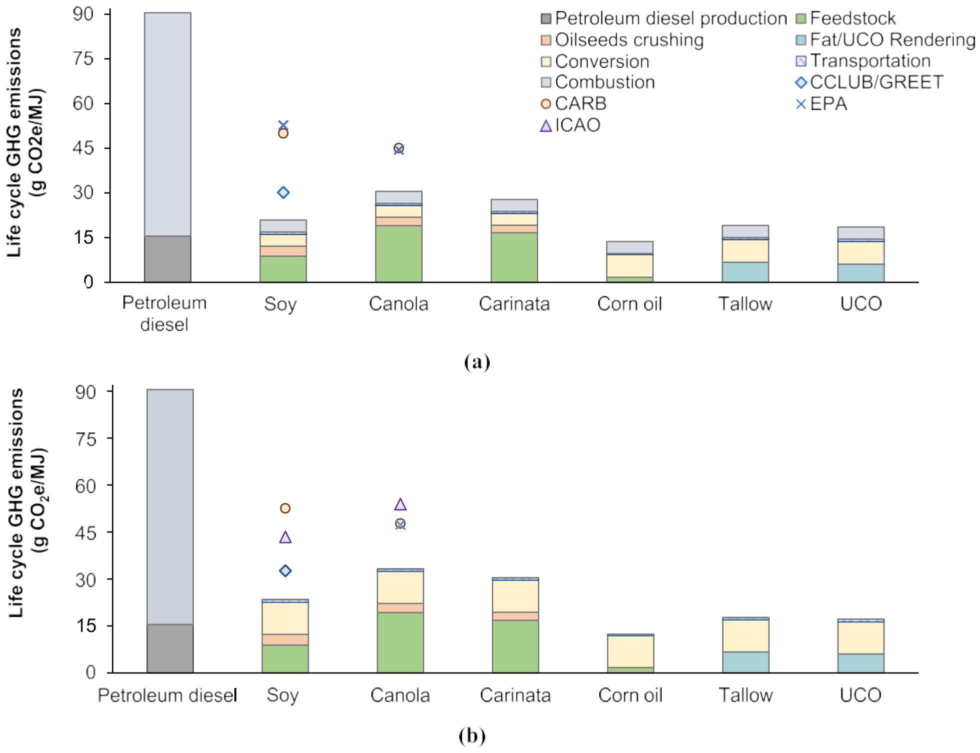

Figure 2. Life-cycle greenhouse gas (GHG) emissions of petroleum diesel versus (a) biodiesel (BD) and (b) renewable diesel (RD) pathways. Marker symbols represent life-cycle GHG emissions, including land-use change (LUC) emissions. UCO refers to used cooking oil. The rendering bar for UCO also includes UCO collection emissions. The corn oil pathway is based on distillers corn oil (DCO), not edible corn oil.

LCI data from the other 14 multifeedstock plants is used to model tallow, DCO, and UCO to BD pathways.

We constructed the LCI database for commercial RD production (Table 3) by compiling data from five different RD producers, including four U.S. companies and one international RD producer. The NBB industry survey mentioned above covers three RD producers, and we collected additional data points from petitions submitted to California's LCFS program. As of January 2021, there are only six commercial RD plants in the United States.[35] The RD LCI database we constructed includes four of the six RD producers. Because of the small sample, the participating companies request that we not release the exact feedstock composition and annual production information to protect the confidentiality and business-sensitive information. EPA's Renewable Identification Number (RIN) transactions data shows soybean RD and animal fats/UCO derived RD contributed 9.3% and 27.3% (volume basis) of total RD consumed in the U.S. in 2020.[36] While EPA does not provide a detailed breakdown for other feedstocks, data from the LCFS program indicate DCO is another important feedstock.[37]

Coproduct Allocation Methods. This study applied a process-level hybrid allocation method to attribute energy use and emissions to the different products from oilseed crushing, animal fat rendering, and biofuel conversion. A mass-based allocation was selected for both oilseed crushing and animal fat rendering, mainly because oilseed meals and MBM are protein or feed products rather than energy products.[9] The facilities are designed to separate incoming feedstocks into lipids and meals, and the mass balance is stable. We also applied market-based allocation to oilseed crushing and animal fat rendering as an alternative allocation method to test the sensitivity of results to a different coproduct allocation method. We use 10-year average prices to reduce the effect of price variability. An energy-based allocation method was used for RD production at the RD plants because coproducts from hydroprocessing, fuel gas, LPG, and naphtha, are also energy products. In contrast, the market-based allocation was applied to BD production at BD plants because the glycerine coproduct from the transesterification process is not an energy product.

Land-Use Change Emissions. LUC-induced emissions are also estimated for the oilseeds to BD and RD pathways (Table S2). We estimated LUC emissions using the CCLUB module in GREET for soybean oil-based pathways.[38] For soybean BD, the California Air Resource Board (CARB)-8 case was selected. Detailed discussions on LUC estimations, including comparison with alternative scenarios, can be found in Chen et al.[9] In this study, LUC emissions for soybean RD were converted from soybean BD LUC values after adjusting differences in biofuel yields (i.e., MJ of energy products produced from 1 kg of soybean oil). Alternative LUC emissions (Table S2) for soybean oil to BD and RD pathways, along with canola oil to BD and RD pathways, were collected from other studies, including those published by CARB, the International Civil Aviation Organization (ICAO), and the U.S. Environmental Protection Agency (EPA; Table S2). LUC from ICAO represent scenarios where biorefineries will produce both RD and renewable jet fuels. LUC values for carinata pathways are not available.

RESULTS

Life-Cycle GHG Emissions of BD and RD Pathways. Without including the LUC emissions, the WTW emissions of soybean, canola, and carinata oils to BD pathways (Figure 2a) range from 21 to 31 g of CO_2e/MJ, with soybean BD presenting the lowest value. The WTW emissions of the

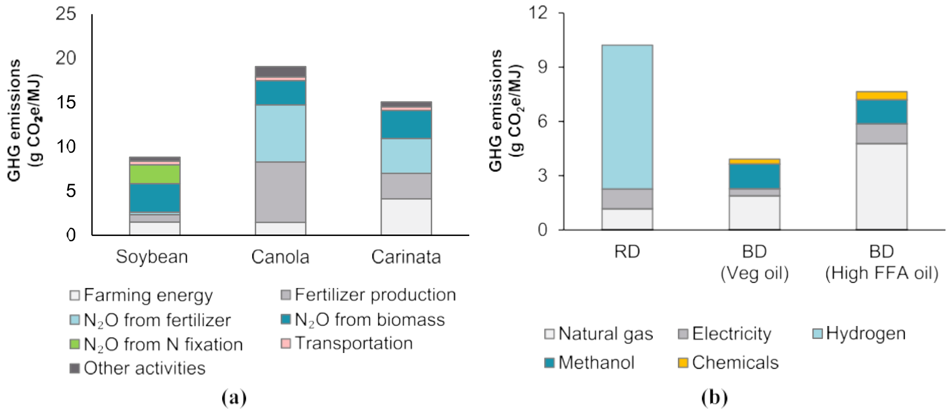

Figure 3. Breakdown of life-cycle greenhouse gas (GHG) emissions of (a) oilseed production and (b) biofuel conversion processes. FFA refers to free fatty acid. Other activities refer to GHG emissions associated with other farming activities, such as insecticides and CO_2 from urea application.

soybean, canola, and carinata oil to RD pathways are about 8−10% higher than their BD counterparts (Figure 2b). Depending on the LUC values, the WTW emissions of soybean oil and canola oil to BD and RD pathways with different LUC estimations (Table S2) may increase to 30 to 53 g of CO_2e/MJ (Figure 2).

The wide range of WTW emissions with LUC estimations reflects the significant variance in LUC estimations adopted by different organizations (Table S2). With GREET default LUC results, life-cycle GHG emissions of soybean BD and soybean RD would be around 30 and 33 g of CO_2e/MJ (Figure 2). GREET does not have LUC values for canola, and LUC estimations for carinata are not available. Tallow, UCO, and DCO pathways do not have associated LUC as these feedstocks are waste grease and byproducts.

Along with oilseeds to BD and RD supply chains, feedstock production and biofuel conversion are the two most essential stages, representing 61% to 88% of WTW emissions (Tables S3 and S4). The primary components contributing to feedstock production GHG emissions include N_2O emissions from fertilizer application and residue biomass, fertilizer manufacturing, and on-farm energy use (Figure 3a). For BD pathways, oilseed crushing, biodiesel conversion, and combustion contributions are comparable (Table S3). Compared to the BD route, conversion emissions for the RD route are 6.3 g of CO_2e/MJ higher, while contributions from farming and crushing stages are almost identical (Table S3 and S4). Although biomass input is higher for RD production, coproducts from hydroprocessing are also energy products (Table 3). After allocation, the feedstock burden is similar for both BD and RD pathways. A breakdown of BD and RD conversion emissions (Figure 3b) reveals that natural gas and methanol dominate BD conversion emissions, whereas hydrogen contributed 73% of hydro-processing GHG emissions. The GHG emissions associated with methanol input for transesterification are 83% lower than hydrogen input for hydroprocessing (Figure 3b).

The carbon intensity of BD is impacted by the fact that it contains fossil carbon originating from the conventional methanol used in BD production. Since BD includes fossil carbon from methanol, BD has higher combustion emissions than RD, which reduces net differences between BD and RD routes. Combustion emissions are not zero due to non-CO_2 emissions (e.g., methane, nitrous oxide) from fuel combustion and C embedded in fossil methanol inputs.

The life cycle GHG emissions of BD and RD from the waste feedstocks, tallow, UCO, and DCO are lower than the oilseed pathways, with results ranging from 12 to 19 g of CO_2e/MJ (Figure 2). The DCO pathways have the lowest emissions as corn oil does not share ethanol production emissions, whereas tallow and UCO-based pathways are close. For all three feedstocks, conversion is the stage with the most significant contribution for both BD and RD pathways (Figure 2). In theory, conversion emissions for hydroprocessing can vary slightly across feedstocks due to variations in fatty acids profiles,[39] if an RD plant uses a single feedstock. However, all commercial RD plants use a mix of multiple feedstocks, and conversion data for specific feedstock is not available. Here, we assume RD conversion emissions are the same for all feedstocks. While conversion emissions are the same for all RD pathways, biodiesel production using feedstocks with high FFA content presents significantly higher conversion emissions (7.7 g of CO_2e/MJ) than vegetable oil (3.9 g of CO_2e/MJ, Figure 3b). The additional natural gas demand needed for FFA treatment is the critical factor, resulting in 1.5 times greater natural gas use compared with vegetable oil conversion (Figure 3b). Collection and rendering is another critical stage for tallow and UCO-based pathways, representing about 35% of WTW emissions (Tables S3 and S4).

DISCUSSION

This study indicates that replacing petroleum diesel with BD and RD converted from oilseed crops and low-value feedstocks could significantly reduce GHG emissions. Without LUC emissions, the WTW GHG emissions of BD and RD produced from oilseed crops can be 63% to 77% lower than petroleum diesel. Soybean-based pathways present lower GHG emissions than canola and carinata because soybean farms have higher yields and lower fertilizer demand. Utilizing UCO, tallow, and DCO for BD and RD production could achieve even more significant GHG reductions (79% to 86% lower than petroleum diesel), mainly because they do not share emissions of upstream activities. LUC emissions will add 9.2 to 29 g of CO_2e/MJ to soybean oil and canola oil pathways, depending on the studies used for LUC estimations. With LUC emissions accounted for, life-cycle GHG emissions of soybean BD and RD could still be 64% to 67% (using GREET LUC value) or 42% to 52% (using LUC values from EPA, CARB, and ICAO) lower than petroleum diesel. Results with LUC emissions vary widely because both economic models and soil organic carbon modeling are subject to significant uncertainties,[40,41] even though both have been improved recently.[42] The uncertainties are due to differences in databases (e.g., baseline land-use data), model types, and critical assumptions (e.g., shock size); LUC modeling results can vary significantly across studies.[43]

Our results on soybean oil, canola oil, and tallow to BD pathways are comparable to those reported in previous studies.[9] While results for the canola pathway are close, GHG emissions of the soybean BD and tallow BD pathways are slightly lower than those reported in Chen et al.,[9] mainly due to lower soybean farming and tallow rendering emissions. Recently, Raizi et al.[11] estimated life-cycle GHG emissions of RD from soybean oil, tallow, and poultry fat. Compared to their results, the tallow RD pathway reported in this study has significantly lower GHG emissions due to large differences in rendering emissions. With the same allocation method, tallow rendering GHG emissions are about 13 g of CO_2/MJ lower in this study. The differences are likely driven by different data sources used for LCA. Results on soybean RD are more comparable. While our estimations for the feedstock stage are similar, conversion emissions are lower in this study, mainly due to different data sources used for RD conversion modeling.

Results on carinata pathways should be interpreted with caution since field trials and industrial scale-up of carinata for feedstock growth and biofuel production is still in the process. In northern states, carinata is typically planted as a scavenger crop to recover excessive nitrogen content. On the other hand, recent field experiments[44,45] in the southeast U.S. suggest that the fertilizer rate could be much higher if the objective maximizes biomass yield. Using recommended fertilizer rates[45] from trials conducted in the southeast U.S. would double carinata feedstock production GHG emissions. In this case, life-cycle GHG emissions of carinata BD and RD would increase by 11 g of CO_2e/MJ (Figure S1), but still more than 50% lower than petroleum diesel.

One of the contributions made in this study is providing more representative LCA results for tallow and UCO-based pathways by incorporating the latest industrial survey data. Compared to a 2018 LCA study[9] that utilized industrial data from Lopez et al.,[46] our results suggest rendering energy use for tallow has decreased by 20%. Meanwhile, animal fat rendering companies phased out residual oils and replaced them with natural gas (Table 2). Using the latest industrial data (Table 2), we found that GHG emissions associated with tallow rendering are 34% lower than the previous estimate.[9] While meat processors can render waste animal fat on-site, rendering companies must collect UCO from many locations. Our analysis reveals that UCO collection (Figure S2) represents 22% of total UCO collection and rendering emissions. During the UCO collection stage, GHG emissions estimated in this study are about half of that published by EPA,[47] but the WTW GHG emissions of UCO to the BD pathway evaluated in this study are 5.6 g of CO_2/MJ higher than EPA′s estimation.[47] Since EPA did not provide different numbers for rendering versus biofuel conversions emissions, it is not clear which stage contributes the most significant difference. Compared to CARB′s default numbers,[48] our estimations on UCO to BD and RD pathways are 7% and 28% lower due to lower emissions from rendering and conversion.

From a waste reduction and climate change mitigation perspective, recycling and converting waste greases to BD and RD could promote the circular economy and GHG reductions. Unlike edible vegetable oils (e.g., soybean oil), UCO and inedible tallow are recycled from waste streams, and DCO is extracted from the remaining stillage after ethanol distillation. Due to the high FFA content and other impurities, all three oils are unsuitable for human consumption and have lower market value than soybean oil. However, the supply of these feedstocks can be limited by the demand for the main products (e.g., meat, cooking oil).

Since waste grease is increasingly used for BD production, reducing energy use for FFA treatment would be critical to lowering life-cycle GHG emissions of waste grease to BD pathways. While vegetable oil to BD via transesterification could lower GHG emissions more than the RD route, GHG emissions of high FFA oil to BD pathways are higher than the RD route due to the extra energy required for FFA treatment. Furthermore, survey results suggest energy use at BD plants that process high-FFA oils have increased by 27% since 2015. Companies did not disclose the reason for the increase in energy use. Considering that BD yield at high-FFA oil plants increased by 5% since the 2015 survey, whereas BD yield at vegetable oil plants increased by only 1%, BD producers may have intensified the pretreatment step to convert FFA to BD via processes such as esterification or glycerolysis. Still, samples included in the 2015 and 2021 NBB surveys are not identical, so differences in data samples may also contribute to the higher energy use.

The selection of allocation methods may have significant impacts on biofuel LCA results (Figure S3). Applying market-value-based allocation to the oilseed crushing would increase soybean oil′s share of farming and crushing emissions by 10% (Table S5). The increase reflects that the market price of soybean oil is higher than soybean meal on a mass basis.[49] In this case, life-cycle GHG emissions of soybean BD and soybean RD pathways would increase by about 5.7 g of CO_2e/MJ (Figure S3), and the increases come primarily from the farming stage (Figure S4). Changes in GHG emissions of canola BD and RD are more significant than soybean pathways (Figure S3) because farming emissions for canola are larger than soybean cultivation (Figure S4). Compared to mass-based allocation, using market-based allocation for oilseed crushing may be affected by market volatility. Conventionally, business decisions regarding oilseed crushing are mainly driven by the soybean meal and protein market,[50] because soybean oil accounts for only about 18% to 20% of the weight of soybean seeds.[51] Even though the market price of soybean oil ($0.77/kg, 2011−2020 average)[49] is higher than that of soybean meal ($0.41/kg, 2011−2020 average)[52] in the U.S. market, revenues from soybean meal still represent about 68% of revenues from whole soybeans. However, since late 2020, the soybean oil price has increased from $0.75/kg to $1.47/kg (Figure S5). With the recent market price, soymeal would represent about 52% of total revenues from soybeans. If the soybean oil price remains high in the coming years, using economic-based allocation will increase GHG emissions for soybean-oil-based BD and RD. The allocation method selected for the feedstock stage has a minor impact on waste oil and greases (Figure S3) because tallow and UCO do not share upstream farming emissions.

Compared to the allocation method, feedstock classification has a more significant impact on DCO-based pathways. If DCO is classified as a coproduct with ethanol in corn ethanol plants, DCO will share ethanol production and upstream corn farming emissions with ethanol. In this scenario, life-cycle

GHG emissions of DCO to BD and RD pathways would be about 32 g of CO_2e/MJ higher (Figure S6), but they are still 50% lower than petroleum diesel.

Moving forward, the U.S. biomass-based diesel industry can take additional steps to achieve deeper GHG emissions reductions as part of the effort to decarbonize the transportation sector. The presented analysis can serve as a reference to identify critical areas with significant GHG reduction potentials. Our study reveals that crop production or farming is the most carbon-intensive stage for oilseeds to BD and RD pathways with current industry practices. Depending on the feedstock or crop used for BD/RD production, the composition of farming emissions can vary. On the other hand, recent studies suggested that a 71% reduction in GHG emissions from row crop agriculture is possible through novel and low-emission technologies.[53] When coupled with sustainable farming practices (e.g., cover crop) and increased soil organic carbon sequestration, there is a potential to produce net-zero or carbon-negative biomass feedstock. Replacing fossil energy and chemicals with low-emission alternatives would be the key to decarbonizing the biofuel conversion processes. For RD, the choice of H_2 production technologies can affect GHG results significantly. Replacing hydrogen made from natural gas with renewable hydrogen (e.g., electrolysis with nuclear power or wind power) could reduce RD emissions by 7.7 to 8.0 g of CO_2e/MJ (Figure S7). In contrast, if hydrogen is produced via coal gasification, RD emissions would increase by 6.5 g of CO_2e/MJ (Figure S7). For BD, if biobased methanol were used rather than conventional methanol, the carbon intensity of BD would reduce by 4.0 g of CO_2e/MJ. The rendering industry can also help with reducing feedstock carbon intensity. Taking UCO, the results are presented based on conventional rendering emissions and are modeled based on the conventional rendering method (Table 2). The settling method will reduce UCO rendering emissions by 64% (Figure S2). Follow on studies evaluating GHG reduction potentials of major BD and RD pathways and identifying strategies to accelerate the progress toward net-zero transportation would be beneficial to informing industry and policy decisions.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c00289.

> Additional data sets for survey results, allocation factors, and life-cycle analysis results based on alternative allocation methods, including supporting figures and tables (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCE 6

ANL/ESD/08-2

Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels

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Energy Systems Division

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Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels

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Notation

Acronyms and Abbreviations

BFW	boiler feed water
BP	British Petroleum
CETC	CANMET Energy Technology Centre
CH_4	methane
CIDI	compression-ignition, direct-injection
CO	carbon monoxide
CO_2	carbon dioxide
CSO	clarified slurry oil
$DeCO_2$	decarboxylation
DOE	U.S. Department of Energy
ERS	Economic Research Service (USDA)
FCC	fluidized catalytic cracker
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HDO	hydrodeoxygenation
IPCC	Intergovernmental Panel on Climate Change
K	potassium
LCA	life-cycle analysis
LCO	light-cycle oil
LHV	lower heating value
LPG	liquefied petroleum gas
LSD	low-sulfur diesel
N	nitrogen
N_2O	nitrous oxide
NaOH	sodium hydroxide
NG	natural gas
NO_x	nitrogen oxide
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
P	phosphorus
PM_{10}	particulate matter with a diameter of 10 micrometers or less
$PM_{2.5}$	particulate matter with a diameter of 2.5 micrometers or less
PTW	pump-to-wheels
RFG	reformulated gasoline
SI	spark-ignition
SMR	steam methane reforming
SO_x	sulfur oxides
USDA	U.S. Department of Agriculture
VGO	vacuum gas oil
VOC	volatile organic compound
WTP	well-to-pump

WTW	well-to-wheels
WWT	wastewater treatment

Units of Measure

bpd	barrel(s) per day
Btu	British thermal unit(s)
bu	bushel(s)
°C	degree(s) Celsius
°F	degree(s) Fahrenheit
ft^3	cubic foot (feet)
g	gram(s)
gal	gallon(s)
h	hour(s)
ha	hectare(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
L	liter(s)
lb	pound(s)
mmBTU	million Btu
ppm	part(s) per million
psia	pound(s) per square inch absolute
psig	pound(s) per square inch gauge
scf	standard cubic foot (feet)
USD	U.S. dollar(s)
yr	year(s)

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Abstract

We assessed the life-cycle energy and greenhouse gas (GHG) emission impacts of the following three soybean-derived fuels by expanding, updating, and using Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model: (1) biodiesel produced from soy oil transesterification, (2) renewable diesel produced from hydrogenation of soy oil by using two processes (renewable diesel I and II), and (3) renewable gasoline produced from catalytic cracking of soy oil. We used four allocation approaches to address the co-products: a displacement approach; two allocation methods, one based on energy value and one based on market value; and a hybrid approach that integrates both the displacement and allocation methods. Each of the four allocation approaches generates different results. The displacement method shows a 6–25% reduction in total energy use for the soybean-based fuels compared with petroleum fuels, except for renewable diesel II. The allocation and hybrid approaches show a 13–31% increase in total energy use. All soybean-derived fuels achieve a significant reduction (52–107%) in fossil energy use and in petroleum use (more than 85%). With the displacement approach, all four soybean-based fuels achieve modest to significant reductions (64–174%) in well-to-wheels GHG emissions. With the allocation and hybrid approaches, the fuels achieve a modest reduction in GHG emissions (57–74%). These results demonstrate the importance of the methods that are used in dealing with co-product issues for these renewable fuels.

1 Introduction

There has long been a desire to find alternative liquid fuel replacements for petroleum-based transportation fuels. Biodiesel, produced from seed oils or animal fats via the transesterification process, has been the focus of biofuel production because of its potential environmental benefits and because it is made from renewable biomass resources. Biodiesel can be derived from various biological sources such as seed oils (e.g., soybeans, rapeseeds, sunflower seeds, palm oil, jatropha seeds, waste cooking oil) and animal fats. In the United States, a majority of biodiesel is produced from soybean oil. In Europe (especially in Germany), biodiesel is produced primarily from rapeseeds. Biodiesel can be blended with conventional diesel fuel in any proportion and used in diesel engines without significant engine modifications (Keller et al. 2007). In recent years, the sales volume for biodiesel in the United States has increased dramatically: from about 2 million gallons in 2000, to 75 million gallons in 2005, to 250 million gallons in 2006 (National Biodiesel Board 2007).

Transesterification of seed oils and animal fats has been the major technology for biodiesel production to date. New process technologies based on hydrogenation to convert seed oils and animal fats to diesel fuel and gasoline have recently emerged. The CANMET Energy Technology Centre (CETC) of Natural Resources Canada (NRCan) has developed a technology to convert seed oils and animal fats into a high-cetane, low-sulfur diesel fuel blending stock called “SuperCetane” [$(S\&T)^2$ Consultants Inc. 2004]. UOP developed conversion processes based on conventional hydroprocessing technologies that are already widely deployed in petroleum refineries. The hydro-generation technologies utilize seed oils or animal fats to produce an isoparaffin-rich diesel substitute referred to as “green diesel” (Kalnes et al. 2007). UOP also proposed a technology that can produce “green gasoline” by cracking seed oils and grease in a fluidized catalytic cracker (FCC) unit (UOP 2005). The diesel and gasoline produced from these processes are often referred to as renewable diesel and gasoline.

In this report, we present a life-cycle analysis of the energy and GHG emission impacts of biodiesel, renewable diesel, and renewable gasoline relative to those of petroleum diesel and gasoline. In the United States, soybeans are the major feedstock for biodiesel production now and, potentially, for renewable diesel and gasoline production in the future. In our study, we evaluated production of biodiesel, renewable diesel, and renewable gasoline from soybeans.

For this study, we expanded and updated the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model (see http://www.transportation.anl.gov/software/GREET/index.html). In 1995, with funding from the U.S. Department of Energy (DOE), Argonne National Laboratory’s Center for Transportation Research developed the GREET model for use in estimating the full fuel-cycle energy and emissions impacts of alternative transportation fuels and advanced vehicle technologies. Since that time, the model has been updated to include new fuels and transportation technologies. The latest version — GREET 1.8a — is capable of analyzing more than 100 transportation fuel pathways.

For a given vehicle and fuel system, GREET evaluates total energy use, fossil fuels, natural gas (NG) use, coal use, and petroleum use; emissions of carbon dioxide (CO_2)-equivalent greenhouse gases (GHGs) including CO_2, methane (CH_4), and nitrous oxide (N_2O); and emissions of six criteria pollutants — volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter with a diameter of 10 micrometers or less (PM_{10}) and 2.5 micrometers or less ($PM_{2.5}$), and sulfur oxides (SO_x). These criteria pollutant emissions are further separated into total and urban emissions to reflect human exposure to air pollution caused by emissions of the six criteria pollutants.

Our analysis in this study includes the following six fuel pathways:

(1) Conventional petroleum-based reformulated gasoline (RFG);

(2) Conventional petroleum-based low-sulfur diesel (LSD) with 15 parts per million (ppm) sulfur content;

(3) Soybean-based biodiesel produced by using the transesterification process;

(4) Soybean-based renewable diesel I ("SuperCetane") produced by using the hydrogenation process;

(5) Soybean-based renewable diesel II ("green diesel") produced by using the hydrogenation process; and

(6) Renewable gasoline ("green gasoline") produced by using catalytic cracking.

We used petroleum gasoline and diesel as the baseline fuels; our analysis was conducted for year 2010. We estimated consumption of total energy, fossil energy, and petroleum oil and emissions of GHGs (CO_2, N_2O, and CH_4) for each of the six pathways. Figure 1-1 illustrates the system boundary for the six fuel pathways. The four soybean-based pathways consist of six stages: (1) farming activities, including manufacture of fertilizer and other chemicals, soybean farming, and soybean harvest; (2) soybean transportation from farms to processing plants; (3) soy oil extraction in processing plants; (4) production of biodiesel or other renewable fuels in plants; (5) fuel transportation and distribution from plants to refueling stations; and (6) fuel use during vehicle operation. As shown, the four soybean-based fuel pathways have three common stages: soybean farming, soybean transportation, and soy oil extraction. The four paths differ in terms of their fuel production processes and vehicle operations.

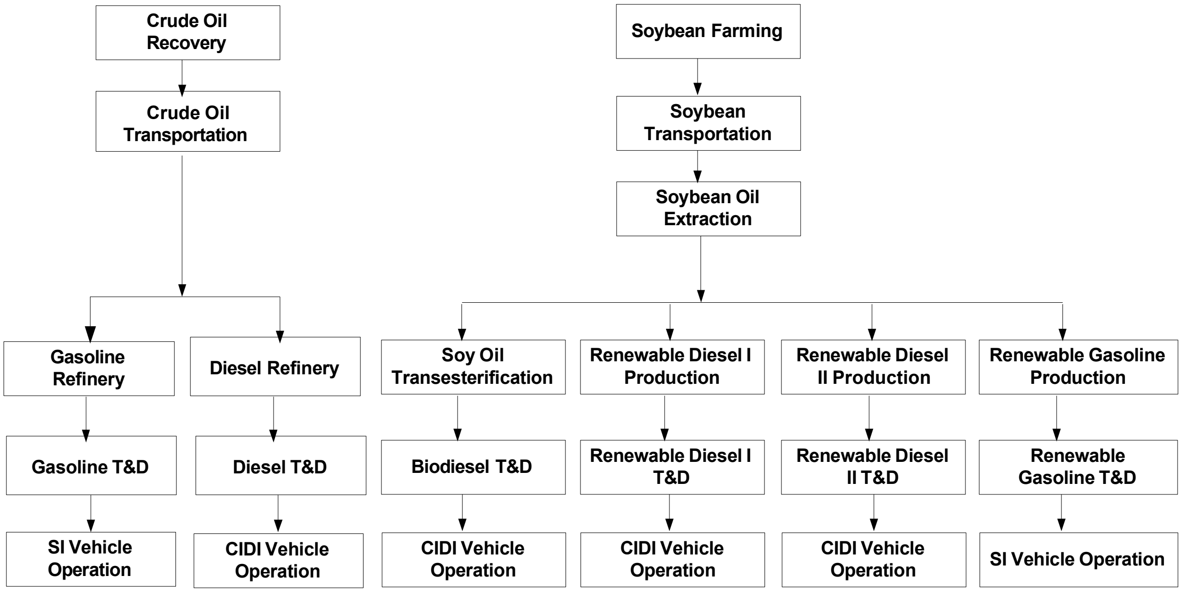


Figure 1-1 System Boundaries for Life-Cycle Analysis of Petroleum Gasoline and Diesel Fuels and Soybean-Based Biodiesel and Renewable Fuels

The pathways for petroleum gasoline, petroleum diesel, and soybean-based biodiesel had been incorporated into the GREET model before this study. However, for this study, we updated soybean farming simulations in GREET with the latest U.S. Department of Agriculture data on energy and fertilizer use associated with soybean farming (USDA 2007a, b). We updated N_2O emission simulations for soybean fields by using newly released data from the Intergovernmental Panel on Climate Change (IPCC 2006). Moreover, we expanded GREET to include pathways for soybean-based renewable diesel and gasoline.

Process energy and mass balance data for the four soybean-based fuels are from our evaluation of available literature and process simulations by the National Renewable Energy Laboratory (NREL) using the ASPEN model. The processing of energy and mass balance data is described in Section 2. Section 3 presents the key issues regarding life-cycle simulations, gives GREET input assumptions, and compares the different production processes and fuel properties of soybean-derived fuels. Section 4 presents the approaches used to address co-product credits. Section 5 provides an analysis and comparison of the life-cycle (or well-to-wheels [WTW]) energy and emission results for the six pathways examined in this study. Section 6 presents our conclusions. Finally, Appendices 1 and 2 present ASPEN simulations by NREL.

Note that this study does not consider potential land use changes. Increased CO_2 emissions from potential land use changes are an input option in GREET, but it was not used in the current analysis since reliable data on potential land use changes induced by soybean-based fuel production are not available. Furthermore, the main objective of this study is to concentrate on the process-related issues described above.

2 Production Processes of Soybean-Based Renewable Fuels

This section describes the three basic processes that have been proposed for renewable diesel and gasoline production: two for renewable diesel fuel and one for renewable gasoline. It also presents the results of the process modeling work undertaken by NREL to characterize the mass and energy balances associated with the three processes. The NREL-simulated results were inputs to the life-cycle analysis (LCA) described in Sections 3 and 4.

Table 2-1 provides a list of current and planned renewable energy diesel facilities. For example, ConocoPhillips is currently operating a 1,000-barrel-per-day (bpd) facility in Ireland using soybean and other vegetable oils; the company entered into a partnership with Tyson foods in April 2007 to produce up to 12,000 bpd from animal fat generated in the United States.

Refinery-based biofuels have received strong support from vehicle manufacturers, both in the United States and abroad, because their physical and chemical properties are similar to conventional petroleum-based fuels. Refinery-based biofuels have also been supported by major international oil companies because they can be delivered by using the existing fuel delivery infrastructure with no modifications.

Table 2-1 Current and Planned Renewable Diesel Facilities

Company	Size (bpd)	Location	Online Date
ConocoPhillips	1,000	Ireland	2006
ConocoPhillips	12,000	United States	To be determined
British Petroleum (BP)	1,900	Australia	2007
Neste	3,400	Finland	2007
Neste	3,400	Finland	2009
Petrobras	4 × 4,000	Brazil	2007
UOP/Eni	6,500	Italy	2009

Feedstocks that can be used in biofuel production processes include seed oils (e.g., soy, corn, canola, or palm oil), recycled oils (e.g., yellow grease or brown [trap] grease), and animal fats (e.g., tallow, lard, or fish oil). Table 2-2 lists current estimates of these oils, which amount to about 100,000 bpd (UOP 2005). Vegetable oils, particularly soybean-derived oils, are of particular interest in this study because (1) soy oil is the principal feedstock used in the United States for production of biodiesel via the transesterification process and (2) soy oil is a currently modeled pathway in GREET.

Table 2-2 Feedstock Availability for Renewable Diesel Production in the United States (UOP 2005)

Feedstock	Feedstock	Total U.S. Production (bpd)	Available for Conversion to Fuels (bpd)
Vegetable oils	Soybeans, corn, canola, palm	194,000	33,500
Recycled products	Yellow grease, brown (trap) grease	51,700	33,800
Animal fats	Tallow, lard, fish oil	71,000	32,500

Because crude oil and bio-feedstocks are derived from the same sources (i.e., crude oil owes its existence to plants and animals that have decomposed over 600 million years), the question arises: Why not add the bio-feedstocks directly to the feeds for conventional refineries? The answer is that the molecular structures of all of the bio-feedstocks listed in Table 2-2 contain significant amounts of oxygen that must be removed prior to their processing with other petroleum-based feedstocks. The two standard processes to remove oxygen from hydrocarbon feeds are hydrodeoxygenation (HDO) and decarboxylation ($DeCO_2$). Under the proper conditions and with the addition of hydrogen, the HDO reaction, given in Equation 2-1, converts the oxygen in the product feed into plain water.

$$C_nCOOH + 3H_2 \rightarrow C_{n+1} + 2H_2O \tag{2-1}$$

In the $DeCO_2$ reaction, shown in Equation 2-2, the oxygen in the feed is removed as simple CO_2 in a lead/hydrogen catalytic reaction.

$$C_nCOOH \xrightarrow{Pb/H} C_n + CO_2 \tag{2-2}$$

In reality, it is difficult to have a processing vessel where only one process occurs; in all the current renewable diesel design schemes, both reactions take place. The particular operating designs and conditions determine which process is favored. A basic tradeoff is that, in order to optimize the HDO reaction shown in Equation 2-1, additional hydrogen is required; production of the hydrogen can be expensive and can result in environmental impacts. On the other hand, the only byproduct of the HDO process (Equation 2-1) is water, while the principal by-product of the $DeCO_2$-process (Equation 2-2) is CO_2 — a GHG that is of concern in life-cycle modeling. However, the CO_2 from this process is the CO_2 uptaken during soybean growth.

2.1 Renewable Diesel Production Based on SuperCetane

The first renewable diesel production pathway, renewable diesel I, was modeled after a process called SuperCetane that was originally developed in the 1980s at the Saskatchewan Research Council and is now being developed by NRCan's CETC.

The SupereCetane process is based on adapting a conventional hydrotreating process so it can operate under proprietary operating conditions. Figure 2-1 shows a general process schematic for the SuperCetane process. A number of reactions occur in the process, including hydrocracking, hydrotreating, and hydrogenation. The hydrocracking process breaks apart large molecules; the hydrotreating removes oxygen. The process uses a conventional commercial refinery hydrotreating catalyst and hydrogen to produce a hydrocarbon liquid. This liquid can be distilled into three basic fractions: naphtha, middle distillate (or SuperCetane), and waxy residues. The principal product, the middle distillate, can be produced at yields of 70–80%. Because of the high cetane number (around 100), CETC believes that SuperCetane may prove most valuable as a blending agent for lower-quality diesels (CETC undated).

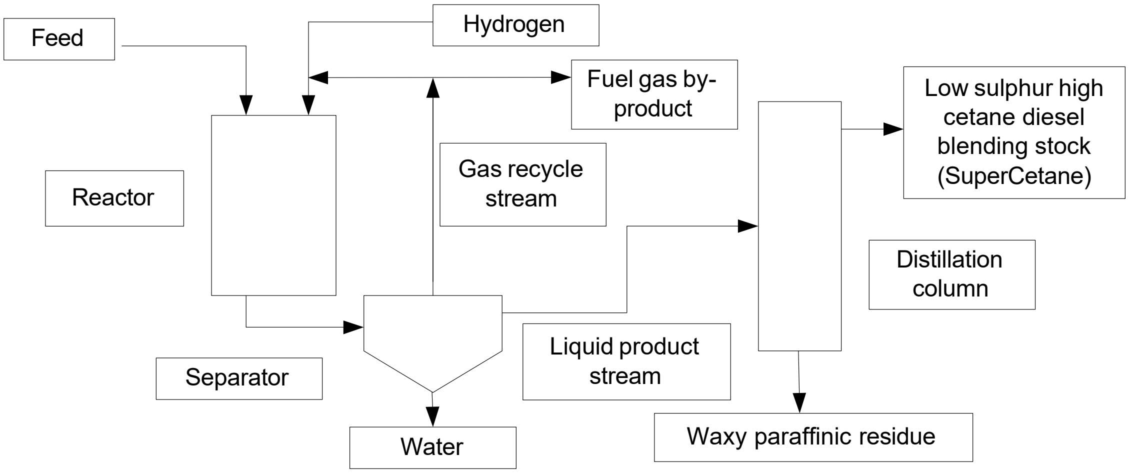


Figure 2-1 SuperCetane Process Flow
(NRCan 2003)

The process has been used successfully in a 1-bpd pilot reactor. Feedstocks used in the pilot process include canola oil, soy oil, yellow grease, animal tallow, and tall oil (a by-product of the kraft pulping process). An important characteristic of this processing scheme is that internally generated fuel gas is combusted on site to meet facility steam requirements. Thus, all energy demands except electricity are met on site.

2.2 Renewable Diesel Production Based on UOP Hydrogenation Technology

The second renewable diesel production pathway, renewable diesel II, was modeled on a hydrogenation process developed by UOP, a leading supplier and licensor of process technology, catalysts, adsorbents, process plants, and consulting services to the petroleum refining, petrochemical, and gas processing industries. UOP, located in Des Plaines, Illinois, is a wholly owned subsidiary of Honeywell International. In 2005, UOP conducted a study for DOE entitled *Opportunities for Biorenewables in Oil Refineries* (UOP 2005). In November 2006, UOP announced the formation of a new Renewable Energy and Chemicals business unit focused on using the company's refinery skills to develop profitable and efficient ways to enable refineries to convert bio-feedstocks (e.g., vegetable oils and greases) into valuable fuels and chemicals.

UOP took another major step in June 2007, when the company announced that it had entered into an agreement with Eni S.p.A, a large European refiner, to build a 6,500-bpd renewable diesel unit in Livorno, Italy. The facility, which will process soy, rapeseed, palm, and other oils, is expected to come online in 2009. Facility operations will be based on a newly branded UOP process called Ecofining^{TM}. UOP has also announced that the technology that it developed in partnership with Eni integrates seamlessly into existing refinery operations and is currently available for licensing. The most recent license was granted to Galp Energia, Portugal's largest refiner, to develop a 6,500-bpd facility in Sines, Portugal (Reuters News 2007).

In its study for DOE, UOP examined two potential approaches for renewable diesel production. The first involved co-processing the bio-feedstock in an existing hydroprocessing unit; the second involved processing the bio-feedstock in a standalone processing unit. In order to design a process comparable to the CETC process modeled for renewable diesel I, the UOP standalone process scheme was characterized for this project by using ASPEN modeling. Figure 2-2 shows the basic production scheme for the UOP process in standalone mode.

In the standalone process, the bio-feedstock is fed into a diesel hydrotreater, where hydrogen and steam are added. An advantage of the UOP operating scheme is that, although the principal product is renewable diesel, the by-product is a valuable propane fuel mix. UOP reports that its resultant renewable diesel has a cetane value in the 70–90 range, offering significant blending benefits for existing refinery operations. UOP notes that when the standalone process is used, additional pretreatment is required to remove contaminants such as water, alkali metals,

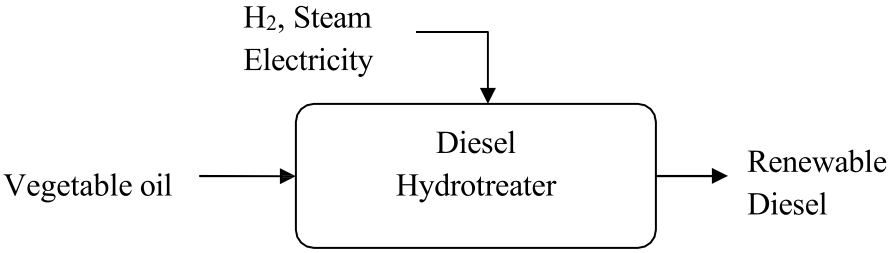


Figure 2-2 UOP-Proposed Standalone Renewable Diesel Production (UOP 2005)

phosphorous, and ash. These would be removed by using a combination of existing equipment, such as hydrocyclones, desalting, acid washing, ion exchange, or fixed-guard bed catalyst systems (UOP 2005).

2.3 Renewable Gasoline Production Based on UOP FCC Technology

As mentioned earlier, because bio-feedstocks are basically chains of carbon and hydrogen with added oxygen, standard refinery vessels could be modified to produce gasoline from these feedstocks. UOP has proposed such a scheme based on the use of an FCC unit (UOP 2005). (It should be noted that renewable gasoline is not nearly as far along the commercialization path as the renewable diesel processes discussed in Sections 2.2 and 2.3.) Figure 2-3 shows the general flow of the system proposed by UOP. As in the case of renewable diesel, the first step is pretreatment of the bio-feedstock; in this case, primarily to remove metals like calcium and potassium that would poison the FCC catalyst. Pretreatment also prevents metallurgy issues in the feed system, especially when processing greases. The pretreated oil is fed into the FCC unit along with the vacuum gas oil (VGO) stream. It should be noted that in the ASPEN modeling runs used to characterize renewable gasoline in Table 2-3, the FCC unit was characterized with only soybean oil feedstock. Although the standalone production of green gasoline would probably not be as economical as dual processing with VGO, it does allow for comparable life-cycle analysis, which is the principal thrust of this study. One of the differences between the renewable gasoline and the renewable diesel processes is that additional hydrogen is not required for the gasoline process. Another difference is that a significant portion of the energy value of the feedstock is contained in process by-products rather than the desired end product: renewable gasoline. The other principal product streams include light ends, light-cycle oil (LCO), and clarified slurry oil (CSO).

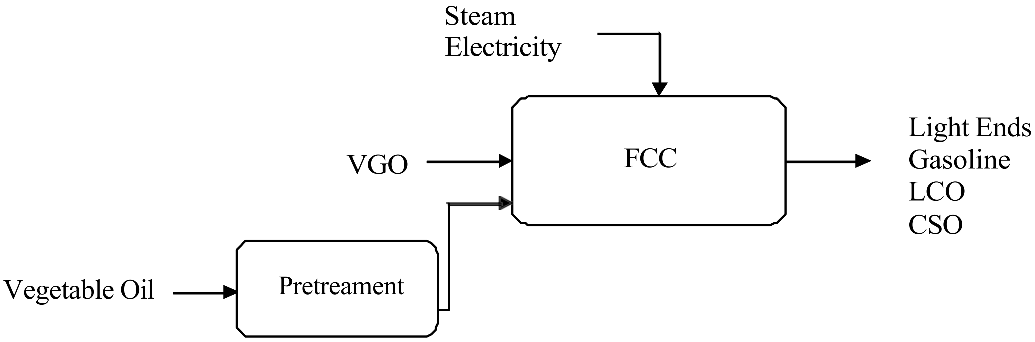


Figure 2-3 UOP Proposed Renewable Gasoline Production (UOP 2005)

2.4 ASPEN Model Results

A specific goal of the GREET WTW modeling has been to compare various transport fuels on a consistent basis. Consistency is achieved by basing model calculations on process mass and energy balances that are validated by using data from commercial operating facilities. Modeling of new renewable energy fuels thus presents a problem because facility mass and energy balances are either unavailable or available only from limited pilot plant operations that may not reflect mature commercial operating conditions.

For the three new fuels characterized in this report (pathways 4 through 6), NREL developed initial mass and energy balances by using the ASPEN process simulation model. The NREL-modeled mass and energy balances for the three fuels are listed in Table 2-3. Details of NREL's ASPEN simulations are presented in Appendices 1 and 2. Note that all data have been normalized to the basis of one pound of final fuel product. This adjustment allows the data to be incorporated into GREET on a consistent basis with existing fuel paths. The emissions presented in the table were estimated by using standard AP-42 emission factors.

To conduct the GREET analysis by using the three new renewable fuel pathways, additional component energy data are needed. The values used in the simulation were provided by NREL and are listed in Table 2-4. As data from commercial facility operations become available, the information will need to be updated to reflect any changes that might occur as the technologies mature.

The ASPEN simulations showed the mass and energy flow differences that were expected from proposed technology design schemes. For example, when renewable diesel I and renewable diesel II are compared, differences in hydrogen requirements, as well as the resultant CO_2 emissions, demonstrate the extent to which the HDO or $DeCO_2$ reaction was favored by the

Table 2-3 NREL-Simulated Renewable Fuels Mass and Energy Balances

	Fuel		
Inputs and Outputs	**Renewable Diesel I (SuperCetane)**	**Renewable Diesel II (UOP-HDO)**	**Renewable Gasoline**
Inputs (lb per lb of final fuel product)			
Soybean oil	1.510	1.174	2.2313
Hydrogen	0.030	0.032	
Steam		0.0329	0.0286
Air	0.9588		1.6782
Boiler feed water (BFW)			1.47
Outputs (lb/lb soybean oil)			
Renewable diesel	1.000	1.000	
Renewable gasoline			1.000
Fuel gas	0.253		
Product gas			0.3447
Heavies	0.175		
Water vapor	0.200		0.0287
Propane fuel mix		0.059	
CO_2[a]	0.049	0.082	0.4103
LCO			0.2454
CSO			0.2914
Water-to-wastewater treatment (WWT)	0.0663	0.0971	0.2599
Return BFW/steam			1.47
O_2	0.0201		0.0593
N_2	0.7355		1.2675
Energy Inputs (unit per lb of final fuel product)			
Steam (Btu)	Process is self-sufficient in energy	84.05	–1,237
Electricity (kWh)	0.0394	0.0275	0.0544
CW (lb/h)	65.06	27.11	50.3

[a]: This is the amount of CO_2 from feedstock oil, which is eventually from the air during soybean growth

process design. Another difference is that all facility energy demands (except electricity) are met by recycling process-generated fuel gas in the renewable diesel I scheme. This process characteristic increases facility emissions and reduces facility energy by-products. These types of tradeoffs are central to the use of GREET in linking the new fuels to the existing fuel pathways in order to assess their life-cycle energy and GHG emission impacts.

Table 2-4 NREL-Provided Base Energy Values of Renewable Fuel Components

Component	Lower Heating Value (Btu/lb)
Soybean oil	16,000
H_2[a]	52,226
Renewable diesel I – SuperCetane	18,746
Renewable diesel II – UOP	18,925
Renewable gasoline	18,679
Fuel gas	27,999
Product gas	18,316
Heavies	20,617
Propane fuel mix	18,568
LCO	19,305
CSO	18,738

[a] Simulation of hydrogen production is done inside GREET. In this analysis, we assumed that hydrogen would be produced from natural gas via steam methane reforming.

3 Data Sources and Assumptions for GREET Simulations

3.1 Soybean Farming

3.1.1 Yield

Soybean yield (in bushels per acre or bu/acre) is a key factor in life-cycle analysis because it will affect energy use and fertilizer use per bushel of soybeans harvested. Soybeans were ranked the second-leading U.S. crop in terms of both harvested acreage (74.6 million acres) and revenue (19.7 billion U.S. dollars [USD]) in 2006 (USDA 2007a). Over the past several decades, both harvested acreage and soybean yield per harvested acre have experienced enormous growth, leading to total soybean production increases of 4% annually. Table 3-1 lists planted and harvested acreage and yield over the past five decades in the United States. Figure 3-1 shows the 3-year moving average of soybean yield in the United States. The soybean yield has been increasing at an annual rate of 1.2%, and this trend is expected to continue in the near future.

Table 3-1 U.S. Historical Soybean Acreage and Yields (USDA 2007a)

	Acreage (10^6 acres)		Total Production (10^6 bu)	Yield (bu/acre)		3-Year Moving Average Yield (bu/acre)	
Year	Planted	Harvested		Planted Acres	Harvested Acres	Planted Acres	Harvested Acres
1950	15.0	13.8	299.2	19.9	21.7	19.5	21.8
1960	24.4	23.7	555.1	22.7	23.5	22.9	23.7
1970	43.1	42.2	1127.1	26.2	26.7	26.3	26.9
1980	69.9	67.8	1797.5	25.7	26.5	28.8	29.3
1990	57.8	56.5	1925.9	33.3	34.1	30.4	31.1
1991	59.2	58.0	1986.5	33.6	34.2	32.8	33.5
1992	59.2	58.2	2190.4	37.0	37.6	34.6	35.3
1993	60.1	57.3	1869.7	31.1	32.6	33.9	34.8
1994	61.6	60.8	2514.9	40.8	41.4	36.3	37.2
1995	62.5	61.5	2174.3	34.8	35.3	35.6	36.4
1996	64.2	63.3	2380.3	37.1	37.6	37.6	38.1
1997	70.0	69.1	2688.8	38.4	38.9	36.8	37.3
1998	72.0	70.4	2741.0	38.1	38.9	37.9	38.5
1999	73.7	72.4	2653.8	36.0	36.6	37.5	38.2
2000	74.3	72.4	2757.8	37.1	38.1	37.1	37.9
2001	74.1	73.0	2890.7	39.0	39.6	37.4	38.1
2002	74.0	72.5	2756.1	37.3	38.0	37.8	38.6
2003	73.4	72.5	2453.7	33.4	33.9	36.6	37.2
2004	75.2	74.0	3123.7	41.5	42.2	37.4	38.0
2005	72.0	71.3	3063.2	42.5	43.0	39.2	39.7
2006	75.5	74.6	3188.2	42.2	42.7	42.1	42.7

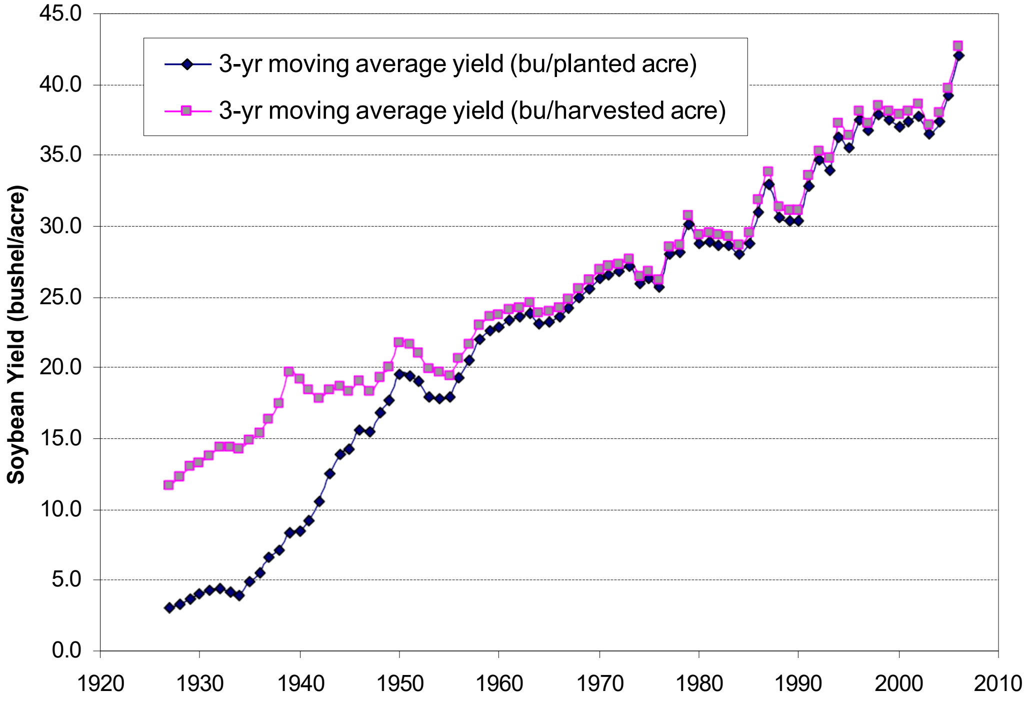


Figure 3-1 Three-Year Moving Average of Soybean Yield in the United States (USDA 2007a)

3.1.2 Energy Use

The USDA's Economic Research Service (ERS) survey data provides U.S. energy use values for soybean farming (on a per-acre basis) in 2002 (USDA 2007b); these values are listed in Table 3-2. On the basis of these energy use values and the average yields for soybeans, we estimated the energy use (by type) per bushel of soybeans harvested. We converted the values listed in Table 3-2 to Btu-based values by using the lower heating values (LHVs) of fuels in GREET: 128,450 Btu/gal for diesel; 116,090 Btu/gal for gasoline; 84,950 Btu/gal for liquefied petroleum gas (LPG); 3,412 Btu/kWh for electricity (energy loss for electricity generation is simulated separately in GREET); and 983 Btu/ft^3 for natural gas. The total energy use is estimated to be 22,084 Btu/bu: 64% diesel, 18% gasoline, 8% LPG, 7% natural gas, and 3% electricity. In comparison, Hill et al. (2006) reported 23,474 Btu/bu and 34,625 Btu/bu when custom-work-related diesel use and farm-related transportation and personal commuting energy use are taken into account. Pimentel and Patzek (2005) reported 20,447 Btu/bu of energy use for soybean production when labor, machinery, and fertilizer were taken into account. Table 3-3 provides a detailed comparison of the energy use for soybean farming across these references.

Table 3-2 Energy Use for Soybean Farming in the United States (USDA 2007b)

State	Diesel (gal/acre)	Gasoline (gal/acre)	LPG (gal/acre)	Electricity (kWh/acre)	Natural Gas (ft^3/acre)
Arkansas	9.9	1.3	L[a]	11.2	L
Illinois	2.5	0.9	0.0	L	0.0
Indiana	2.3	1.6	L	1.3	L
Iowa	3.4	1.1	0.0	0.0	0.0
Kansas	2.9	1.1	1.8	9.1	349.2
Kentucky	2.1	1.4	L	4.5	0.0
Louisiana	6.5	1.1	L	L	L
Maryland	2.9	2.1	L	0.8	0.0
Michigan	4.0	1.5	L	L	0.0
Minnesota	4.0	1.1	L	L	0.0
Mississippi	4.3	1.2	L	3.8	0.0
Missouri	4.3	1.4	L	L	0.0
Nebraska	12.9	1.3	4.4	39.4	586.4
North Carolina	2.4	1.5	L	0.6	0.0
North Dakota	3.2	1.4	L	0.8	0.0
Ohio	2.0	1.3	L	0.0	0.0
South Dakota	2.8	1.4	0.0	L	0.0
Tennessee	2.2	1.3	L	1.0	0.0
Virginia	1.9	1.2	L	L	0.0
Wisconsin	5.2	2.4	0.0	L	0.0
Average of all states	4.1	1.3	0.4	7.8	52.5
Energy use (Btu/bu)	14,221.8	3,934.1	1676.9	634.7	1619.9
Total energy use (Btu/bu)					22,087.4

[a] L = insufficient data for legal disclosure.

Table 3-3 Comparison of Energy Use for Soybean Farming Taken from Three Data Sources

	Source		
Parameter	USDA 2007b	Hill et al. 2006	Pimentel and Patzek 2005
Year	2002	2002	Not available
Energy use (Btu/bu)	22,087	23,474/34,625[a]	20,447[b]
Percentage			
Diesel	64.4	61.7	57.7
Gasoline	17.8	17.2	35.2
LP gas	7.6	4.1	3.3
Electricity	2.9	11.0	3.8
Natural gas	7.3	6.1	0

[a] The 34,625 value includes diesel use of 6.6 L/ha for custom work and farm-related transportation and personal commuting energy use equal to those values associated with corn farming.

[b] Including energy input for labor, machinery, and fertilizer.

3.1.3 Fertilizer Use

We updated fertilizer use values for soybean farming in GREET by using the newly released USDA ERS data (USDA 2007c) (see Table 3-4). We used soybean yield per planted acre to calculate the fertilizer use per bushel of soybeans. Figure 3-2 shows the fertilizer use for soybean farming over the past 15 years. The amount of fertilizer used (nitrogen [N], phosphorous [P], and potassium [K], in grams) per bushel of soybeans did not change significantly. In fact, the usage patterns for each fertilizer type follow a similar time trend. For year 2010 (as our target year for this study), the following amounts were used: nitrogen at 61.2 g/bu, phosphorus at 186.1 g/bu, and potassium at 325.5 g/bu. The energy use and emissions for fertilizer manufacturing are simulated separately in GREET. On the basis of GREET simulations, the total energy use values per gram of fertilizer produced are 45.9 Btu/g N, 13.29 Btu/g P, and 8.42 Btu/g K.

Table 3-4 Fertilizer Use for Soybean Farming (USDA 2007c)

Year	Percent Acreage Receiving Nitrogen Fertilizer	Nitrogen Application Rate (lb/received acre)	Percent Acreage Receiving Phosphorus Fertilizer	Phosphorus Application Rate (lb/received acre)	Percent Acreage Receiving Potassium Fertilizer	Potassium Application Rate (lb/received acre)
1988	16	22	26	48	31	79
1989	17	18	28	46	32	74
1990	17	24	24	47	29	81
1991	16	25	22	47	23	76
1992	15	22	22	47	25	75
1993	14	21	21	46	25	79
1994	13	25	20	47	25	82
1995	17	29	22	54	25	85
1996	15	24	25	49	27	85
1997	20	25	28	50	33	88
1998	17	23	24	48	27	81
1999	18	21	26	46	28	78
2000	18	24	24	48	27	76
2001	NA[a]	24	NA	49	NA	84
2002	20	21	26	49	29	89
2003	NA	NA	NA	NA	NA	NA
2004	21	28	26	69	23	121
2005	NA	NA	NA	NA	NA	NA

[a] NA = not available.

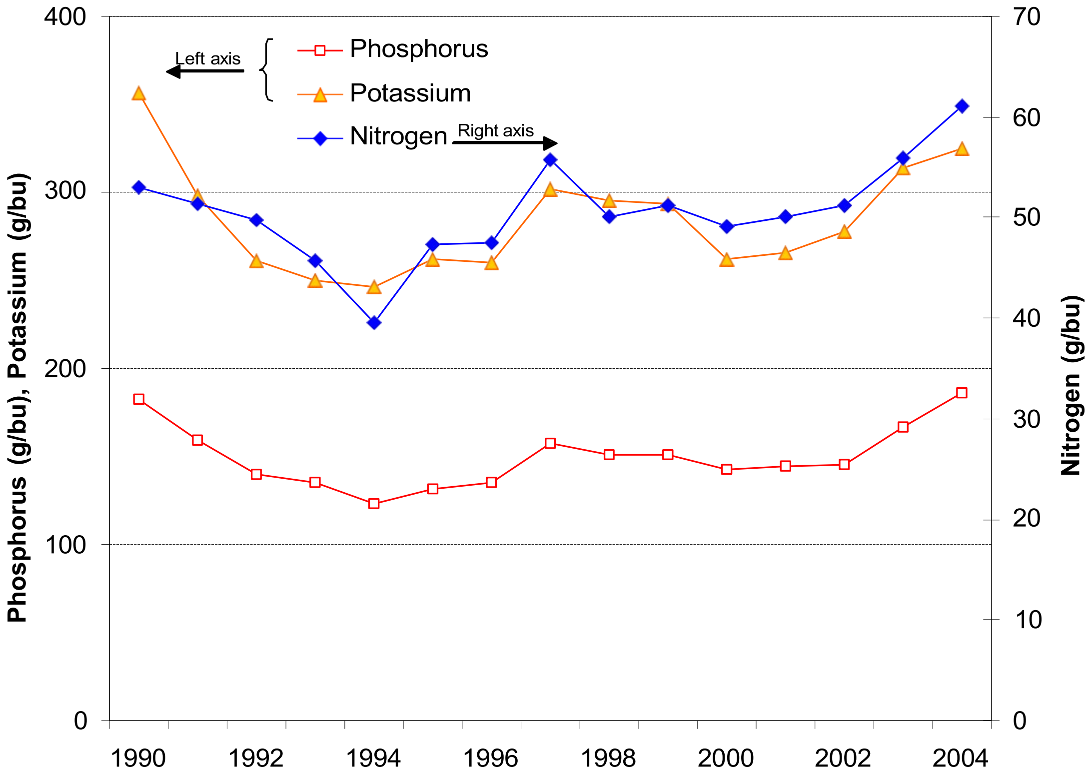


Figure 3-2 Fertilizer Use for Soybean Farming in the United States

3.1.4 N_2O Emissions

N_2O, a potent GHG, is produced from nitrogen in the soil through nitrification and denitrification processes (direct N_2O emissions). N_2O can also be produced through volatilization of nitrate from the soil to the air and through leaching and runoff of nitrate into water streams (indirect N_2O emissions).

Estimation of direct and indirect N_2O emissions from crop farming requires two important parameters: (1) the amount of nitrogen applied to soil and (2) rates for converting nitrogen into N_2O. The application of nitrogen fertilizer is the key to crop farming. For legume crops, such as soybeans, nitrogen fixation is another major nitrogen input. In 1996, IPCC considered nitrogen input to soil from biological nitrogen fixation by legume crops in estimating N_2O emissions from soil. However, in 2006, IPCC elected not to consider this nitrogen input because of a lack of evidence of significant emissions from the nitrogen fixed by legumes.

Even without considering the nitrogen that results from the biological fixation process, two sources of nitrogen inputs to soil for crop farming remain: nitrogen from fertilizer application and nitrogen in the aboveground biomass left in the field after harvest and in the belowground biomass (i.e., roots). For crops such as corn, nitrogen in the aboveground and belowground biomass is from nitrogen fertilizers. For crops such as soybeans, nitrogen in the aboveground and belowground biomass is eventually from nitrogen fertilizers and the biological nitrogen fixation process. GREET 1.8 takes into account the nitrogen in nitrogen fertilizers and the nitrogen in aboveground and belowground biomass in estimating N_2O emissions from crop farming.

For corn, IPCC (2006) estimates that aboveground biomass is 87% of corn yield (on a dry-matter basis). Aboveground biomass has a nitrogen content of 0.6%. Belowground biomass is about 22% of aboveground biomass, with a nitrogen content of 0.7%. The total amount of nitrogen in corn biomass that is left in corn fields per bushel of corn harvested is calculated as shown in Equation 3-1:

$$\begin{aligned}&56\text{ lb/bul} \times 85\%\text{ (dry matter content of corn)} \times (87\% \times 0.6\% + 87\% \times \\ &22\% \times 0.7\%) = 0.312\text{ lb N/bu} = 141.6\text{ g/bu}\end{aligned} \tag{3-1}$$

To estimate N_2O emissions from corn farming, 141.6 g of N are added to nitrogen fertilizer inputs for corn farming (which are about 420 g of N per bushel).

For soybeans, IPCC (2006) states that aboveground biomass is about 91% of soybean yield (on a dry-matter basis). Aboveground biomass has a nitrogen content of 0.8%. Belowground biomass is about 19% of aboveground biomass, with a nitrogen content of 0.8%. The total amount of nitrogen in soybean biomass that is left in soybean fields per bushel of soybean harvested is calculated as shown in Equation 3-2:

$$\begin{aligned}&60\text{ lb/bu} \times 85\%\text{ (dry matter content of soybeans)} \times \\ &(91\% \times 0.8\% + 91\% \times 19\% \times 0.8\%) = 0.442\text{ lb N/bu} = 200.7\text{ g/bu}\end{aligned} \tag{3-2}$$

To estimate N_2O emissions from soybean farming, 200.7 g of N are added to nitrogen fertilizer inputs for soybean farming (which are about 62 g of N per bushel). The rates for converting the nitrogen in soil and water streams to N_2O emissions to the air are subject to great uncertainties (Wang et al. 2003; Crutzen et al. 2007). IPCC (2006) presents a conversion rate of 1% for direct N_2O emissions from soil (compared with 1.25% in IPCC [1996]), with a range of 0.3–3%.

Indirect N_2O emissions include those from volatilization of nitrate from the soil to the air and leaching and runoff of nitrate into water streams where N_2O emissions occur. IPCC (2006) estimates a volatilization rate for soil nitrogen of 10%, with a range of 3–30%. The conversion rate of volatilized nitrogen to N in N_2O emissions is 1%, with a range of 0.2–5%. The leaching and runoff rate of soil nitrogen is estimated to be 30%, with a range of 10–80%. The conversion rate of leached and runoff nitrogen to N in N_2O emissions is 0.75%, with a range of 0.05–2.5%.

Thus, the conversion rate for direct and indirect N_2O emissions is 1.325% (1% + 10% × 1% + 30% × 0.75%). This conversion rate was used in GREET 1.8. In contrast, Crutzen et al. (2007) estimated a conversion rate of 3–5% on the basis of the global N_2O balance. While the top-down approach adopted in Crutzen et al. is a sound approach, especially for checking and verifying results against the bottom-up approach used by the IPCC and others, data for the top-down approach needs to be closely examined in order to generate reliable N_2O conversion factors. In particular, Crutzen et al. adopted the global N_2O emission balance from a 2001 study but adopted the nitrogen inputs from a separate 2004 study for deriving N_2O conversion factors. Furthermore, Crutzen et al. did not get into agricultural subsystems (such as crop farming, animal waste management, and crop residual burning), which are required for generating N_2O conversion rates for the nitrogen inputs into crop farming. Their allocation of aggregate N_2O emissions (even after subtracting N_2O emissions from industrial sources) to the aggregate agricultural system could result in overestimation of N_2O conversion rates from nitrogen inputs into crop farming systems. Nonetheless, N_2O conversion rates, which are subject to great uncertainties, need to be reconciled between the bottom-up and the top-down approach.

3.2 Soy Oil Extraction

At soybean processing plants, soybean seeds are crushed, soy oil is extracted from the crushed seeds, and crude soy oil is refined. Soybeans contain 18–20% oil by weight. To maximize soy oil production, organic solvents are used during oil extraction. The solvent extraction process is a widely used and well-established technology. The standard solvent extraction process uses n-hexane that is produced from petroleum. Most of the n-hexane used in oil extraction is recovered and recycled, with some inevitable loss. Table 3-5 presents the inputs and outputs from oil extraction plants. In calculating emissions and energy use, we assumed that steam is generated from natural gas. N-hexane is a straight-chain hydrocarbon. Commercial hexane is manufactured by distillation of straight-run gasoline produced from crude oil or natural gas liquids. In GREET, hexane is assumed to be produced from crude oil, and its upstream production energy use and emissions are adopted from energy use and emissions calculated for production of LPG from crude oil. Because hexane is volatile, the amount of hexane lost during soy oil extraction is assumed to be in the form of VOC emissions to the atmosphere. For more details, see Wang (1999).

Table 3-5 Inputs and Outputs of Soybean Oil Extraction Plants

Inputs and Outputs	GREET Value[a]
Input	
Soybeans (lb)	5.7
Steam (Btu)	2,900 (44.5%)
NG (Btu)	2,800 (43.0%)
Electricity (Btu)	614 (9.4%)
N-hexane (Btu)	205 (3.1%)
Total energy (Btu)	6,519 (100%)
Output	
Soy oil (lb)	1
Soy meal (lb)	4.48

[a] From previous GREET assumptions. We assumed in GREET that steam is produced from natural gas with an efficiency of 80%. The Btu value for steam is the natural gas Btu used to generate the needed steam. Values in parentheses are percentage shares of process fuels.

3.3 Production of Soybean-Derived Fuels

Figure 3-3 illustrates the fuel production processes for the four soybean-derived fuels.

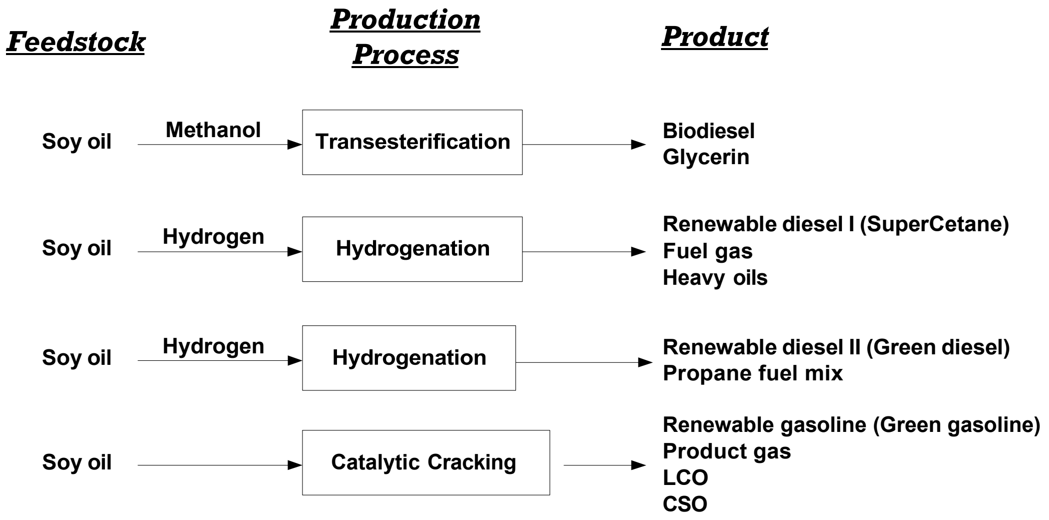
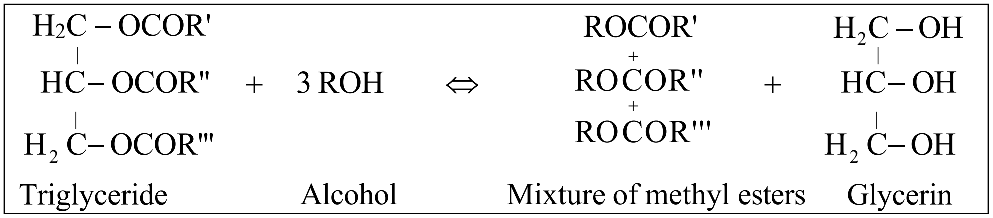


Figure 3-3 Fuel Production Processes for the Four Soybean-Derived Fuels

3.3.1 Biodiesel

Biodiesel is produced through the so-called transesterification process, in which soy oil is combined with alcohol (ethanol or methanol) in the presence of a catalyst (sodium hydroxide [NaOH] in this case) to form ethyl or methyl ester, as illustrated in Figure 3-4. The transesterification process requires steam and electricity as energy inputs and produces both biodiesel and glycerin.

For this study, we updated GREET biodiesel production simulations on the basis of data in Haas et al. (2006). Table 3-6 presents the inputs and outputs of biodiesel plants per pound of biodiesel produced. To apply the values specified in Table 3-6 to GREET, we assumed that (1) steam is generated from natural gas with an energy conversion efficiency of 80% and (2) the energy embedded in the three chemical compounds is half oil and half natural gas.



$$\begin{array}{ccccccc} H_2C-OCOR' & & & & ROCOR' & & H_2C-OH \\ | & & & & + & & | \\ HC-OCOR'' & + & 3\,ROH & \Leftrightarrow & ROCOR'' & + & HC-OH \\ | & & & & + & & | \\ H_2C-OCOR''' & & & & ROCOR''' & & H_2C-OH \end{array}$$

Figure 3-4 Transesterification of Soy Oil to Biodiesel

Table 3-6 Inputs and Outputs of Biodiesel Plants (lb or Btu/lb biodiesel)

Inputs and Outputs	Haas et al. 2006	Sheehan 1998	GREET Value
Inputs			
Soy oil (lb)	1.001	1.050	1.001
Methanol (lb)	0.1001	0.0900	0.1001
Sodium hydroxide (lb)	0.0050	0.0023	0.0050
Sodium methoxide (lb)	0.0125	0.0244	0.0125
Hydrochloric acid (lb)	0.0071	0.0077	0.0071
NG (Btu)	888	789	888
Electricity (Btu)	46	45	46
Outputs			
Biodiesel (lb)	1	1	1
Glycerin (lb)	0.116	0.213	0.213

3.3.2 Renewable Diesel I

The production of renewable diesel I comprises a series of reactions, including those involved in hydrocracking (breaking apart of large triglyceride molecules), hydrotreating (removal of oxygen), and hydrogenation (saturation of double bonds). Besides soy oil, hydrogen is needed as input. Some steam is also needed; ASPEN simulations conducted by NREL assumed that the required steam would be generated with the fuel gas and/or heavy oils that are co-produced from the plant. The output of this process is high-cetane diesel (with fuel gas and heavy oils as co-products). Table 3-7 lists the inputs and outputs of renewable diesel I plants. Note that the output values for fuel gas and heavy oils are net amounts (i.e., after steam generation for internal use). In GREET, hydrogen used in renewable diesel plants is assumed to be produced from natural gas via steam methane reforming (SMR).

Table 3-7 Inputs and Outputs of Renewable Diesel I Plants (lb or Btu per lb of renewable diesel I)

Inputs and Outputs	ASPEN Simulation Results as GREET Input
Inputs	
Soy oil (lb)	1.510
Hydrogen (lb)	0.030
Electricity (Btu)	134.4
Outputs	
Renewable diesel I (lb)	1
Fuel gas (Btu)	7083.7
Heavy oils (Btu)	3608.0

3.3.3 Renewable Diesel II

For the production of renewable diesel II, soy oil is combined with hydrogen in a catalytic reactor and then converted by a hydrogenation reaction to a high-cetane renewable diesel. This process requires electricity and thermal energy as inputs; the outputs are renewable diesel and a small amount of propane fuel mix. We assumed that thermal energy is generated from natural gas with an energy conversion efficiency of 80% and that hydrogen is produced from natural gas via SMR. Table 3-8 presents the inputs and outputs of renewable diesel plants per pound of renewable diesel II produced.

Table 3-8 Inputs and Outputs of Renewable Diesel II Plants (lb or Btu per lb of renewable diesel II)

Inputs and Outputs	ASPEN Simulation Results as GREET Input
Inputs	
Soy oil (lb)	1.174
Hydrogen (lb)	0.032
Natural gas (Btu)	84.05
Electricity (Btu)	93.83
Outputs	
Renewable diesel II (lb)	1
Propane fuel mix (Btu)	1095.5

3.3.4 Renewable Gasoline

The production of renewable gasoline takes place in an FCC unit. This process requires electricity and steam. The steam is assumed to be generated by combusting the by-product and product gas mix that results from the cracking process. The process also generates extra steam for export. The outputs are renewable diesel, product gas, LCO, and CSO. Table 3-9 presents the inputs and outputs from renewable gasoline plants per lb of renewable gasoline produced.

Table 3-9 Inputs and Outputs of Renewable Gasoline Plants (lb or Btu per lb of renewable gasoline)

Inputs and Outputs	Aspen Simulation Results as GREET Input
Inputs	
Soy oil (lb)	2.231
Electricity (Btu)	185.6
Outputs	
Renewable gasoline (lb)	1
Product gas (Btu)	6313.5
LCO (Btu)	4737.4
CSO (Btu)	5460.3

3.3.5 Comparison of the Four Soybean-Derived Fuels

On the basis of the analysis and assumptions outlined in Sections 3.3.1 through 3.3.4, Table 3-10 summarizes the energy use and amounts of product and co-product that can be produced from 1 ton of soybeans. According to Table 3-10, the transesterification process can generate a much larger amount of diesel product and co-products from 1 ton of soybeans than the other processes; however, it requires a lot more energy and chemical inputs than do the other processes. The hydrogenation process (used to produce renewable diesel II) has the best yield (in terms of energy content from 1 ton of soybeans) of the three new fuels, while it generate less energy co-product than the other processes. Because all of the processes produce other products (besides the target fuel), the energy value or market value of the co-products of these processes is an important factor in evaluating the energy and emission benefits of each soybean-based fuel. The co-product issue is discussed in Section 4. The production processes for the two renewable diesel options require hydrogen. Because hydrogen production is energy intensive, so determining which process is more energy intensive simply on the basis of inputs and outputs would not lead to a proper conclusion. The fuel cycles of hydrogen and other types of energy inputs must be taken into consideration, emphasizing the importance of a complete life-cycle analysis like the one conducted for this study.

Table 3-10 Energy Use and Amount of Fuel Product and Co-Products from One Ton of Soybeans

	Fuel			
Inputs and Outputs	**Biodiesel**	**Renewable Diesel I**	**Renewable Diesel II**	**Renewable Gasoline**
Outputs				
Product				
lb	351	232	299	157
mmBtu	5.66	4.36	5.66	2.94
Co-products				
Soy meal (lb)	1572	1572	1572	1572
Glycerin (lb)	75			
Energy co-product (mmBtu)		2.48	0.33	2.60
Inputs				
Natural gas (mmBtu)				
I. Soy oil extraction	1.80		1.80	
II. Fuel production	0.31		0.03	
Electricity (mmBtu)				
I. Soy oil extraction	0.194	0.194	0.194	0.194
II. Fuel production	0.016	0.031	0.028	0.029
Other inputs				
Methanol (mmBtu)	0.303			
Hydrogen (mmBtu)		0.36	0.49	

3.4 Fuel Properties

Table 3-11 presents the properties of the soybean-based fuels examined in this study. Compared with conventional diesel and biodiesel, renewable diesel fuels have much higher cetane numbers and lower density. Cetane number is one measure of the quality of a diesel fuel — a high number is a valuable feature for renewable diesel as a diesel blending component and a cetane enhancer.

3.5 Fuel Use in Vehicles

For our life-cycle analysis, we assumed that soybean-derived diesel fuels are used in 100% pure form in compression-ignition, direct-injection (CIDI) engine vehicles, and renewable gasoline is used in 100% pure form in spark-ignition (SI) engine vehicles. Since there were no testing data, we assumed that the fuel economy and CH_4 and N_2O emissions for CIDI vehicles are the same for all three diesel types. Likewise, we assumed that the fuel economy and CH_4 and N_2O emissions for SI vehicles are the same for the two gasoline types.

Table 3-11 Properties of the Four Soybean-Based Fuels

Fuel	Lower Heating Value (Btu/gal)	Density (lb/gal)	Carbon Content (%)[e]	Oxygen Content (%)	Cetane Value
Petroleum gasoline[a]	113,602	6.23	84.0	NA[f]	NA
Petroleum diesel[a]	129,488	7.06	87.1	0.0	40
Biodiesel[a]	119,550	7.40	77.6	11.0	50–65
Renewable diesel I[b]	117,059	6.24	87.1	0.0	100
Renewable diesel II[c]	122,887	6.49	87.1	0.0	70–90
Renewable gasoline[d]	115,983	6.21	84.0	NA	NA

[a] From the GREET model.

[b] From $(S\&T)^2$ Consultants Inc. (2004).

[c] From Kalnes et al. (2007).

[d] From UOP (2005).

[e] Because of a lack of data, the carbon content of renewable diesel fuels is assumed to be the same as that for petroleum-based diesel; the carbon content of renewable gasoline is assumed to be the same as that of petroleum-based gasoline.

F NA = not applicable.

4 Co-Product Credits for Biofuels

4.1 Methods for Addressing Co-Product Credits

The objective of calculating the credit allotted for co-products in life-cycle analysis is to fairly address the energy and emission burdens of the primary product, especially when the co-products have value in the marketplace. Two methods that are commonly used are the displacement method and the allocation method.

With the displacement method, a conventional product is assumed to be displaced by a new product. The life-cycle energy that would have been used and the emissions that would have been generated during production of the displaced product are counted as credits for the new product that is co-produced from the fuel pathway under evaluation. These credits are subtracted from the total energy use and emissions associated with the fuel pathway under evaluation. The difficulties with the displacement method involve accurately determining the displaced products and identifying the approach to obtain their life-cycle energy use and emissions. Also, if the amounts of co-products are relatively large compared with the amount of primary product from a given process (as is the case for renewable diesel I and renewable gasoline, see Table 3-10), the displacement method results — which are WTW analysis results that are mathematically normalized to production of a unit of the primary product — can generate distorted results for the primary product.

The allocation method allocates the feedstock use, energy use, and emissions between the primary product and co-products on the basis of mass, energy content, or economic revenue. This method is easier to implement in life-cycle analyses than the displacement method. However, it could result in inaccurate results if the values of product and co-products cannot be simply measured on a single basis (such as mass or energy content).

In this study, various co-products are produced during the production of soybean-based fuels, including protein products such as soy meal; solvents such as glycerin; and energy products such as propane fuel mix and heavy oils (see Table 3-10), which makes addressing their credit very difficult. If the displacement method is used, it is time-consuming to identify a displaced product for each of the co-products and obtain the life-cycle energy use and emissions of the identified products. Besides, the co-products almost have Btu values equivalent to those of their primary products (e.g., renewable diesel I and renewable gasoline), which makes the displacement method not a preferable approach. On the other hand, because these co-products have different values (for instance, the primary products and most of the co-products have Btu values and can be treated as energy products; some of the co-products, however — such as soy meal and glycerin — have nonenergy values), the Btu-based allocation method would not be able to fairly treat the co-products that have low energy contents but are valuable in other ways. The market value-based allocation method is subject to the variation in price of the co-products.

On the basis of these considerations, four approaches were employed to address the co-product issues: (1) the displacement approach, (2) an energy-based allocation method, (3) an allocation method based on the market values of the primary products and co-products, and (4) a hybrid approach that employs both the displacement and the allocation methods, in which the displacement method is used for soy meal and glycerin, and the allocation method is used for other energy co-products. For biodiesel, the hybrid approach is the same as the displacement approach. Table 4-1 summarizes the four approaches.

Table 4-1 Approaches to Address Co-Products of Soybean-Based Fuels

Fuel Product	Process	Approach 1 (Displacement)	Approach 2 (Energy-Value-Based Allocation)	Approach 3 (Market Value-Based Allocation)	Approach 4 (Hybrid)
Biodiesel production	Soy oil extraction	Displacement	Allocation	Allocation	Displacement
	Transesterification	Displacement	Allocation	Allocation	Displacement
Renewable diesel I production	Soy oil extraction	Displacement	Allocation	Allocation	Displacement
	Hydrogenation	Displacement	Allocation	Allocation	Allocation
Renewable diesel II production	Soy oil extraction	Displacement	Allocation	Allocation	Displacement
	Hydrogenation	Displacement	Allocation	Allocation	Allocation
Renewable gasoline production	Soy oil extraction	Displacement	Allocation	Allocation	Displacement
	Catalytic cracking	Displacement	Allocation	Allocation	Allocation

4.2 Displacement Approach

The first step in using the displacement method is to determine an equivalent product replaced by each co-product. Soy meal, which is primarily used as a livestock feed in the United States, is assumed in this study to replace soybeans. Soybean-based glycerin is assumed to replace petroleum-based glycerin. Other energy co-products are assumed to replace similar energy forms on the basis of their energy value; for example, fuel gas is assumed to replace equivalent-Btu natural gas for industrial use, heavy oil is assumed to replace equivalent-Btu residual oil. Table 4-2 lists the products that are to be displaced by the co-products from soybean-based fuel production.

Table 4-2 Products to Be Displaced by Co-Products

Product	Product to Be Displaced
Soy meal	Soybeans
Glycerin	Petroleum-based glycerin
Fuel gas	Natural gas
Heavy oil	Residual oil
Propane fuel mix	LPG
Product gas	Natural gas
LCO	Diesel fuel
CSO	Residual oil

The energy use and emissions resulting from production of one million Btu of natural gas, residual oil, LPG, and diesel fuel are already simulated in GREET and can be readily used. Also, GREET has addressed life-cycle energy use and emissions for obtaining soybeans, including soybean farming and fertilizer manufacturing, and these results are also readily used.

However, the displacement ratio between soy meal and soybeans for the purpose of feeding animals is yet to be determined in our study. Moreover, life-cycle analysis for petroleum-based glycerin is not included in GREET and thus needs further examination in this study.

4.2.1 Soy Meal

The displacement ratio of soy meal to soybeans is determined by protein content. Literature reports a protein content of 44–50% in soybean meal and 35–40% in soybeans (Ahmed et al. 1994; Maier et al. 1998; Britzman 2000). In this study, we assumed that soy meal contains 48% protein and soybeans contain 40%. On the basis of that assumption, we estimated that 1 lb of soy meal can replace 1.2 lb of soybeans.

4.2.2 Glycerin

Glycerin produced from petrochemical sources is called synthetic glycerin; natural glycerin is produced from plant oils and animal fats. Petroleum-based glycerin uses propylene, chlorine, and sodium hydroxide as raw materials. The theoretical raw material input to produce 1 lb of glycerin can be calculated according to the mass balance of the chemical reactions. In practice, there are some differences between theoretical mass balance and actual plant mass balance. Table 4-3 shows the amount of raw material needed to produce 1 lb of synthetic glycerin.

Table 4-3 Raw Material Input for One Pound of Synthetic Glycerin (lb/lb glycerin)

	Theoretical Input[a]	Industry Input[b]
Propylene	0.46	0.62
Chlorine	1.54	2.00
Sodium compounds	0.87	0.90

[a] Based on Chemical Economics Handbook (Greiner et al. 2005; Malveda et al. 2005).

[b] From Ahmed et al. (1994).

Production of synthetic glycerin requires little energy, so this energy is not addressed in our analysis. The energy use and emissions embedded in the raw material are the key issues in determining the life-cycle energy use and emissions of synthetic glycerin.

In this study, the production data for propylene, chlorine, and sodium hydroxide were taken from the Eco-Profile life-cycle inventory (Association of European Plastic Industry 2005). The Eco-Profile reports average industry data in detail for various petrochemical processes, including the amount of petroleum and natural gas used as feedstocks to produce each type of chemical, and the amount of petroleum, natural gas, electricity, and other fuels used as process fuels. We use the GREET model to generate the upstream energy use and emissions for the fuel (e.g., petroleum, natural gas, and electricity) used in producing propylene, chlorine, and sodium hydroxide. Table 4-4 compares the total energy embedded in raw material per pound of glycerin between our study and the study conducted by Ahmed et al. Some European studies report 30,000 to 90,000 Btu of total or fossil energy (Scharmer and Gosse 1996; Malça and Freire 2006).

Table 4-4 Total Btu in Raw Material per Pound of Glycerin

Study	Propylene	Chlorine	Sodium Hydroxide	Total
Our study	9,373	12,267	10,128	39,460
Ahmed et al. (1994)	8,577	5,319	11,275	21,296

4.3 Allocation Approach

Two different allocation approaches are applied in this study: energy-value-based and market-value-based. Generally, the allocation method is easier to implement than the displacement method in terms of data requirements. With the energy-value-based allocation method, the energy contents of the primary product and co-products are used to split the burden of energy input, feedstock input, and pollutant emissions. With the market-value-based allocation method, the market value of the products becomes the determining factor in splitting the burden.

4.3.1 Allocation at the System Level and Subsystem Level

The process of producing soybean-based fuels from soybeans involves two stages: soy oil extraction and fuel production. Both stages generate co-products, resulting in two different ways of allocating co-product credit: system level and subsystem level. As Figure 4-1 shows, system-level allocation takes soy oil extraction and fuel production processes as a whole system, with soybeans and the required energy and chemicals as inputs and fuel, soy meal, and other co-products as outputs. With the whole system level, the effect of soy oil is eliminated. Subsystem-level allocation includes two subsystems. In the first, soybeans are the inputs, and soy oil and soy meal are the outputs; in the second, soy oil is the input.

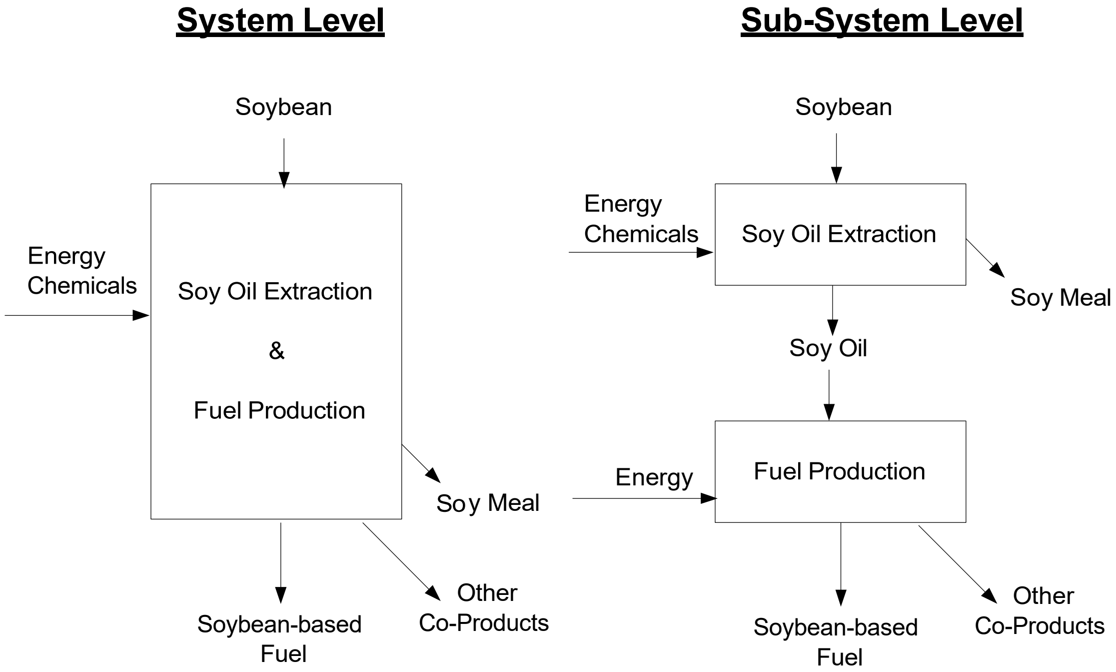


Figure 4-1 Two System Levels of Soybean-Based Fuel Production in the Allocation Approach

The displacement method will give the same final results no matter which system level is considered, but the allocation method will not. Because the allocation ratio is determined by the energy value or market value of the primary product and co-products, the variation in market value of soy oil could obviously affect the allocation results of the first subsystem level but not affect the result of the second subsystem level, which means that it could affect the final results. However, in the soybean-to-biodiesel/renewable fuels case, soy oil is only a transitional product, which is produced and then consumed, so there is no reason that its market value or other value could affect the final results. On the basis of this consideration, we selected the whole-system level for the allocation approach.

4.3.2 Energy Value and Market Value

As mentioned, the energy value and market value of the primary product and co-products are the major determining factors for splitting energy and emissions among these products by using the allocation method. The energy value of soy meal was obtained from the Soybean Meal Info Center (http://www.soymeal.org). Note that soy meal is an animal food rather than a fuel, so its energy value is measured as the energy released when it is digested. The energy content of renewable fuels and their co-products were obtained on the basis of ASPEN simulation results (see Section 2.4).

Unlike the energy content value — which is stable and will not change — the market value of products could vary over time and by region. For soy meal, we used the average growth rate of the state-average market price during the last decade (1997–2007) to project market prices in 2010 (Ash and Dohlman 2007).

The glycerin market is heavily oversupplied worldwide (Malveda et al. 2005), so the price for glycerin is not expected to rise in the near future; in fact, extensive biodiesel production could even lower glycerin's market price. We assumed a price of \$0.15/lb for glycerin, as provided in the Haas et al. (2006) study.

Because of the high cost of feedstock, the production cost of biodiesel is higher than that of conventional petroleum diesel. A wealth of research has been conducted to examine the cost for producing biodiesel at different industry scales (Haas et al. 2006; Bender 1999). These researchers estimate a production cost of \$2.00–\$2.30 per gallon of pure biodiesel, taking credits for soy meal and glycerin into consideration. The cost of biodiesel could vary significantly as a result of soybean and soy meal price variations. The United States has recently begun providing incentives to make biodiesel production costs competitive with those of petroleum-based diesel. Also, as biodiesel use increases and the infrastructure is established, the price of biodiesel could decrease. In this study, we used the biodiesel price before incentives.

For renewable diesel and gasoline fuels that are not yet on the market, we assumed the same market value as that of biodiesel fuel (on a per-million-Btu basis). Because the co-products of renewable diesel and gasoline production all have energy value and can be used in industry, we assumed the same prices per million Btu as their corresponding fuel (natural gas, residual oil, diesel, and LPG), determined as in Table 4-2. DOE's Energy Information Administration (EIA) *Annual Energy Outlook 2007* (EIA 2007a) projected the prices of natural gas, residual oil, diesel, and LPG in the industrial sector in 2010; these projected prices are used in our study.

Table 4-5 summarizes the energy content and market value of all products involved in this study. Note that prices in Table 4-5 are normalized to 2005 U.S. dollars (2005$) on the basis of an implicit U.S. price deflator from 1997 to 2006, as reported in the EIA *Annual Energy Review* (EIA 2007b).

Table 4-5 Energy Content and Market Value of Primary Products and Co-Products

Product or Co-Product	Energy Content (Btu/lb)	Market Value ($ 2005/lb)
Biodiesel	16,149	0.490
Renewable diesel I	18,746	0.569
Renewable diesel II	18,925	0.574
Renewable gasoline	18,679	0.567
Soy meal	4,246	0.274
Glycerin	7,979	0.150
Fuel gas	27,999	0.174
Heavy oils	20,617	0.195
Propane fuel mix	18,568	0.301
Product gas	18,316	0.114
LCO	19,305	0.248
CSO	18,738	0.177

4.3.3 Allocation Ratios

Table 4-6 presents the allocation ratios for the energy and emission burdens between primary products and co-products for the four soybean pathways. As indicated in Table 4-6, the allocation ratios of primary products based on energy value are a little lower than those based on market value.

4.4 Hybrid Approach

There are some shortcomings to both the displacement and allocation approaches. First, the production processes for renewable diesel I and renewable gasoline generate a large amount of

Table 4-6 Allocation Ratios of Total Energy and Emission Burdens between Primary Products and Co-Products from Using the Allocation Approach (shown as %)

Product or Co-Product	Biodiesel	Renewable Diesel I	Renewable Diesel II	Renewable Gasoline
Energy-value-based allocation				
Primary fuel (biodiesel, renewable fuels)	42.9	32.2	44.7	24.1
Co-products (soy meal, glycerin, and others)	57.1	67.8	55.3	75.9
Market-value-based allocation				
Primary fuel (biodiesel, renewable fuels)	45.7	39.4	47.4	29.9
Co-products (soy meal, glycerin, and others)	54.3	60.6	52.6	70.1

co-products, resulting in overestimation of credits for those products if the displacement method is used. In fact, using this method can even result in negative energy input and emissions. On the other hand, in the energy-based allocation method, soy meal and glycerin have values not because they have energy content but for their other applications. Soy meal, particularly, has low energy value but high protein content and is thus valuable in the animal feed market; if soy meal is treated as fuel (like other energy co-products), its credit could be greatly underestimated. The market-value-based allocation method is subject to variations in the product prices, which may lead to numerous uncertainties.

To overcome these shortcomings, we introduced a hybrid approach, in which the displacement method is used for soy meal and glycerin, and the energy-based allocation method is used for other energy co-products. For biodiesel, the hybrid approach is the same as the displacement approach. Unlike the allocation approach, which considers the production processes from soybean to fuel as a whole system, the hybrid approach separates the production system into two subsystems because each subsystem is addressed by using different allocation methods. Table 4-7 presents the allocation ratio between primary products and co-products of the second subsystem that results from using the hybrid approach.

Table 4-7 Allocation Ratios of Total Energy and Emission Burdens between Primary Products and Co-Products of the Second Subsystem from Using the Hybrid Approach (%)

Parameter	Renewable Diesel I	Renewable Diesel II	Renewable Gasoline
Primary fuel (renewable fuels)	63.7	94.5	53.1
Co-products (heavy oil, etc)	36.3	5.5	46.9

5 Life-Cycle Energy and GHG Emission Results for Soybean-Derived Fuels

On the basis of the data and key assumptions presented in Section 3 and Section 4, we used GREET to conduct life-cycle simulations of energy use and GHG emissions for the six pathways examined in this study. GHG emissions are the sum of emissions of three gases — CO_2, CH_4, and N_2O — weighted by their global warming potentials. According to IPCC, the global warming potentials of CO_2, CH_4, and N_2O are 1, 25, and 298, respectively.

Figure 5-1 shows the GREET WTW modeling boundary. Results of a WTW analysis are separated into two stages: well-to-pump (WTP) and pump-to-wheels (PTW). Well-to-pump stages start with fuel feedstock recovery and end with fuels available at refueling stations. Pump-to-wheels stages cover vehicle operation activities. For example, for gasoline, the simulated stages include crude recovery; transportation of crude oil from oil fields to central storage terminals; crude oil storage at terminals; crude oil transportation from terminals to petroleum refineries; crude oil storage at refineries; crude refining to gasoline; transportation, storage, and distribution of gasoline; and combustion of gasoline in vehicles.

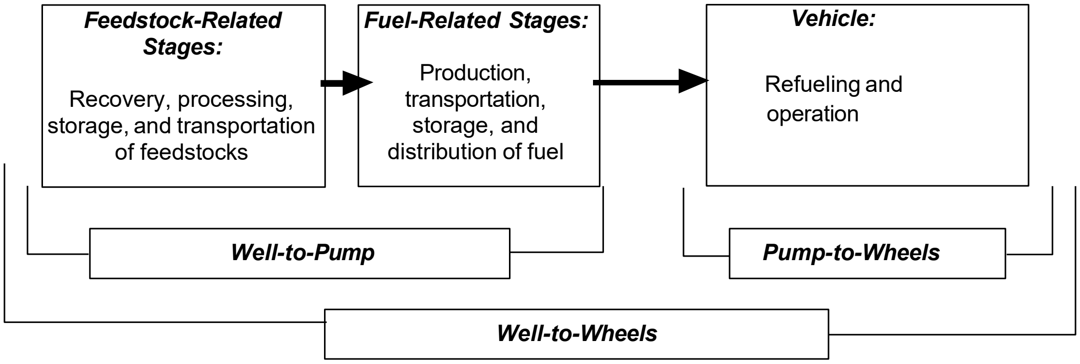


Figure 5-1 GREET Well-to-Pump and Pump-to-Wheels Stages

In the following sections, petroleum-based RFG is the baseline for soybean-based renewable gasoline, and petroleum-based LSD is the baseline for soybean-based biodiesel and renewable diesel fuels.

5.1 Total Energy Use

Figure 5-2 presents WTW total energy use for 1 million Btu of fuel produced and used. Total energy use comprises all energy sources, including fossil energy and renewable energy (excluding energy embedded in soybeans, which is eventually from solar energy).

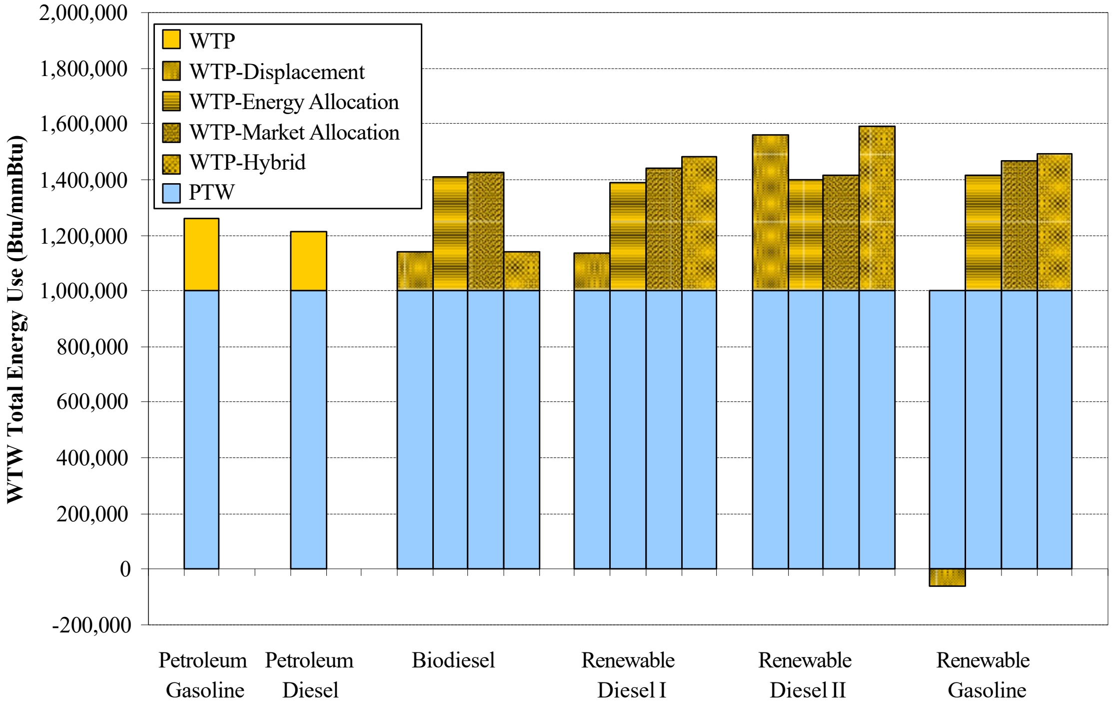


Figure 5-2 Well-to-Wheels Total Energy Use of Six Fuel Types

Figure 5-2 shows that different allocation approaches provide different results. The displacement approach gives the lowest total energy use among the four allocation approaches except in the case of renewable diesel II, whose production process generates a much smaller amount of co-product than the others. With the displacement approach, soybean-based fuels offer 6–25% lower total energy use than petroleum diesel or gasoline per million Btu, again except in the case of renewable diesel II, for which WTW total energy increases by 29% relative to LSD.

The two allocation approaches — energy-based allocation and market-based allocation — show good agreement with each other, with very similar results (1–4% difference). With the two allocation approaches, soybean-based fuels have 13–18% higher total energy use than petroleum diesel or gasoline.

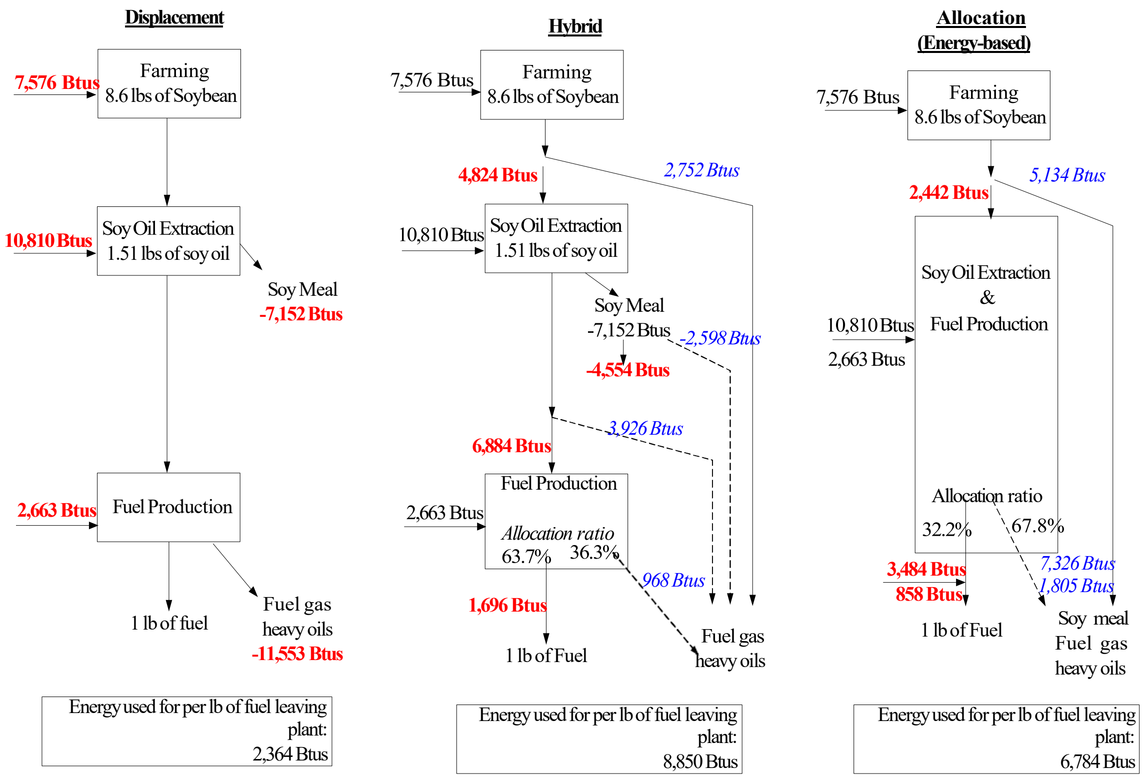


Figure 5-3 Comparison of Total Energy Use among Three Allocation Approaches for Renewable Diesel I
(Note: Red indicates energy values allocated to primary product; blue values and dashed lines indicate energy values allocated to co-products.)

The hybrid approach gives the highest total energy use results for the renewable diesel and gasoline, 19–31% higher than their conventional counterparts. Biodiesel is an exception because the hybrid approach is exactly the same as the displacement approach for biodiesel. It is interesting that the hybrid approach provides higher energy use results than the displacement and allocation approaches, because the hybrid approach is derived from the integration of the both of the latter methods. To explore the reason, Figure 5-3 compares the allocation of energy use per pound of fuel leaving the plant for the three allocation approaches, taking renewable diesel I as an example. Note that the energy use in Figure 5-3 includes farming, transportation of feedstock, and production in the plant only, not over the whole life cycle. The higher energy use of the hybrid approach compared with the displacement approach is attributable to two factors. First, the farming and production energy use allocated to the final co-products (fuel gas and heavy oil) is much lower than their displacement credit (2,752 + 3,926 + 968 for the hybrid method versus 11,533 for the displacement method). Second, part of the credit for soy meal (–2,598) is allocated to the co-product (fuel gas and heavy oil), while all soy meal credit belongs to the primary product with the displacement approach. The reason that energy use is higher for the hybrid approach than the allocation approach is because the allocation approach allocates more energy to the co-products (5,134 + 7,326 + 1,805 for the allocation method versus 2,752 + 3,926

+ 968 for the hybrid method) because the allocation ratio for co-products is much higher with the soy meal included (67.8% allocation versus 36.3% hybrid), and the difference between them (6,619) is larger than the soy meal credit earned in the hybrid approach (–4,554).

Renewable diesel II has fewer co-products; thus, its co-products and the method used to address them have a smaller effect on the results, which is apparent from the very similar energy use results among the four allocation approaches for this fuel.

5.2 Fossil Energy Use

Figure 5-4 presents the WTW fossil energy use of the six fuel options on the basis of 1 million Btu of fuel produced and used. Fossil energy use includes petroleum, natural gas, and coal.

Figure 5-4 reveals that all soybean-derived fuels offer significant reductions (52–107%) in fossil energy use. These reductions result from the fact that soybeans, as the feedstock for the four renewable fuel options, are a nonfossil feedstock. Soybean-based fuels, even with a certain amount of fossil energy input when they are used as process fuels during soybean farming and fuel production processes, can still achieve substantial reductions in fossil energy use.

Like the results for total energy use, the results for fossil energy use vary on the basis of the allocation method applied. With the displacement method, renewable gasoline can reduce WTW fossil energy use by 107% compared with petroleum gasoline. This large reduction in fossil energy use results from the large amount of co-products produced with renewable gasoline; these products were assumed to displace fossil energy (product gas to replace natural gas, LCO to replace diesel fuel, and CSO to replace residual oil), which helps renewable gasoline earn a large credit in fossil energy saving. Biodiesel, renewable diesel I, and renewable diesel II can achieve WTW fossil energy reductions of 84%, 90%, and 55%, respectively. With the allocation approach, the reduction ratios are around 63–71%. The hybrid approach shows a 52–61% reduction in fossil energy use for soybean-based renewable fuels compared with conventional fuels.

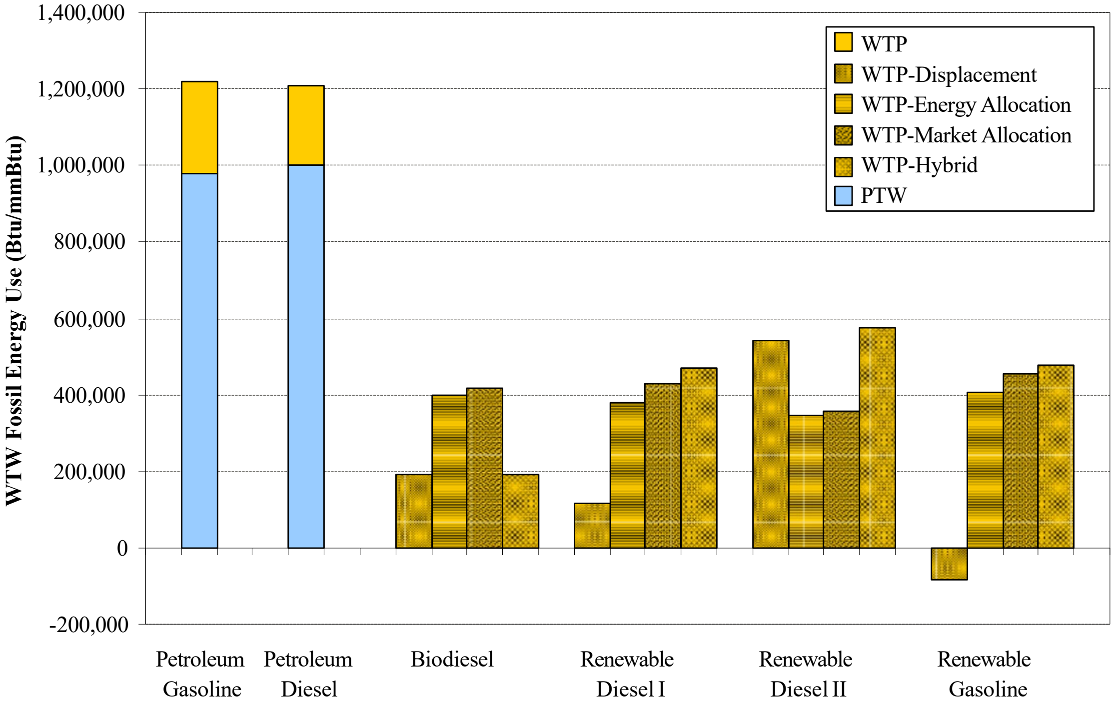


Figure 5-4 Well-to-Wheels Fossil Energy Use of the Six Fuel Types

5.3 Petroleum Use

Figure 5-5 presents the WTW petroleum energy use for the six fuel options. Soybean-derived fuels offer significant oil savings. Petroleum energy used in the soybean-based fuel cycle is entirely from the WTP stage, primarily from diesel use for farming equipment and for the trucks and locomotives needed to transport feedstock and fuel. For soybean-based fuels, PTW fuel use is zero.

All of the four soybean-derived fuels can save more than 85% of petroleum use. With the displacement approach, for each million Btu of fuel produced and used, renewable gasoline reduces petroleum use by 148% compared with petroleum gasoline, and soybean-based diesel fuels reduce petroleum use by 99–106% relative to petroleum diesel. Like fossil energy use, the petroleum use associated with renewable gasoline is low because its production process generates large quantities of co-products (product gas, LCO, and CSO) in terms of Btu, and the co-products (LCO and CSO) are assumed to replace petroleum fuels (diesel and residual oil), providing large petroleum savings credits.

With the allocation approach, petroleum use among the four soybean-based fuels is very similar; use by all is about 88–92% lower than that of conventional petroleum fuels.

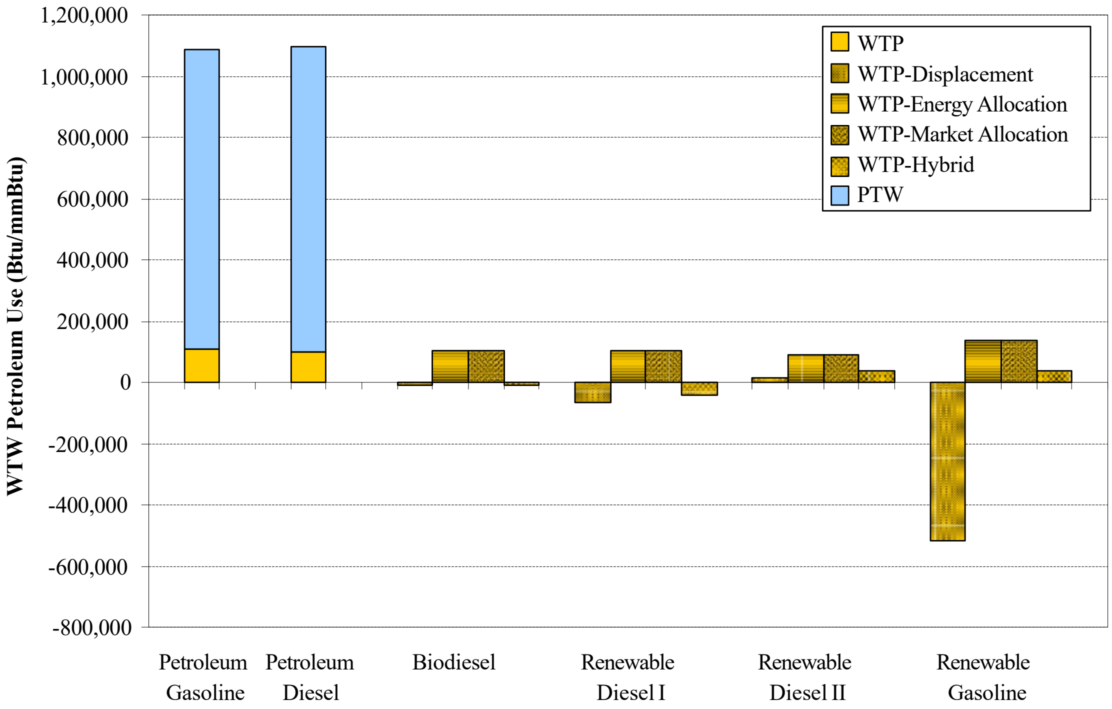


Figure 5-5 Well-to-Wheels Petroleum Energy Use of the Six Fuel Types

With the hybrid approach, soybean-based fuels reduce WTW petroleum use by 97–104% relative to petroleum fuels. Unlike total energy use and fossil energy use results, WTW petroleum use for the hybrid approach is lower than that for the allocation approach for the three renewable fuels. This is because the production process for renewable fuels uses very little petroleum, so petroleum use allocated to the co-products is very small. On the other hand, farming of soybeans, assigned to be displaced by soy meal, consumes large amounts of diesel and gasoline, and makes the hybrid approach result in lower petroleum use because of the petroleum credit from soy meal.

5.4 GHG Emissions

Figure 5-6 presents WTW CO_2-equivalent grams of GHGs (including CO_2, CH_4, and N_2O) for the six fuel pathways studied. To clearly show the GHG reduction benefit of different soybean-based fuels, Figure 5-7 presents the changes in GHG emissions of the soybean-based fuels relative to their petroleum counterparts.

The emission results for the two renewable diesel fuels depend on the allocation approach used. Of the four allocation approaches, the displacement approach offers the best GHG reduction benefit, except for renewable diesel II. When this approach is used, all four soybean-based fuels can achieve a modest to significant reduction in WTW GHG emissions (64–174%) compared

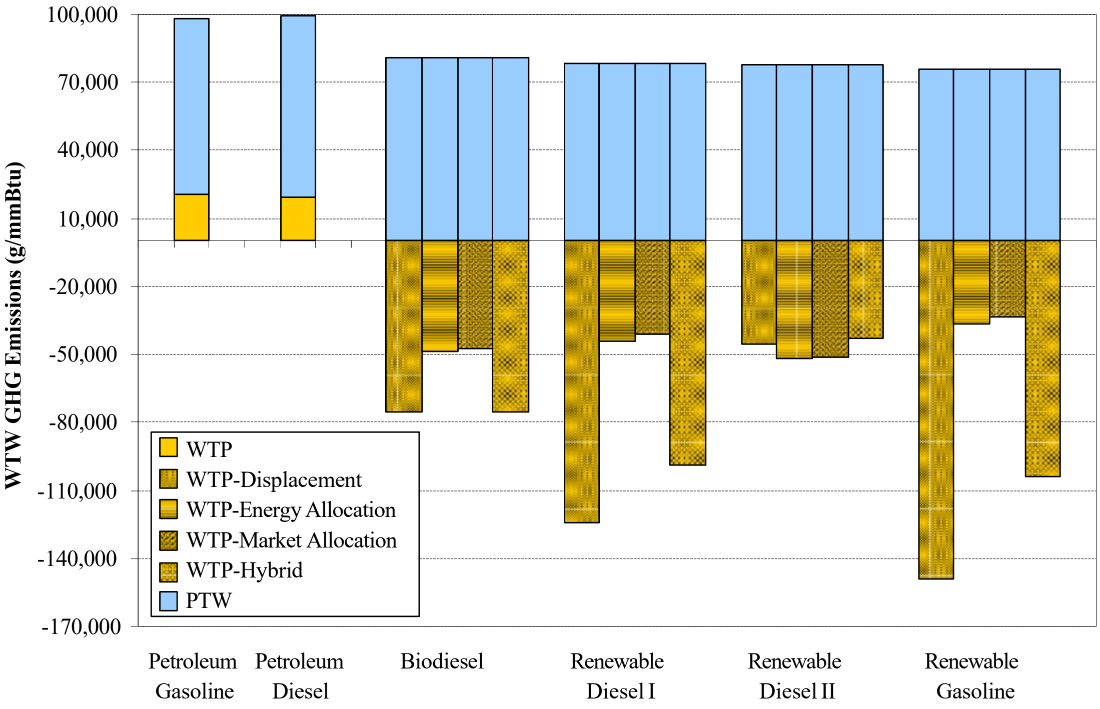


Figure 5-6 Well-to-Wheels GHG Emissions of the Six Fuel Types

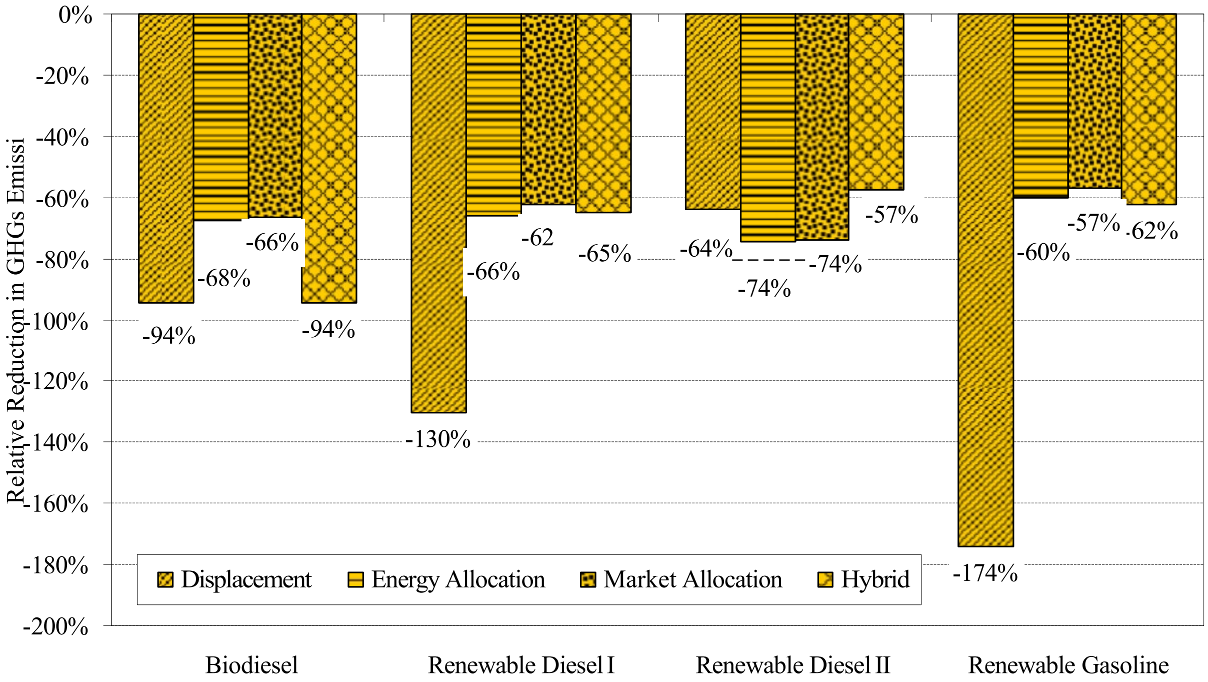


Figure 5-7 Well-to-Wheels GHG Emission Reductions for Soybean-Derived Fuels Compared with Petroleum Gasoline or Diesel

with petroleum-based fuels. The reason that renewable diesel I and renewable gasoline can achieve a much larger GHG emission reduction (-130% and –174%) is because they have a significant amount of co-products (fuel gas and heavy oil; product gas, LCO, and CSO) and because the production and combustion of the replaced fuels (natural gas, diesel fuel, and residual oil) could release lots of GHGs.

With the allocation approach, soybean-based fuels achieve a modest reduction in GHG emissions (57–74%). The results from using the hybrid approach are similar to the results obtained from using the allocation approach.

These results are based on 1 million Btu of fuel produced and used. While we do not expect significant engine efficiency differences between the two gasoline types in SI engines and among the four diesel types in CIDI engines, it is well known that CIDI engines are more efficient than SI engines. Fuel consumption in CIDI engines could be 15–20% less than that of SI engines per distance traveled. To compare WTW results on a per-mile basis among the six options, researchers could reduce energy use and GHG emissions for the four diesel fuel options as presented in Figure 5-6.

6 Conclusions

We assessed the life-cycle energy and GHG emission impacts of soybean-derived biodiesel and soybean-derived renewable diesel and gasoline fuels by expanding, updating, and using the GREET model. Soybean-derived renewable diesel is produced from hydrogenation of soy oil, and renewable gasoline is produced from catalytic cracking of soy oil.

The method applied to determine energy and emission credits for co-products is a key issue in life-cycle analysis. The production processes of the four soybean-based fuels generate various kinds of co-products, which could lead to very different results depending on the method that is used to address the co-products. We used four different allocation approaches in this study: displacement, energy-based allocation, market-value-based allocation, and a hybrid approach (integrating the displacement and allocation methods). The four allocation approaches generate considerably different results.

For WTW total energy use, the displacement approach gives the lowest total energy use for the four bio-based fuels — showing a 6–25% reduction in total energy use for the biofuels (except for renewable diesel II) compared with petroleum fuels. The two allocation approaches show good agreement with each other, providing very similar results. The hybrid approach gives the highest total energy use results. Both the allocation and hybrid approaches show a 13–31% increase in total energy use compared with petroleum fuels.

All soybean-derived fuels achieve a significant reduction (52–107%) in fossil energy use. The displacement approach offers the best benefit in fossil energy use, with a reduction of 55–107%. With the allocation approach, the reduction ratios are around 63–71%. The hybrid approach shows a 52–61% reduction in fossil energy use for soybean-based renewable fuels compared with conventional fuels.

All four of the soybean-derived fuels can save more than 85% of petroleum use. With the displacement approach, renewable gasoline reduces petroleum use by 148% compared with petroleum gasoline because its production process generates a large amount of energy co-products. Soybean-based diesel fuels reduce petroleum use by 99–106% relative to petroleum diesel. With the allocation approach, the use of petroleum by the four soybean-based fuels is about 88–92% lower than its use by conventional petroleum fuels. With the hybrid approach, soybean-based fuels reduce WTW petroleum use by 97–104% relative to petroleum fuels.

With the displacement approach, all four soybean-based fuels can achieve a modest to significant reduction in WTW GHG emissions (64–174%) compared with petroleum-based fuels. While with the allocation approach, soybean-based fuels achieve a modest reduction in GHG emissions (57–74%).

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Appendix 1: ASPEN Simulation Process of Renewable Diesel I (Super Cetane)

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Center for Transportation Technologies and Systems
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A1-1 Introduction

A preliminary analysis was conducted for a hydrogenation-derived renewable diesel (HDRD) facility on the basis of the Natural Resources Canada (NRCan) process [(S&T)^2 Consultants 2004]. NRCan has named its renewable diesel "SuperCetane." Material and energy balances were developed by using ASPEN Plus® 12.1 (super_cetane2.inp). The overall goal of the study was to confirm the preliminary overall material and energy balances provided by NRCan [(S&T)^2 Consultants 2004] and to provide input for a life-cycle analysis (LCA). The following report summarizes the basis for the analysis and its results.

A1-2 Design Basis and Process Description

HDRD is made from reacting hydrogen with oil or grease in a refinery-hydrotreating process. Several reactions occur in the conversion including hydrocracking, hydrotreating, and hydrogenation [(S&T)^2 Consultants 2004]. A commercial refinery catalyst is used to facilitate conversion.

For this analysis, the production of HDRD is based on the NRCan process, which involves hydrogen production, hydrogenation, water separation, distillation gas recycle, and steam generation. All of the unit operations were modeled except hydrogen production. It is assumed that hydrogen is supplied by an off-site hydrogen plant. Figure A1-1 is a block flow diagram of the NRCan process.

One of the important characteristics of the process is that energy demands, except electricity, are met on site. That is, a portion of the fuel gas product is combusted on site to generate steam for the process. The remaining fuel gas as well as the heavy waxy fraction are sent off site and assumed to be used for fuel. For this process configuration, the LCA will determine the emissions from the off-site fuel gas and heavies combustion as well as the electricity generation

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and will apportion it appropriately to the main process. This analysis will estimate the emissions from the fuel gas combusted on site.

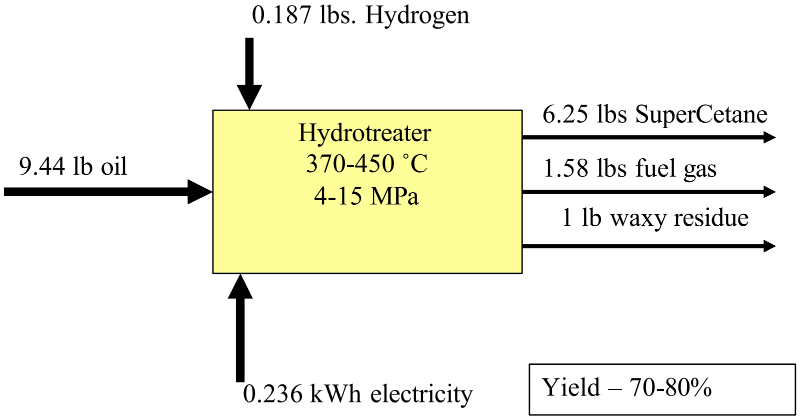

Figure A1-1 HDRD (SuperCetane) Block Flow Diagram

The renewable diesel process was modeled by using numerous assumptions and data sources. Table A1-1 summarizes the key design parameters and their sources.

Table A-1 Design Basis

Parameter	Value	Source
Feedstock		
Type	Soybean oil	Most common oil in U.S. for biodiesel
Throughput	100 lb/h	For LCA analysis
Feedstock fatty acid composition (wt fraction)		
Linolenic acid	0.075	
Palmitic acid	0.11	
Stearic acid	0.041	
Oleic acid	0.22	
Linoleic acid	0.54	
Arachidic acid	0.014	
Hydrogenation design		
Temperature	325 ºC	
Pressure	500 psia	
Yields (per pound inlet feed)		
SuperCetane		Derived from published yields [(S&T)^2 Consultants 2004]
Water	64.9%	
CO_2	5.0%	
Propane	8.2%	
Hydrogen	8.2%	
Naphtha	10.4%	
	0.35	

Several of these assumptions, particularly the feedstock choice and facility size, require further explanation. The feedstock selected was soybean oil, even though many of the feedstocks in the literature were rapeseed oil or other oils, because it is the most prevalent oil in fuels production (i.e., biodiesel), and one of the purposes of the study was to compare the environmental impacts of HDRD to biodiesel, and the most thorough LCA of biodiesel (Sheehan et al. 1998) was based on soybean oil. The facility size of 100 lb/h was selected as an easy, round number for the LCA. The results of most LCAs are shown on a pound of feed or product basis since the impacts are directly scalable to throughput. Therefore, this simple number was selected, even though this would not be a typical facility size.

A1-3 Model Description

An ASPEN Plus® model (super_cetane) was developed for the NRCan SuperCetane process, based largely on the $(S\&T)^2$ report [$(S\&T)^2$ 2004]. ASPEN Plus® is a steady-state process simulator, and Appendix A1-6 contains the input file for the model.

The ASPEN Plus® HDRD model has one flowsheet to model the four major process areas: hydrogenation, sour water separation, stripping, and pressure swing adsorption (PSA)/gas recycle. Each of these areas is briefly discussed, and the flow diagram from ASPEN Plus® is presented. The flow diagram shows only those unit operations modeled in ASPEN Plus®. Equipment used for operations such as conveyance, size reduction, and storage is generally not included in the model. The power requirements of this equipment, however, are included and are modeled as work streams.

ASPEN Plus® is composed of physical property and unit operation models that are combined into a process model. The simulation can be broken into three major sections: components (i.e., chemical species), physical property option sets (e.g., what set of physical property models to use), and the flowsheet (i.e., the series of unit operations). Each of these sections is described in more detail below.

Components

Fourteen components were modeled in the simulation; all were modeled as conventional (e.g., water) components in the mixed substream. The following is a list of the components in the simulation:

- Hydrogen – H_2
- Linolenic acid – $C_{18}H_{30}O_2$
- Palmitic acid – $C_{16}H_{32}O_2$

- Stearic acid – $C_{18}H_{36}O_2$
- Linoleic acid – $C_{18}H_{32}O_2$
- Arachidic acid – $C_{20}H_{40}O_2$
- Oleic acid – $C_{18}H_{34}O_2$
- Green Diesel – $C_{18}H_{38}$
- Water – H_2O
- Hydrogen Sulfide – H_2S
- Ammonia – NH_3
- Propane – C_3H_8
- Naphtha
- Oxygen – O_2
- Nitrogen – N_2
- Wax – $C_{26}H_{54}$
- Carbon dioxide – CO_2

Green diesel is not a specific compound but is a complex mixture of hydrocarbons; however, for simplicity, it was modeled as a single component, $C_{18}H_{38}$, which is within the range of diesel hydrocarbons. Green diesel was specified with a specific gravity of 0.78 (Marker, T. 2007) and a MW of 254. Naphtha was specified with a specific gravity of 0.7 and a MW of 100.

As noted earlier, the vegetable oil feed was modeled as a mixture of six fatty acids: linolenic acid, palmitic acid, stearic acid, linoleic acid, arachidic acid, and oleic acid. All of these components are available in the ASPEN Plus® databanks. Table A1-2 shows the molecular formula, the component name in the model, and the weight fraction in the feed of each fatty acid.

Table A1-2 Organic Acid Composition of Bio-Oil

Organic Fatty Acid	Composition	Component Name	Weight Fraction
Linolenic	$C_{18}H_{30}O_2$	LINOL3	0.075
Palmitic	$C_{16}H_{32}O_2$	PALM	0.11
Stearic	$C_{18}H_{36}O_2$	STEARIC	0.041
Oleic	$C_{18}H_{34}O_2$	OLEIC	0.22
Linoleic	$C_{18}H_{32}O_2$	LINOL2	0.54
Arachidic	$C_{20}H_{40}O_2$	ARACHID	0.014

One Henry component, CO_2, was specified. The Henry's constants were obtained from ASPEN Plus®.

Physical Property Option Sets

The physical property set selected was POLYUF with properties estimated by using the POLYNRTL method. Physical property databanks used in the simulation were PURE13, AQUEOUS, SOLIDS AND INORGANIC.

Flowsheet

One flowsheet was developed for the process: (A1000). The flowsheet is briefly discussed, and flow diagrams from ASPEN Plus® are presented. The flow diagrams (Figure A1-2) show only those unit operations modeled in ASPEN Plus®. Equipment used for operations such as conveyance and storage are generally not included in the model and are thus not shown. Similarly, certain complex unit operations (e.g., gas turbine) require several ASPEN Plus® models (e.g., compressors, reactors, heat exchangers).

Bio-oil is introduced into the process in stream 101. It is assumed to be at ambient conditions (i.e., 68°F and 14.7 psia) with a flow rate of a nominal 100 lb/h. The 100 lb/h value was selected as it would be easily scaled to any other value; since the model was developed to be the basis for an LCA, any flow rate would be reasonable.

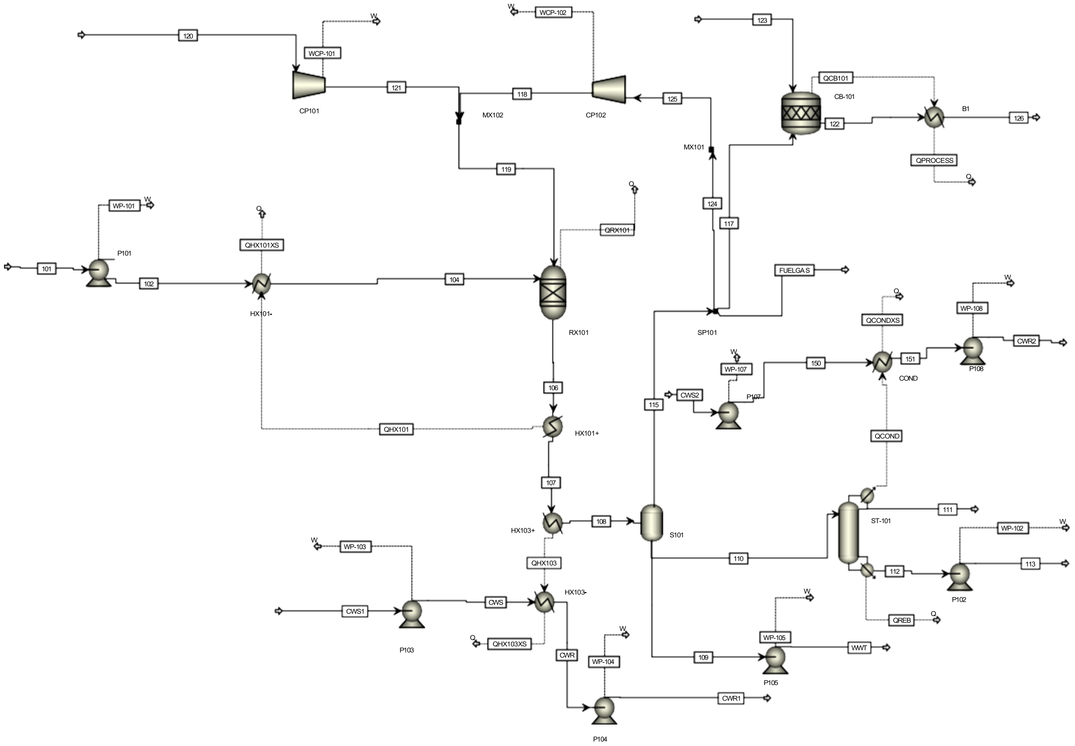

Figure A1-2 ASPEN Simulation Process Flowcharts for Renewable Diesel I (SuperCetane)

Hydrogenation

As shown in Figure A1-2, the soybean oil feed (Stream 101) is pumped to 500 psia (P-101) and then mixed with recycle oil (Stream 110C) from the splitter, SP-101, following the sour water separator (S101). This stream is then heated to 290°F by exchange with hydrogenator effluent (Stream 106) in HX101+ and HX101−. The next stage of the process is the hydrogenator, where the oil stream is combined with the inlet hydrogen (Stream 120) and recycle fuel gas (Stream 118) and reacted.

The hydrogenator (RX101) is modeled as an RYIELD reactor. All of the incoming oil is converted to gas (e.g., CO_2, H_2, propane), water, green diesel (GDSL), waxes, and a small amount of naphtha. As noted in the design basis, the yield of green diesel is estimated at 64.5% of the total inlet feed streams on a mass basis. The hydrogenation reactions are exothermic, and there is excess heat (QRX101) after the reactor is brought to reaction temperature (325°C).

After the oil feed is preheated, the hydrogenator effluent (Stream 107) is cooled with cooling water (Stream CWS1) to 100°F in HX103. The cooled reactor products are then sent to the sour water separation, S101.

Sour Water Separation

In sour water separation, the gases (Stream 115) are flashed off and sent to a splitter (SP101) for recycle, combustion, and product recovery. The aqueous stream is decanted and sent to wastewater treatment (Stream 109). After the separator, the organic stream (110) is sent to a distillation column (ST-101) for product recovery.

Product Recovery

The product recovery area consists of a distillation column where the SuperCetane (Stream 111) with a small amount of naphtha is separated from the heavies (Stream 112). The distillation column is modeled as a RADFRAC column with eight stages with both a condenser and a reboiler. The system is operated at 100 psi (stage 1). The feed is introduced on stage 5, while SuperCetane is recovered on stage 1, and the heavies are taken off on stage 8.

Gas Recycle

As noted earlier, the off-gas from the water separator, S101, is sent to a splitter where it is separated for gas recycle (124), combustion (117), and product (FUELGAS). The amount of product is controlled by overall process yields, while the amount sent to combustion is specified so that the system's energy demand is satisfied.

Heat Generation

The last major section of the flowsheet is steam generation. Here, some of the fuel gas is combusted (CB-101), which is operated at 1700°F. Heat is recovered from the off-gases in a HEATER block, B1. The amount of heat recovery is compared to the process heat demands [e.g., the reboiler (QREB)] to ensure that enough heat is available. A more rigorous model could be developed that would generate steam and meet the specific heat demands of each unit operation. For this analysis, this gross heat balance was deemed sufficient.

A1-4 Results and Discussion

This effort was aimed at confirming the material and energy balances summarized for the NRCan process. As shown in the table below, the ASPEN Plus® model shows good agreement with the published literature. All of the yields and utility requirements are similar between the model and the literature. Table A1-3 compares the results of this modeling effort and the values from the $(S\&T)^2$ Consultants (2004).

Table A1-3 Comparison of Overall Mass and Energy Balances

Feedstock	NRCan Yield per 100 lb oil	Current Analysis per 100 lb Oil
Oil	100	100
H_2	1.98	1.98
Air		63.47
Products		
Fuel Gas	16.74	16.74
HDRD	66.21	66.2
Naphtha	0.36	
Heavies (113)	11.60	11.6
Waste water		4.39
Flue Gas (lb/h)		66.52
Flue Gas (126) (scf)		24.2
Utilities		
Electricity (kWh)	2.50	2.61
Cooling water (lb/h)		4307

Besides SuperCetane, this process generates three other products: fuel gas, naphtha, and heavies. The amount of naphtha is very small and is included in the SuperCetane product. Table A1-4 summarizes the calculated compositions of the other products.

Table A1-4 Product Compositions

Product	Composition
Fuel gas	
Propane	25.45
Carbon dioxide	27.96
Water	2.33
Hydrogen	43.68
Naphtha	0.58
LHV (Btu/lb)	27,999
Heavies	
Wax	80
Naphtha	20
LHV (Btu/lb)	20,617

In addition to the material and energy balance, the analysis projected the air emissions from the process. As noted earlier, it is assumed that a portion of the fuel gas, which is primarily propane, is combusted to make steam to meet the energy demand of the process. Air emissions of criteria pollutants were estimated on the basis of the U.S. Environmental Protection Agency's AP-42 emission factors. The fuel gas is a mix of several gases, but for this analysis, the emissions were assumed to be equivalent to natural gas combustion. Table A1-5 summarizes the emission factors and the emission rate of each pollutant.

Table A1-5 Air Emission Factors

Pollutant	Emission Factors (lb/MM scf fuel)	Emissions (lb/100 lb product)
CO	84	3.07E-03
NO_x	32	1.17E-03
PM	7.6	2.78E-04
VOCs	5.5	2.01E-04

The NRCan process uses hydrogenation to convert bio-oils like soybean oil into a diesel substitute. Several companies are looking into this process. This analysis developed an ASPEN Plus® model of the process and compared its results with published results by $(S\&T)^2$ Consultants (2004). Good agreement was obtained between the two studies. These results will be used to develop an LCA for this process.

A1-5 References

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A1-6 ASPEN Plus® Input File: Super_Cetane2.inp

```
;
;Input Summary created by Aspen Plus Rel. 20.0 at 16:58:40 Sun Oct 21, 2007
;Directory E:\HDRD  Filename E:\HDRD\super_cetane2.inp
;




TITLE ‘Super Cetane’

IN-UNITS ENG DENSITY=‘lb/gal’ POWER=kW VOLUME=gal  &
        MOLE-DENSITY=‘lbmol/gal’ MASS-DENSITY=‘lb/gal’

DEF-STREAMS CONVEN ALL

DATABANKS PURE13  / AQUEOUS  / SOLIDS  / INORGANIC  /  &
        NOASPENPCD

PROP-SOURCES PURE13  / AQUEOUS  / SOLIDS  / INORGANIC

COMPONENTS
    H2 H2 /
    LINOL3 C18H30O2 /
    PALM C16H32O2 /
    STEARIC C18H36O2 /
    OLEIC C18H34O2 /
    LINOL2 C18H32O2 /
    ARACHID C20H40O2 /
    GDSL C18H38 /
```

```
    H2O H2O /
    H2S H2S /
    NH3 H3N /
    PROPANE C3H8 /
    NAPTHA /
    CO2 CO2 /
    WAX C26H54 /
    O2 O2 /
    N2 N2

PC-USER
    IN-UNITS ENG
    PC-DEF ASPEN GDSL GRAV=0.749 MW=254.
    PC-DEF ASPEN NAPTHA GRAV=0.7 MW=72.

ADA-SETUP
    ADA-SETUP PROCEDURE=REL9

HENRY-COMPS HC-1 CO2

FLOWSHEET
    BLOCK RX101 IN=119 104 OUT=106 QRX101
    BLOCK S101 IN=108 OUT=115 110 109
    BLOCK P101 IN=101 OUT=102 WP-101
    BLOCK P102 IN=112 OUT=113 WP-102
    BLOCK CP102 IN=125 OUT=118 WCP-102
    BLOCK CP101 IN=120 OUT=121 WCP-101
    BLOCK HX101+ IN=106 OUT=107 QHX101
    BLOCK HX101- IN=102 QHX101 OUT=104 QHX101XS
    BLOCK MX102 IN=118 121 OUT=119
    BLOCK ST-101 IN=110 OUT=111 112 QCOND QREB
    BLOCK HX103+ IN=107 OUT=108 QHX103
    BLOCK HX103- IN=CWS QHX103 OUT=CWR QHX103XS
    BLOCK P105 IN=109 OUT=WWT WP-105
    BLOCK P103 IN=CWS1 OUT=CWS WP-103
    BLOCK P104 IN=CWR OUT=CWR1 WP-104
    BLOCK SP101 IN=115 OUT=117 FUELGAS 124
    BLOCK CB-101 IN=117 123 OUT=122 QCB101
    BLOCK MX101 IN=124 OUT=125
    BLOCK COND IN=150 QCOND OUT=151 QCONDXS
```

```
    BLOCK P107 IN=CWS2 OUT=150 WP-107
    BLOCK P108 IN=151 OUT=CWR2 WP-108
    BLOCK B1 IN=122 QCB101 OUT=126 QPROCESS

PROPERTIES POLYUF HENRY-COMPS=HC-1
    PROPERTIES POLYNRTL

PROP-DATA HENRY-1
    IN-UNITS ENG
    PROP-LIST HENRY
    BPVAL CO2 H2O 175.2762325 -15734.78987 -21.66900000  &
        6.12550005E-4 31.73000375 175.7300026 0.0

STREAM 101
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=68. PRES=14.7 MASS-FLOW=100.
    MASS-FRAC LINOL3 0.075 / PALM 0.11 / STEARIC 0.041 /  &
        OLEIC 0.22 / LINOL2 0.54 / ARACHID 0.014

STREAM 117
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=68. PRES=14.7 MASS-FLOW=1.
    MASS-FRAC H2 1.

STREAM 120
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=68. PRES=14.7 MASS-FLOW=100.
    MASS-FRAC H2 1.

STREAM 123
    SUBSTREAM MIXED TEMP=68. PRES=14.7 MASS-FLOW=67.
    MOLE-FRAC O2 0.21 / N2 0.79

STREAM 125
    SUBSTREAM MIXED TEMP=68. PRES=14.7 MASS-FLOW=10.
    MASS-FRAC H2 1.

STREAM CWS
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=35. <C> PRES=500. MASS-FLOW=100.
```

```
    MASS-FRAC H2O 1.

STREAM CWS1
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=35. <C> PRES=14.7 MASS-FLOW=100.
    MASS-FRAC H2O 1.

STREAM CWS2
    SUBSTREAM MIXED TEMP=35. <C> PRES=14.7 MASS-FLOW=100.
    MASS-FRAC H2O 1.

DEF-STREAMS HEAT QCB101

DEF-STREAMS HEAT QCOND

DEF-STREAMS HEAT QCONDXS

DEF-STREAMS HEAT QHX101

DEF-STREAMS HEAT QHX101XS

DEF-STREAMS HEAT QHX103

DEF-STREAMS HEAT QHX103XS

DEF-STREAMS HEAT QPROCESS

DEF-STREAMS HEAT QREB

DEF-STREAMS HEAT QRX101

DEF-STREAMS WORK WCP-101

DEF-STREAMS WORK WCP-102

DEF-STREAMS WORK WP-101

DEF-STREAMS WORK WP-102

DEF-STREAMS WORK WP-103
```

```
DEF-STREAMS WORK WP-104

DEF-STREAMS WORK WP-105

DEF-STREAMS WORK WP-107

DEF-STREAMS WORK WP-108

BLOCK MX101 MIXER

BLOCK MX102 MIXER
    IN-UNITS ENG

 BLOCK SP101 FSPLIT
     FRAC FUELGAS 0.5
     MASS-FLOW 124 10.

BLOCK B1 HEATER
    PARAM TEMP=100. PRES=14.7

BLOCK COND HEATER
    PARAM PRES=14.7 DELT=15.

BLOCK HX101+ HEATER
    IN-UNITS ENG
    PARAM TEMP=110. PRES=500.

BLOCK HX101- HEATER
    IN-UNITS ENG
    PARAM TEMP=567. PRES=500.

BLOCK HX103+ HEATER
    IN-UNITS ENG
    PARAM TEMP=100. PRES=500.

BLOCK HX103- HEATER
    IN-UNITS ENG
    PARAM PRES=500. DELT=15.
```

```
BLOCK S101 FLASH2
    IN-UNITS ENG
    PARAM TEMP=100. PRES=175.
    BLOCK-OPTION FREE-WATER=YES

BLOCK ST-101 RADFRAC
    IN-UNITS ENG
    PARAM NSTAGE=8
    COL-CONFIG CONDENSER=TOTAL REBOILER=KETTLE
    FEEDS 110 5
    PRODUCTS 111 1 L / 112 8 L
    PRODUCTS QREB 8 / QCOND 1
    P-SPEC 1 100.
    COL-SPECS DP-STAGE=1. MASS-D=66.2 MOLE-RR=0.1

BLOCK CB-101 RSTOIC
    PARAM TEMP=1700. PRES=0. COMBUSTION=YES PROD-NOX=NO2
    STOIC 1 MIXED H2 -1. / O2 -0.5 / H2O 1.
    STOIC 2 MIXED PROPANE -1. / O2 -5. / CO2 3. / H2O 4.
    STOIC 3 MIXED NAPTHA -1. / O2 -8. / CO2 5. / H2O 6.
    CONV 1 MIXED H2 1.
    CONV 2 MIXED PROPANE 1.
    CONV 3 MIXED NAPTHA 1.

BLOCK RX101 RYIELD
    IN-UNITS ENG
    PARAM TEMP=325. <C> PRES=500.
    MASS-YIELD MIXED GDSL 0.8415 / H2O 0.02125 / CO2  &
        0.10625 / PROPANE 0.029 / H2 0.001 / NAPTHA 0.01 /  &
        WAX 0.104

BLOCK P101 PUMP
    IN-UNITS ENG
    PARAM PRES=500.

BLOCK P102 PUMP
    IN-UNITS ENG
    PARAM DELP=10.
```

```
BLOCK P103 PUMP
   IN-UNITS ENG
   PARAM PRES=500. PUMP-TYPE=TURBINE

BLOCK P104 PUMP
   IN-UNITS ENG
   PARAM DELP=10.

BLOCK P105 PUMP
   IN-UNITS ENG
   PARAM DELP=10.

BLOCK P107 PUMP
   PARAM DELP=10.

BLOCK P108 PUMP
   PARAM DELP=10.

BLOCK CP101 COMPR
   IN-UNITS ENG
   PARAM TYPE=ISENTROPIC PRES=500. MODEL-TYPE=TURBINE

BLOCK CP102 COMPR
   IN-UNITS ENG
   PARAM TYPE=ISENTROPIC PRES=500. MODEL-TYPE=TURBINE

DESIGN-SPEC COMBAIR
   DEFINE O2OUT MASS-FLOW STREAM=122 SUBSTREAM=MIXED  &
      COMPONENT=O2
   DEFINE O2IN MASS-FLOW STREAM=123 SUBSTREAM=MIXED  &
      COMPONENT=O2
   SPEC “O2IN” TO “11*O2OUT”
   TOL-SPEC “1”
   VARY STREAM-VAR STREAM=123 SUBSTREAM=MIXED  &
      VARIABLE=MASS-FLOW
   LIMITS “50” “150”

DESIGN-SPEC DS-FGAS
   DEFINE SPLT BLOCK-VAR BLOCK=SP101 SENTENCE=FRAC  &
      VARIABLE=FRAC ID1=FUELGAS
```

```
    DEFINE FGAS STREAM-VAR STREAM=FUELGAS SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    SPEC “FGAS” TO “16.74”
    TOL-SPEC “0.05”
    VARY BLOCK-VAR BLOCK=SP101 SENTENCE=FRAC VARIABLE=FRAC  &
        ID1=FUELGAS
    LIMITS “0.05” “0.95”

DESIGN-SPEC DS-HX101
    IN-UNITS ENG
    DEFINE QXS INFO-VAR INFO=HEAT VARIABLE=DUTY  &
        STREAM=QHX101XS
    SPEC “QXS” TO “0.0”
    TOL-SPEC “0.1”
    VARY BLOCK-VAR BLOCK=HX101+ VARIABLE=TEMP SENTENCE=PARAM
    LIMITS “100” “617”

DESIGN-SPEC DS-HX103
    IN-UNITS ENG
    DEFINE CWIN STREAM-VAR STREAM=CWS1 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE QXS INFO-VAR INFO=HEAT VARIABLE=DUTY  &
        STREAM=QHX103XS
    SPEC “QXS” TO “0”
    TOL-SPEC “0.1”
    VARY STREAM-VAR STREAM=CWS1 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    LIMITS “100” “10000”

DESIGN-SPEC DS-QCOND
    DEFINE QXS INFO-VAR INFO=HEAT VARIABLE=DUTY STREAM=QCONDXS
    DEFINE CWIN STREAM-VAR STREAM=CWS2 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    SPEC “QXS” TO “0”
    TOL-SPEC “0.1”
    VARY STREAM-VAR STREAM=CWS2 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    LIMITS “5” “5000”

EO-CONV-OPTI
```

```
CALCULATOR H2IN
    IN-UNITS ENG
    DEFINE H2IN STREAM-VAR STREAM=120 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE OILIN STREAM-VAR STREAM=101 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
F       H2IN = 0.0198*OILIN
    READ-VARS OILIN

CALCULATOR HYDCRK
    IN-UNITS ENG
    DEFINE FEED STREAM-VAR STREAM=101 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE GDYLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
        SENTENCE=MASS-YIELD ID1=MIXED ID2=GDSL
    DEFINE PROYLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
        SENTENCE=MASS-YIELD ID1=MIXED ID2=PROPANE
    DEFINE CO2YLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
        SENTENCE=MASS-YIELD ID1=MIXED ID2=CO2
    DEFINE H2OYLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
        SENTENCE=MASS-YIELD ID1=MIXED ID2=H2O
    DEFINE FD105 STREAM-VAR STREAM=104 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE FD119 STREAM-VAR STREAM=119 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE H2IN STREAM-VAR STREAM=120 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE H2YLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
        SENTENCE=MASS-YIELD ID1=MIXED ID2=H2
    DEFINE NPYLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
        SENTENCE=MASS-YIELD ID1=MIXED ID2=NAPTHA
    DEFINE FGAS STREAM-VAR STREAM=FUELGAS SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE WXYLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
        SENTENCE=MASS-YIELD ID1=MIXED ID2=WAX
F       TTLFD = FD105+FD119
F       GDYLD = 0.649*(FEED+H2IN)/TTLFD
F       PROYLD = 0.082*(FEED+H2IN)/TTLFD
F       CO2YLD = 0.082*(FEED+H2IN)/TTLFD
F       H2OYLD = 0.050*(FEED+H2IN)/TTLFD
```

```
F      NPYLD = 0.0035*(FEED+H2IN)/TTLFD
F      WXYLD = 0.104*(FEED+H2IN)/TTLFD
F      SUM = GDYLD+PROYLD+CO2YLD+H2OYLD+NPYLD+WXYLD
F      DIFF = TTLFD - (SUM*TTLFD)
F       H2YLD = DIFF/TTLFD
F      WRITE(NHSTRY,*)SUM,DIFF,H2YLD
   READ-VARS FEED FD105 FD119 H2IN FGAS
   WRITE-VARS GDYLD PROYLD CO2YLD H2OYLD H2YLD NPYLD WXYLD
   BLOCK-OPTION SIM-LEVEL=4

STREAM-REPOR NOMOLEFLOW MASSFLOW

PROPERTY-REP NOPARAM-PLUS
;
```

Appendix 2: ASPEN Simulation Process of Renewable Diesel II (Hydrogenation-Derived Renewable Diesel)

Victoria Putsche
Center for Transportation Technologies and Systems
National Renewable Energy Laboratory[2]

A2-1 Introduction

A preliminary analysis was conducted for a hydrogenation-derived renewable diesel (HDRD) facility on the basis of the UOP process (UOP 2006). Material and energy balances were developed by using ASPEN Plus® 12.1 (uop_hdrd.inp). The overall goal of the study was to confirm the preliminary overall material and energy balances provided by UOP (UOP 2006; Markel 2006) and to provide input for a life-cycle analysis (LCA). The following report summarizes the basis for the analysis and its results.

A2-2 Design Basis and Process Description

HDRD is made from reacting hydrogen with oil or grease in a refinery-hydrotreating process. Two primary reactions occur in the conversion: hydrodeoxygenation and decarboxylation (UOP 2006)

Hydrodeoxygenation:

C_nCOOH (bio-oil) + $3\ H_2 \rightarrow$ C_{n+1} (HDRD) + $2\ H_2O$

Decarboxylation:

C_nCOOH (bio-oil) $\rightarrow$ C_n (HDRD) + CO_2

The selectivity of the reactions depends on the processing conditions.

For this analysis, the production of HDRD is based on the UOP process, which is composed of hydrogen production, hydrogenation, separation, distillation, and pressure swing adsorption (PSA). All of the unit operations were modeled except hydrogen production. It is assumed that

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hydrogen is supplied by a hydrogen plant. Figure A2-1 is a block flow diagram of the HDRD process.

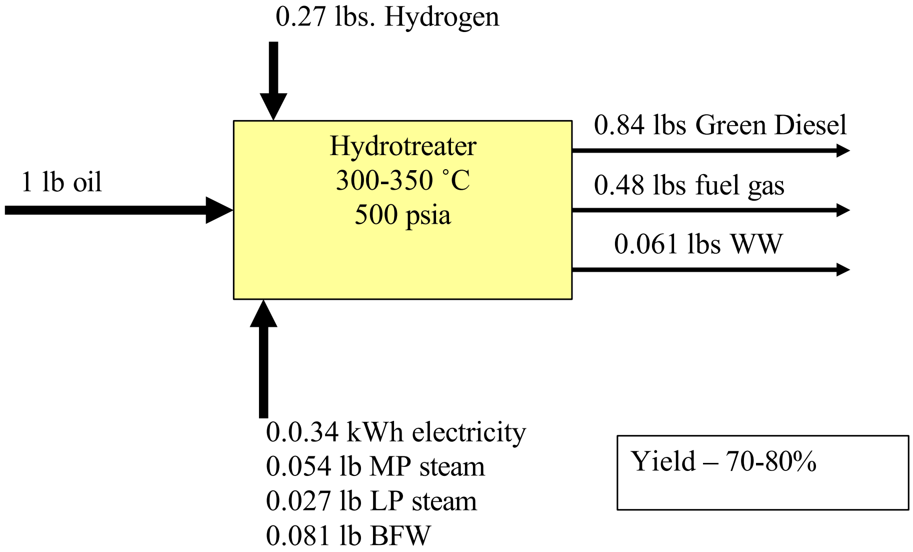

Figure A2-1 HDRD Block Flow Diagram

One of the important characteristics of the process is that energy demands are met off site. That is, the fuel gas product is not combusted on site to generate steam for the process; it is assumed that steam is sent to the process from an off-site source. Similarly, the process also generates a fuel gas, which is also sent off site and used for fuel. For this process configuration, the LCA will determine the emissions from the fuel gas combustion as well as the steam and electricity generation and will apportion it appropriately to the main process.

The renewable diesel process was modeled by using numerous assumptions and data sources. Table A2-1 summarizes the key design parameters and their sources.

Several of these assumptions, particularly the feedstock choice and facility size, require further explanation. The feedstock selected was soybean oil, even though many of the feedstocks in the literature were rapeseed oil or other oils, because it is the most prevalent oil in fuels production (i.e., biodiesel) and because one of the purposes of the study was to compare the environmental impacts of HDRD to biodiesel, and the most thorough LCA of biodiesel (Sheehan et al. 1998) was based on soybean oil. The facility size of 100 lb/h was selected as an easy, round number for the LCA. The results of most LCAs are shown on a pound of feed or product basis, since the impacts are directly scalable to throughput. Therefore, this simple number was selected, even though this would not be a typical facility size.

Table A2-1 Design Basis

Parameter	Value	Source
Feedstock		
Type	Soybean oil	Most common oil in US for biodiesel
Throughput	100 lb/h	For LCA analysis
Feedstock fatty acid composition (wt fraction)		
Linolenic acid		
Palmitic acid	0.075	
Stearic acid	0.11	
Oleic acid	0.041	
Linoleic acid	0.22	
Arachidic acid	0.54	
	0.014	
Hydrogenation design		
Temperature	325°C	UOP 2006
Pressure	500 psia	UOP 2006
Yields (per pound inlet feed)		
HDRD		UOP 2006
Water	84.15%	
CO_2	2.125%	
Propane	10.625%	
Hydrogen	2.9%	
	0.1%	

A2-3 Model Description

An ASPEN Plus® model (uop_hdrd) was developed for the pyrolysis process, largely on the basis of the UOP report (UOP 2006). ASPEN Plus® is a steady-state process simulator. Appendix A2-6 contains the input file for the model.

The ASPEN Plus® HDRD model has one flowsheet to model the four major process areas: hydrogenation, sour water separation, stripping, and pressure swing adsorption (PSA)/gas recycle. Each of these areas is briefly discussed, and the flow diagram from ASPEN Plus® is presented. The flow diagram shows only those unit operations modeled in ASPEN Plus®. Equipment used for operations such as conveyance, size reduction, and storage us generally not included in the model. The power requirements of this equipment, however, are included and are modeled as work streams.

ASPEN Plus® is composed of physical property and unit operation models that are combined into a process model. The simulation can be broken into three major sections: components (i.e., chemical species), physical property option sets (e.g., what set of physical property models to use), and the flowsheet (i.e., the series of unit operations). Each of these sections is described in more detail below.

Components

Fourteen components were modeled in the simulation; all were modeled as conventional (e.g., water) components in the mixed substream. The following is a list of the components in the simulation:

- Hydrogen – H_2
- Linolenic acid – $C_{18}H_{30}O_2$
- Palmitic acid – $C_{16}H_{32}O_2$
- Stearic acid – $C_{18}H_{36}O_2$
- Linoleic acid – $C_{18}H_{32}O_2$
- Arachidic acid – $C_{20}H_{40}O_2$
- Oleic acid – $C_{18}H_{34}O_2$
- Green Diesel – $C_{18}H_{38}$
- Water – H_2O
- Hydrogen Sulfide – H_2S
- Ammonia – NH_3
- Propane – C_3H_8
- Naptha
- Carbon dioxide – CO_2

Green diesel is not a specific compound but is a complex mixture of hydrocarbons; however, for simplicity, it was modeled as a single component, $C_{18}H_{38}$, which is within the range of diesel hydrocarbons. Green diesel was specified with a specific gravity of 0.78 (Marker, T. 2007) and a MW of 254. Naphtha was specified with a specific gravity of 0.7 and a MW of 100.

As noted earlier, the vegetable oil feed was modeled as a mixture of six fatty acids: linolenic acid, palmitic acid, stearic acid, linoleic acid, arachidic acid, and oleic acid. All of these components are available in the ASPEN Plus® databanks. Table A2-2 shows the molecular formula, the component name in the model, and the weight fraction in the feed of each fatty acid.

One Henry component, CO_2, was specified. The Henry's constants were obtained from ASPEN Plus®.

Table A2-2 Organic Acid Composition of Bio-Oil

Organic Fatty Acid	Composition	Component Name	Weight Fraction
Linolenic	$C_{18}H_{30}O_2$	LINOL3	0.075
Palmitic	$C_{16}H_{32}O_2$	PALM	0.11
Stearic	$C_{18}H_{36}O_2$	STEARIC	0.041
Oleic	$C_{18}H_{34}O_2$	OLEIC	0.22
Linoleic	$C_{18}H_{32}O_2$	LINOL2	0.54
Arachidic	$C_{20}H_{40}O_2$	ARACHID	0.014

Physical Property Option Sets

The physical property set selected was POLYUF with properties estimated by using the POLYNRTL method. Physical property databanks used in the simulation were PURE13, AQUEOUS, SOLIDS AND INORGANIC.

Flowsheet

One flowsheet was developed for the process: (A1000). The flowsheet is briefly discussed, and flow diagrams from ASPEN Plus® are presented. The flow diagrams (Figure A2-2) show only those unit operations modeled in ASPEN Plus®. Equipment used for operations such as conveyance and storage are generally not included in the model and are thus not shown. Similarly, certain complex unit operations (e.g., gas turbine) require several ASPEN Plus® models (e.g., compressors, reactors, heat exchangers).

Bio-oil is introduced into the process in stream 101. It is assumed to be at ambient conditions (i.e., 68°F and 14.7 psia) with a flow rate of a nominal 100 lb/h. The 100-lb/h value was selected as it would be easily scaled to any other value; since the model was developed to be the basis for an LCA, any flow rate would be reasonable.

Hydrogenation

As shown in Figure A2-2, the soybean oil feed (Stream 101) is pumped to 500 psia (P-101) and then mixed with recycle oil (Stream 110C) from the splitter, SP-101, following the sour water separator (S101). This stream is then heated to 290°F by exchange with hydrogenator effluent (Stream 106) in HX101+ and HX101−. It is then further heated to 370°F with medium-pressure steam, MPSS (150 psig). The next stage of the process is the hydrogenator, where the oil stream is combined with the inlet hydrogen (Stream 119) and reacted.

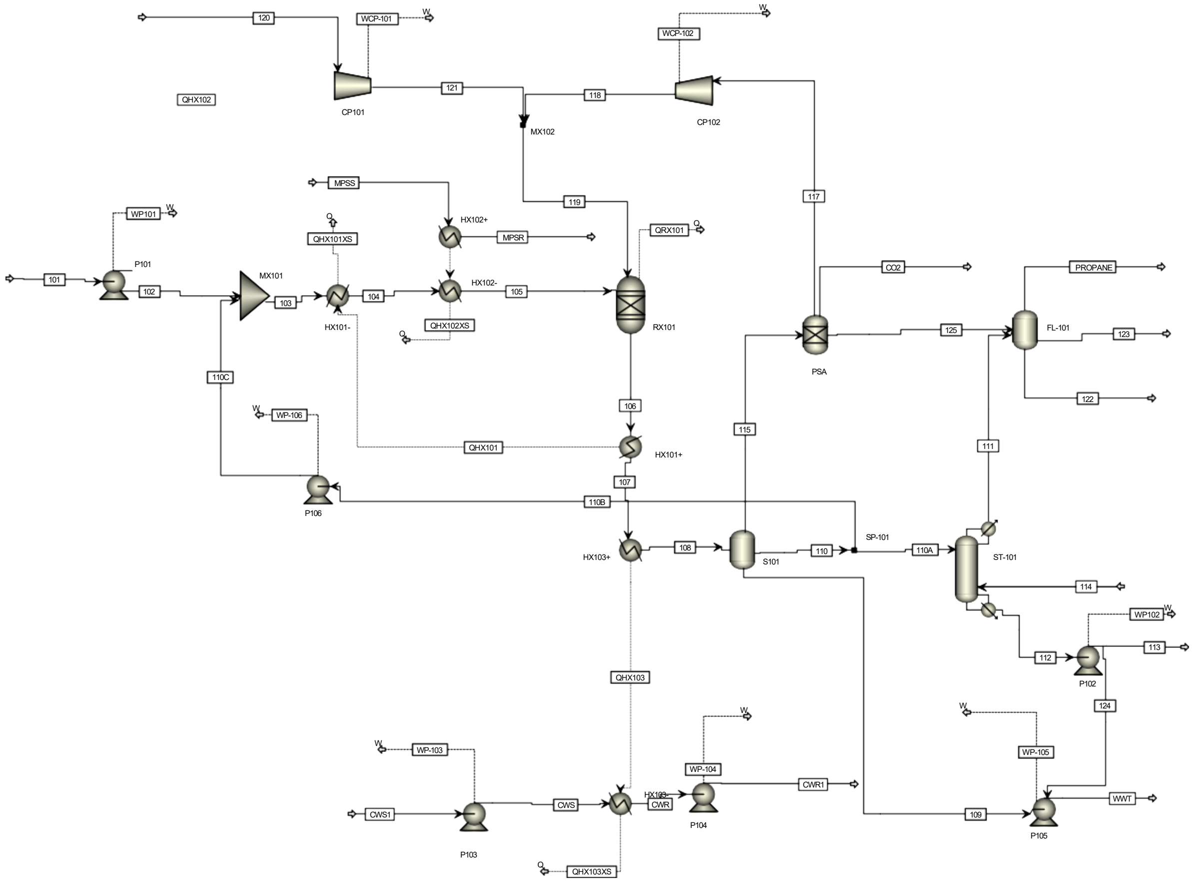

Figure A2-2 ASPEN Simulation Process Flowcharts FOR Renewable Diesel II

The hydrogenator (RX101) is modeled as an RYIELD reactor. All of the incoming oil is converted to gas (e.g., CO2, H2, propane), water, and green diesel (GDSL). As noted in the design basis, the yield of green diesel is estimated at 84.15% of the inlet feed streams on a mass basis. The hydrogenation reactions are exothermic, and there is excess heat (QRX101) after the reactor is brought to reaction temperature (325°C).

After the oil feed is preheated the hydrogenator effluent (Stream 107) is cooled with cooling water (Stream CWS1) to 100°F in HX103. The cooled reactor products are then sent to the sour water separation, S101.

Sour Water Separation

In sour water separation, the gases (Stream 115) are flashed off and sent to the PSA for recovery, and the aqueous stream is decanted and sent to wastewater treatment (Stream 109). After the separator, a portion of the organic stream (110B) is recycled to the hydrogenator inlet. The remainder (Stream 110A) is sent to a stripping column (ST-101) for product recovery.

Product Recovery

The product recovery area consists of a stripping column where LP (50 psig) steam (Stream 114) is used to remove the light ends from the green diesel product (112). The stripping column is modeled as a RADFRAC column with eight stages without a condenser or reboiler under atmospheric pressure.

The overheads are sent to the flash unit of the PSA system, FL-101. The product stream is taken from the bottom of the column (Stream 112).

Pressure Swing Adsorption (PSA)

The PSA system is a complex batch unit operation that was treated basically as a black box for this simulation. It is modeled as two unit operations in series, a separator block (PSA) followed by a flash block (FL-101). The separator block is assumed to remove all of the hydrogen in the overhead stream (111). The recovered hydrogen is then compressed (CP102) to 500 psia before introduction into the hydrogenator.

In addition to hydrogen, the PSA unit operation has two other outlet streams: CO_2 and Stream 125. The CO_2 stream contains all of the carbon dioxide from the operation and is released to the atmosphere. Stream 125 contains a mixture of water, propane, and other organics. These are separated in FL-101 modeled as a FLASH2. As shown in the diagram, FL-101 has two inlets (Streams 111 and 125) and three outlets: PROPANE and Streams 122 and 123. Stream 111 is the overheads from the stripping column, ST-101. PROPANE is a fuel gas, composed primarily of propane (93%) with small amounts of green diesel and CO_2.

A2-4 Results and Discussion

This effort was aimed at confirming the material and energy balances summarized for the UOP HDRD process as found in UOP (2006) and Markel (2006). As shown in Table A2-3, the ASPEN Plus® model shows good agreement with the published literature. All of the yields and utility requirements are similar between the model and the literature except cooling water. The uop_hdrd.bkp model predicts a much higher cooling water load than projected by UOP. This discrepancy can be due to many factors, including improved equipment design and heat integration in the UOP process and differing cooling water specifications (e.g., allowable temperature rise). The discrepancy was not explored further since cooling water is a very small

Table A2-3 Comparison of Overall Mass and Energy Balances

Feedstock	UOP Yield per 100 lb of feed	Current Analysis Yield per 100 lb of feed
Oil	100.00	100.00
H_2	2.72	2.72
LP steam	2.72	2.80
Products		
Propane mix gas	4.75	5.02
HDRD	84.19	85.23
CO_2		7.01
Waste water	6.11	8.27
Utilities		
Electricity (kWh)	3.39	2.34
LP Steam (into process)	2.72	2.80
MP steam	5.43	5.37
Cooling water	1,356	2,310
Boiler feed water	8.15	8.17
Total steam (Btu)		7,161

contributor to the impacts in an LCA. Table 3 compares the results of this modeling effort and the values from the UOP report (2006). Carbon dioxide was not reported in the UOP study.

The propane mix gas is composed of 93.3% propane, 5.7% CO_2, and 1% water. The lower heating value (LHV) of the mix is estimated at 18,568 Btu/lb. The entire mass balance for the simulation is contained in Appendix A2-6.

In addition to the material and energy balance, the analysis projected the air emissions from the process. As noted earlier, it is assumed that the fuel gas, which is primarily propane, is combusted with make-up natural gas in order to meet the energy demand of the process. Thus, it was assumed that there were minimal air emissions from the main process. The LCA analysis will provide the emissions from the combustion of the fuel gas and any other fuel needed to generate the necessary steam and electricity. This assessment is outside the process lines for this process configuration.

The UOP HDRD process uses hydrogenation to convert bio-oils like soybean oil into a diesel substitute. Several companies are looking into this process. This analysis developed an ASPEN Plus® model of the process and compared its results with published results by UOP and NREL (UOP 2006). Good agreement was obtained between the two studies. These results will be used to develop an LCA for this process.

A2-5 References

Marker, T., 2006, Email to V. Putsche with cc to C. Johnson of NREL, “Follow-up on Green Diesel and Green Gasoline LCA Requests,” Aug. 15.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, H. Shapouri, 1998, *An Overview of Biodiesel and Petroleum Diesel Life Cycles*, joint study sponsored by U.S. Department of Agriculture and U.S. Department of Energy, NREL/TP-580-24772.

UOP, 2006, *Opportunities for Biorenewables in Oil Refineries*, Final Technical Report, DOE Award Number DE-FG36-05GO15085, contributors were Terry Marker, John Petri, Tom Kalnes, Micke McCall, Dave Mackowiak, Bob Jerosky, Bill Reagan, Lazlo Nemeth, Mark Krawczyk (UOP); Stefan Czernik (NREL); Doug Elliott (PNNL); David Shonnard (Michigan Technological University).

A2-6 ASPEN Plus® Input File: UOP_HDRD.inp

```
;
;Input Summary created by Aspen Plus Rel. 13.1 at 18:15:55 Fri Sep 22, 2006
;Directory C:\AspenTech\Aspen Plus 2004  Filename C:\AspenTech\Aspen Plus 2004\uop_hdrd.inp
;



TITLE ‘HDRD - UOP’

IN-UNITS ENG DENSITY=‘lb/gal’ POWER=kW VOLUME=gal  &
    MOLE-DENSITY=‘lbmol/gal’ MASS-DENSITY=‘lb/gal’

DEF-STREAMS CONVEN ALL

DATABANKS PURE13  / AQUEOUS  / SOLIDS  / INORGANIC  /  &
    NOASPENPCD

PROP-SOURCES PURE13  / AQUEOUS  / SOLIDS  / INORGANIC

COMPONENTS
  H2 H2 /
  LINOL3 C18H30O2 /
```

```
    PALM C16H32O2 /
    STEARIC C18H36O2 /
    OLEIC C18H34O2 /
    LINOL2 C18H32O2 /
    ARACHID C20H40O2 /
    GDSL C18H38 /
    H2O H2O /
    H2S H2S /
    NH3 H3N /
    PROPANE C3H8 /
    NAPTHA /
    CO2 CO2

PC-USER
    IN-UNITS ENG
    PC-DEF ASPEN GDSL GRAV=0.78 MW=254.
    PC-DEF ASPEN NAPTHA GRAV=0.7 MW=100.

ADA-SETUP
    ADA-SETUP PROCEDURE=REL9

HENRY-COMPS HC-1 CO2

FLOWSHEET
    BLOCK RX101 IN=105 119 OUT=106 QRX101
    BLOCK S101 IN=108 OUT=115 110 109
    BLOCK P101 IN=101 OUT=102 WP101
    BLOCK P102 IN=112 OUT=113 19 WP102
    BLOCK CP102 IN=117 OUT=118 WCP-102
    BLOCK CP101 IN=120 OUT=121 WCP-101
    BLOCK HX101+ IN=106 20 OUT=107 QHX101
    BLOCK HX101- IN=103 QHX101 OUT=104 QHX101XS
    BLOCK HX102- IN=104 QHX102 OUT=105 QHX102XS
    BLOCK MX101 IN=102 OUT=103
    BLOCK MX102 IN=118 121 OUT=119
    BLOCK PSA IN=115 OUT=117 CO2 125
    BLOCK ST-101 IN=114 110A OUT=111 112
    BLOCK HX103+ IN=107 OUT=108 QHX103
    BLOCK HX103- IN=CWS QHX103 OUT=CWR QHX103XS
    BLOCK HX102+ IN=MPSS OUT=MPSR QHX102
```

```
    BLOCK SP-101 IN=110 OUT=110A 110B
    BLOCK P105 IN=109 18 OUT=WWT WP-105
    BLOCK P106 IN=110B OUT=110C WP-106
    BLOCK P103 IN=CWS1 OUT=CWS WP-103
    BLOCK P104 IN=CWR OUT=CWR1 WP-104
    BLOCK FL-101 IN=125 111 OUT=PROPANE 17 16
    BLOCK B8 IN=19 OUT=18
    BLOCK B9 IN=QRX101 OUT=20 21

PROPERTIES POLYUF HENRY-COMPS=HC-1
    PROPERTIES POLYNRTL

PROP-DATA HENRY-1
    IN-UNITS ENG
    PROP-LIST HENRY
    BPVAL CO2 H2O 175.2762325 -15734.78987 -21.66900000  &
        6.12550005E-4 31.73000375 175.7300026 0.0

STREAM 101
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=68. PRES=14.7 MASS-FLOW=100.
    MASS-FRAC LINOL3 0.075 / PALM 0.11 / STEARIC 0.041 /  &
        OLEIC 0.22 / LINOL2 0.54 / ARACHID 0.014

STREAM 114
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=400. PRES=50. MASS-FLOW=2.8
    MASS-FRAC H2O 1.

STREAM 117
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=68. PRES=14.7 MASS-FLOW=1.
    MASS-FRAC H2 1.

STREAM 120
    IN-UNITS ENG
    SUBSTREAM MIXED TEMP=68. PRES=14.7 MASS-FLOW=100.
    MASS-FRAC H2 1.
```

```
STREAM CWS
   IN-UNITS ENG
   SUBSTREAM MIXED TEMP=35. <C> PRES=500. MASS-FLOW=100.
   MASS-FRAC H2O 1.

STREAM CWS1
   IN-UNITS ENG
   SUBSTREAM MIXED TEMP=35. <C> PRES=14.7 MASS-FLOW=100.
   MASS-FRAC H2O 1.

STREAM MPSS
   IN-UNITS ENG
   SUBSTREAM MIXED TEMP=667. PRES=150. MASS-FLOW=100.
   MASS-FRAC H2O 1.

DEF-STREAMS HEAT 20

DEF-STREAMS HEAT 21

DEF-STREAMS HEAT QHX101

DEF-STREAMS HEAT QHX101XS

DEF-STREAMS HEAT QHX102

DEF-STREAMS HEAT QHX102XS

DEF-STREAMS HEAT QHX103

DEF-STREAMS HEAT QHX103XS

DEF-STREAMS HEAT QRX101

DEF-STREAMS WORK WCP-101

DEF-STREAMS WORK WCP-102

DEF-STREAMS WORK WP-103

DEF-STREAMS WORK WP-104
```

```
DEF-STREAMS WORK WP-105

DEF-STREAMS WORK WP-106

DEF-STREAMS WORK WP101

DEF-STREAMS WORK WP102

BLOCK B8 MIXER

BLOCK MX101 MIXER
   IN-UNITS ENG

BLOCK MX102 MIXER
   IN-UNITS ENG

BLOCK B9 FSPLIT
   FRAC 20 0.15

BLOCK SP-101 FSPLIT
   IN-UNITS ENG
   FRAC 110A 0.99

BLOCK PSA SEP
   IN-UNITS ENG
   PARAM
   FRAC STREAM=117 SUBSTREAM=MIXED COMPS=H2 H2O PROPANE CO2  &
      FRACS=1. 0. 0. 0.
   FRAC STREAM=CO2 SUBSTREAM=MIXED COMPS=PROPANE CO2 FRACS= &
      0. 1.

BLOCK HX101+ HEATER
   IN-UNITS ENG
   PARAM TEMP=100. <C> PRES=500.

BLOCK HX101- HEATER
   IN-UNITS ENG
   PARAM TEMP=290. <C> PRES=500.
```

```
BLOCK HX102+ HEATER
   IN-UNITS ENG
   PARAM PRES=500. VFRAC=0.

BLOCK HX102- HEATER
   IN-UNITS ENG
   PARAM TEMP=325. <C> PRES=500.

BLOCK HX103+ HEATER
   IN-UNITS ENG
   PARAM TEMP=100. PRES=500.

BLOCK HX103- HEATER
   IN-UNITS ENG
   PARAM PRES=500. DELT=15.

BLOCK FL-101 FLASH2
   PARAM TEMP=68. PRES=14.7
   BLOCK-OPTION  FREE-WATER=YES

BLOCK S101 FLASH2
   IN-UNITS ENG
   PARAM TEMP=100. PRES=175.
   BLOCK-OPTION FREE-WATER=YES

BLOCK ST-101 RADFRAC
   IN-UNITS ENG
   PARAM NSTAGE=8
   COL-CONFIG CONDENSER=NONE REBOILER=NONE
   FEEDS 114 9 / 110A 1
   PRODUCTS 111 1 V / 112 8 L
   P-SPEC 1 14.7
   COL-SPECS DP-STAGE=1.

BLOCK RX101 RYIELD
   IN-UNITS ENG
   PARAM TEMP=325. <C> PRES=500.
   MASS-YIELD MIXED GDSL 0.8415 / H2O 0.02125 / CO2  &
      0.10625 / PROPANE 0.029 / H2 0.001
```

```
BLOCK P101 PUMP
   IN-UNITS ENG
   PARAM PRES=500.

BLOCK P102 PUMP
   IN-UNITS ENG
   PARAM DELP=10.
   BLOCK-OPTION  FREE-WATER=YES

BLOCK P103 PUMP
   IN-UNITS ENG
   PARAM PRES=500. PUMP-TYPE=TURBINE

BLOCK P104 PUMP
   IN-UNITS ENG
   PARAM DELP=10.

BLOCK P105 PUMP
   IN-UNITS ENG
   PARAM DELP=10.

BLOCK P106 PUMP
   IN-UNITS ENG
   PARAM DELP=10. PUMP-TYPE=PUMP

BLOCK CP101 COMPR
   IN-UNITS ENG
   PARAM TYPE=ISENTROPIC PRES=500. MODEL-TYPE=TURBINE

BLOCK CP102 COMPR
   IN-UNITS ENG
   PARAM TYPE=ISENTROPIC PRES=500. MODEL-TYPE=TURBINE

DESIGN-SPEC DS-HX101
   IN-UNITS ENG
   DEFINE QXS INFO-VAR INFO=HEAT VARIABLE=DUTY  &
      STREAM=QHX101XS
   SPEC “QXS” TO “0.0”
   TOL-SPEC “0.1”
   VARY BLOCK-VAR BLOCK=HX101+ VARIABLE=TEMP SENTENCE=PARAM
```

```
    LIMITS “100” “617”

DESIGN-SPEC DS-HX102
    IN-UNITS ENG
    DEFINE STMIN STREAM-VAR STREAM=MPSS SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE QXS INFO-VAR INFO=HEAT VARIABLE=DUTY  &
        STREAM=QHX102XS
    SPEC “QXS” TO “0”
    TOL-SPEC “0.1”
    VARY STREAM-VAR STREAM=MPSS SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    LIMITS “0” “10000”

DESIGN-SPEC DS-HX103
    IN-UNITS ENG
    DEFINE CWIN STREAM-VAR STREAM=CWS1 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE QXS INFO-VAR INFO=HEAT VARIABLE=DUTY  &
        STREAM=QHX103XS
    SPEC “QXS” TO “0”
    TOL-SPEC “0.1”
    VARY STREAM-VAR STREAM=CWS1 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    LIMITS “100” “10000”

EO-CONV-OPTI

CALCULATOR H2IN
    IN-UNITS ENG
    DEFINE H2IN STREAM-VAR STREAM=120 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
    DEFINE OILIN STREAM-VAR STREAM=101 SUBSTREAM=MIXED  &
        VARIABLE=MASS-FLOW
F       H2IN = 0.0272*OILIN
    READ-VARS OILIN

CALCULATOR HYDCRK
    IN-UNITS ENG
    DEFINE FEED STREAM-VAR STREAM=101 SUBSTREAM=MIXED  &
```

```
      VARIABLE=MASS-FLOW
    DEFINE GDYLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
      SENTENCE=MASS-YIELD ID1=MIXED ID2=GDSL
    DEFINE PROYLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
      SENTENCE=MASS-YIELD ID1=MIXED ID2=PROPANE
    DEFINE CO2YLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
      SENTENCE=MASS-YIELD ID1=MIXED ID2=CO2
    DEFINE H2OYLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
      SENTENCE=MASS-YIELD ID1=MIXED ID2=H2O
    DEFINE FD105 STREAM-VAR STREAM=105 SUBSTREAM=MIXED  &
      VARIABLE=MASS-FLOW
    DEFINE FD119 STREAM-VAR STREAM=119 SUBSTREAM=MIXED  &
      VARIABLE=MASS-FLOW
    DEFINE H2IN STREAM-VAR STREAM=120 SUBSTREAM=MIXED  &
      VARIABLE=MASS-FLOW
    DEFINE H2YLD BLOCK-VAR BLOCK=RX101 VARIABLE=YIELD  &
      SENTENCE=MASS-YIELD ID1=MIXED ID2=H2
F      TTLFD = FD105+FD119
F      GDYLD = 0.828*(FEED+H2IN)/TTLFD
F      PROYLD = 0.047*(FEED+H2IN)/TTLFD
F      CO2YLD = 0.075*(FEED+H2IN)/TTLFD
F      H2OYLD = 0.050*(FEED+H2IN)/TTLFD
F      SUM = GDYLD+PROYLD+CO2YLD+H2OYLD
F      DIFF = TTLFD - (SUM*TTLFD)
F       H2YLD = DIFF/TTLFD
F      WRITE(NHSTRY,*)SUM,DIFF,H2YLD
    READ-VARS FEED FD105 FD119 H2IN
    WRITE-VARS GDYLD PROYLD CO2YLD H2OYLD H2YLD
    BLOCK-OPTION SIM-LEVEL=4

TEAR
    TEAR 117

STREAM-REPOR NOMOLEFLOW MASSFLOW
```

PROPERTY-REP NOPARAM-PLUS

	101	102	103	104	105	106	107	108	109	110
	P101	MX101	HX101-	HX102-	RX101	4<	;<	S101	P105	SP-101
		P101	MX101	HX101-	HX102-	RX101	4<	4<	S101	S101
	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	MIXED	MIXED	LIQUID	LIQUID
Substream: MIXED										
Mass Flow lb/hr										
H2	0	0	0	0	0	1.084999	1.084999	1.084999	0	2.04E-07
LINOL3	7.5	7.5	7.5	7.5	7.5	0	0	0	0	0
PALM	11	11	11	11	11	0	0	0	0	0
STEARIC	4.1	4.1	4.1	4.1	4.1	0	0	0	0	0
OLEIC	22	22	22	22	22	0	0	0	0	0
LINOL2	54	54	54	54	54	0	0	0	0	0
ARACHID	1.4	1.4	1.4	1.4	1.4	0	0	0	0	0
GDSL	0	0	0	0	0	85.05216	85.05216	85.05216	0	85.052
H2O	0	0	0	0	0	5.54688	5.54688	5.54688	5.445815	0.0218078
H2S	0	0	0	0	0	0	0	0	0	0
NH3	0	0	0	0	0	0	0	0	0	0
PROPANE	0	0	0	0	0	4.82784	4.82784	4.82784	0	2.468692
NAPTHA	0	0	0	0	0	0	0	0	0	0
CO2	0	0	0	0	0	7.29312	7.29312	7.29312	0	0.2876933
Total Flow lbmol/hr	0.3591571	0.3591571	0.3591571	0.3591571	0.3591571	1.456175	1.456175	1.456175	0.3022887	0.3985819
Total Flow lb/hr	100	100	100	100	100	103.805	103.805	103.805	5.445815	87.8302
Total Flow cuft/hr	1.786671	1.795957	1.795957	1.975812	2.061152	29.28627	25.1053	10.49892	0.0877934	1.907063
Temperature F	68	80.58947	80.58948	290	370	617	507.6096	100	100	100
Pressure psi	14.7	500	500	500	500	500	500	500	175	175
Vapor Frac	0	0	0	0	0	0.8408124	0.7704222	0.4824463	0	0
Liquid Frac	1	1	1	1	1	0.1591876	0.2295778	0.5175537	1	1

PROPERTY-REP NOPARAM-PLUS (Cont.)

	101	102	103	104	105	106	107	108	109	110
	P101	MX101	HX101-	HX102-	RX101	4<	;<	S101	P105	SP-101
		P101	MX101	HX101-	HX102-	RX101	4<	4<	S101	S101
	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	MIXED	MIXED	LIQUID	LIQUID
Solid Frac	0	0	0	0	0	0	0	0	0	0
Enthalpy Btu/lbmol	-3.14E+05	-3.12E+05	-3.12E+05	-2.83E+05	-2.71E+05	-70801.07	-77885.8	-1.00E+05	-1.22E+05	-1.99E+05
Enthalpy Btu/lb	-1126.343	-1120.916	-1120.916	-1017.751	-971.6202	-993.1961	-1092.581	-1406.734	-6797.624	-903.7778
Enthalpy Btu/hr	-1.13E+05	-1.12E+05	-1.12E+05	-1.02E+05	-97162.02	-1.03E+05	-1.13E+05	-1.46E+05	-37018.6	-79378.98
Entropy Btu/lbmol-R	-415.036	-412.2374	-412.2374	-367.7857	-351.4557	-80.66001	-87.58823	-118.2502	-38.21506	-382.6785
Entropy Btu/lb-R	-1.490631	-1.48058	-1.48058	-1.320929	-1.262278	-1.131497	-1.228686	-1.658812	-2.121258	-1.736632
Density lbmol/gal	0.0268725	0.0267335	0.0267335	0.0243	0.0232939	6.65E-03	7.75E-03	0.0185411	0.4602862	0.0279396
Density lb/gal	7.482102	7.443416	7.443416	6.765855	6.485721	0.4738298	0.5527402	1.321727	8.292184	6.156685
Average MW	278.4297	278.4297	278.4297	278.4297	278.4297	71.28609	71.28609	71.28609	18.01528	220.3567
Liq Vol 60F cuft/hr	1.803603	1.803603	1.803603	1.803603	1.803603	2.596039	2.596039	2.596039	0.0874017	1.834368

	110A	110B	110C	111	112	113	114	115	117	118
	ST-101	P106	MX101	FL-101	P102		ST-101	PSA	CP102	MX102
	SP-101	SP-101	P106	ST-101	ST-101	P102		S101	PSA	CP102
	LIQUID	MISSING	MISSING	VAPOR	LIQUID	LIQUID	VAPOR	VAPOR	VAPOR	VAPOR
Substream: MIXED										
Mass Flow lb/hr										
H2	2.04E-07	0	0	2.04E-07	4.05E-35	4.05E-35	0	1.084998	1.084999	1.084999
LINOL3	0	0	0	0	0	0	0	0	0	0
PALM	0	0	0	0	0	0	0	0	0	0
STEARIC	0	0	0	0	0	0	0	0	0	0
OLEIC	0	0	0	0	0	0	0	0	0	0
LINOL2	0	0	0	0	0	0	0	0	0	0

PROPERTY-REP NOPARAM-PLUS (Cont.)

	101	102	103	104	105	106	107	108	109	110
	P101	MX101	HX101-	HX102-	RX101	4<	;<	S101	P105	SP-101
		P101	MX101	HX101-	HX102-	RX101	4<	4<	S101	S101
	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	MIXED	MIXED	LIQUID	LIQUID
ARACHID	0	0	0	0	0	0	0	0	0	0
GDSL	85.052	0	0	1.60E-04	85.05184	85.05184	0	1.58E-04	0	0
H2O	0.0218078	0	0	0.4588025	2.363005	0.029885	2.8	0.0792568	0	0
H2S	0	0	0	0	0	0	0	0	0	0
NH3	0	0	0	0	0	0	0	0	0	0
PROPANE	2.468692	0	0	2.321827	0.1468655	0.1468655	0	2.359148	0	0
NAPTHA	0	0	0	0	0	0	0	0	0	0
CO2	0.2876933	0	0	0.2876933	4.45E-12	4.45E-12	0	7.005427	0	0
Total Flow lbmol/hr	0.3985819	0	0	0.0846584	0.469347	0.3398392	0.1554236	0.7553041	0.5382258	0.5382258
Total Flow lb/hr	87.8302	0	0	3.068483	87.56171	85.22859	2.8	10.52899	1.084999	1.084999
Total Flow cuft/hr	1.907065	0	0	34.10666	1.85258	1.832826	19.0754	25.87814	18.60182	8.231991
Temperature F	100.002			98.90795	143.0657	149.9646	297.7949	100	99.97435	240.933
Pressure psi	175		500	14.7	21.7	31.7	64.7	175	175	500
Vapor Frac	0			1	0	0	1	1	1	1
Liquid Frac	1			0	1	1	0	0	0	0
Solid Frac	0			0	0	0	0	0	0	0
Enthalpy Btu/lbmol	-1.99E+05			-72054.6	-1.90E+05	-2.16E+05	-1.02E+05	-39284.66	163.5656	1154.758
Enthalpy Btu/lb	-903.7778			-1987.963	-1018.401	-861.4131	-5676.514	-2818.112	81.13857	572.831
Enthalpy Btu/hr	-79378.98			-6100.031	-89172.93	-73417.02	-15894.24	-29671.86	88.03524	621.5208
Entropy Btu/lbmol-R	-382.6781			-40.91684	-319.5699	-425.8229	-10.82218	-7.527309	-4.635141	-5.164754
Entropy Btu/lb-R	-1.73663			-1.128883	-1.712954	-1.69792	-0.6007222	-0.5399766	-2.299314	-2.562034
Density lbmol/gal	0.0279396			3.32E-04	0.0338676	0.0247868	1.09E-03	3.90E-03	3.87E-03	8.74E-03
Density lb/gal	6.156679			0.0120268	6.318376	6.216305	0.0196224	0.0543903	7.80E-03	0.0176194

PROPERTY-REP NOPARAM-PLUS (Cont.)

	101	102	103	104	105	106	107	108	109	110
	P101	MX101	HX101-	HX102-	RX101	4<	;<	S101	P105	SP-101
		P101	MX101	HX101-	HX102-	RX101	4<	4<	S101	S101
	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	MIXED	MIXED	LIQUID	LIQUID
Average MW	220.3567			36.24543	186.5607	250.7909	18.01528	13.94006	2.01588	2.01588
Liq Vol 60F cuft/hr	1.834368	0	0	0.0864746	1.792832	1.755387	0.0449381	0.6742691	0.4617512	0.4617512

	119	120	121	122	123	124	125	CO2	CWR	CWR1
	RX101	CP101	MX102			P105	FL-101		P104	
	MX102		CP101	FL-101	FL-101	P102	PSA	PSA	HX103-	P104
	VAPOR	VAPOR	VAPOR	LIQUID	LIQUID	LIQUID	MIXED	VAPOR	LIQUID	LIQUID
Substream: MIXED										
Mass Flow lb/hr										
H2	3.804999	2.72	2.72	0	0	0	0	0	0	0
LINOL3	0	0	0	0	0	0	0	0	0	0
PALM	0	0	0	0	0	0	0	0	0	0
STEARIC	0	0	0	0	0	0	0	0	0	0
OLEIC	0	0	0	0	0	0	0	0	0	0
LINOL2	0	0	0	0	0	0	0	0	0	0
ARACHID	0	0	0	0	0	0	0	0	0	0
GDSL	0	0	0	2.84E-04	0	0	1.58E-04	0	0	0
H2O	0	0	0	4.63E-08	0.4894927	2.33312	0.0792568	0	2309.68	2309.68
H2S	0	0	0	0	0	0	0	0	0	0
NH3	0	0	0	0	0	0	0	0	0	0
PROPANE	0	0	0	1.48E-05	0	0	2.359148	0	0	0
NAPTHA	0	0	0	0	0	0	0	0	0	0

PROPERTY-REP NOPARAM-PLUS (Cont.)

	101	102	103	104	105	106	107	108	109	110
	P101	MX101	HX101-	HX102-	RX101	4<	;<	S101	P105	SP-101
		P101	MX101	HX101-	HX102-	RX101	4<	4<	S101	S101
	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	MIXED	MIXED	LIQUID	LIQUID
CO2	0	0	0	3.64E-08	0	0	0	7.005427	0	0
Total Flow lbmol/hr	1.887512	1.349287	1.349287	1.46E-06	0.0271709	0.1295079	0.0578996	0.1591788	128.2067	128.2067
Total Flow lb/hr	3.804999	2.72	2.72	2.99E-04	0.4894927	2.33312	2.438563	7.005427	2309.68	2309.68
Total Flow cuft/hr	42.90768	520.0834	34.66854	6.53E-06	7.85E-03	0.0381251	1.507645	5.167461	37.93036	37.93266
Temperature F	586.7733	68	724.6138	68	68	149.9646	99.97435	99.97435	110.4626	110.571
Pressure psi	500	14.7	500	14.7	14.7	31.7	175	175	500	510
Vapor Frac	1	1	1	0	0	0	0.9295689	1	0	0
Liquid Frac	0	0	0	1	1	1	0.070431	0	1	1
Solid Frac	0	0	0	0	0	0	0	0	0	0
Enthalpy Btu/lbmol	3577.495	-61.40031	4543.916	-1.88E+05	-1.23E+05	-1.22E+05	-50942.12	-1.69E+05	-1.22E+05	-1.22E+05
Enthalpy Btu/lb	1774.657	-30.45832	2254.061	-914.9968	-6829.944	-6748.178	-1209.537	-3843.429	-6786.474	-6786.371
Enthalpy Btu/hr	6752.566	-82.84663	6131.045	-0.2738398	-3343.207	-15744.31	-2949.533	-26924.86	-1.57E+07	-1.57E+07
Entropy Btu/lbmol-R	-2.354373	-0.1171418	-1.486812	-363.1769	-39.26957	-36.67663	-66.63749	-4.062922	-37.84993	-37.8467
Entropy Btu/lb-R	-1.167913	-0.0581095	-0.7375498	-1.771269	-2.179792	-2.035862	-1.582198	-0.0923185	-2.10099	-2.100811
Density lbmol/gal	5.88E-03	3.47E-04	5.20E-03	0.02986	0.4624672	0.4541016	5.13E-03	4.12E-03	0.4518477	0.4518203
Density lb/gal	0.0118546	6.99E-04	0.0104882	6.122437	8.331475	8.180767	0.2162236	0.1812281	8.140163	8.139668
Average MW	2.01588	2.01588	2.01588	205.0377	18.01528	18.01528	42.11703	44.0098	18.01528	18.01528
Liq Vol 60F cuft/hr	1.619323	1.157571	1.157571	6.32E-06	7.86E-03	0.037445	0.0759562	0.1365617	37.06883	37.06883

	CWS	CWS1	MPSR	MPSS	PROPANE	WWT
	HX103-	P103		4<		
	P103		4<		FL-101	P105
	LIQUID	LIQUID	LIQUID	VAPOR	VAPOR	LIQUID
Substream: MIXED						
Mass Flow lb/hr						
H2	0	0	0	0	2.04E-07	0
LINOL3	0	0	0	0	0	0
PALM	0	0	0	0	0	0
STEARIC	0	0	0	0	0	0
OLEIC	0	0	0	0	0	0
LINOL2	0	0	0	0	0	0
ARACHID	0	0	0	0	0	0
GDSL	0	0	0	0	3.35E-05	0
H2O	2309.68	2309.68	5.372242	5.372242	0.0485666	7.778936
H2S	0	0	0	0	0	0
NH3	0	0	0	0	0	0
PROPANE	0	0	0	0	4.68096	0
NAPTHA	0	0	0	0	0	0
CO2	0	0	0	0	0.2876933	0
Total Flow lbmol/hr	128.2067	128.2067	0.2982047	0.2982047	0.1153857	0.4317965
Total Flow lb/hr	2309.68	2309.68	5.372242	5.372242	5.017253	7.778936
Total Flow cuft/hr	37.61554	37.60596	0.1048887	15.27979	43.78178	0.1280346
Temperature F	95.46259	95	366.04	366.0404	68	114.4461
Pressure psi	500	14.7	164.7	164.7	14.7	41.7
Vapor Frac	0	0	0	1	1	0
Liquid Frac	1	1	1	0	0	1
Solid Frac	0	0	0	0	0	0
Enthalpy Btu/lbmol	-1.23E+05	-1.23E+05	-1.17E+05	-1.02E+05	-53610.59	-1.22E+05
Enthalpy Btu/lb	-6800.593	-6801.025	-6510.467	-5651.786	-1232.925	-6782.69
Enthalpy Btu/hr	-1.57E+07	-1.57E+07	-34975.8	-30362.76	-6185.896	-52762.11
Entropy Btu/lbmol-R	-38.29923	-38.31317	-30.87826	-12.05098	-59.06788	-37.73145
Entropy Btu/lb-R	-2.125931	-2.126704	-1.714004	-0.6689311	-1.35843	-2.094414
Density lbmol/gal	0.4556294	0.4557454	0.3800617	2.61E-03	3.52E-04	0.4508374
Density lb/gal	8.208291	8.210381	6.846918	0.0470009	0.0153193	8.121961
Average MW	18.01528	18.01528	18.01528	18.01528	43.48245	18.01528
Liq Vol 60F cuft/hr	37.06883	37.06883	0.0862209	0.0862209	0.1545686	0.1248467

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